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Timing Synchronization and Frequency Offset Estimation for OFDMA/TDD Mode in Downlink of IEEE 802.16-2004

Fahimeh Rahbari and Hamid Reza Bakhshi

***Abstract*—Timing and frequency synchronization are the important task in receiver. This paper proposes a timing synchronization and carrier frequency offset (CFO) estimation algorithm for orthogonal frequency division multiple access (OFDMA) downlink in IEEE 802.16e standard. This method has high performance and estimates CFO. The proposed scheme utilizes the conjugate symmetry property of preamble structure. Simulations are conducted for AWGN and multipath channels to demonstrate the performance of the proposed timing metric. Our proposed method can achieve reasonable performance at low SNR.**

***Keywords*—timing synchronization, carrier frequency offset estimation, IEEE 802.16, AWGN channel, multipath fading channel.**

I. INTRODUCTION

ORTHOGONAL frequency division multiple access (OFDMA) is one of the physical layer modulation techniques in wireless metropolitan area network (WMAN) standards [1], [2] for fixed and mobile broadband wireless access (BWA) systems, respectively.

Orthogonal frequency division multiplexing (OFDM) is the basic modulation technique in OFDMA and is very sensitive to symbol time misalignments and carrier frequency offsets .In OFDM, symbol-timing errors will cause inter-symbol interference (lSI) and inter-channel interference (lCI).

Therefore, the symbol timing synchronization or the frame boundary alignment must be achieved within an acceptable limit [3], [4]. However, similar to Orthogonal Frequency Division Multiplexing (OFDM), OFDMA is highly sensitive to symbol timing errors. Synchronization is an important issue in transceiver design, especially for coherent wireless transmission. In WiMAX systems, based on the IEEE 802.16e OFDMA physical layer specifications, synchronization involves synchronization of carrier frequency and timing as well as identification of the preamble index. [5].

Synchronization methods for OFDM can be used in downlink of OFDMA systems. For IEEE802.16e, the preamble which is the first symbol of a DL subframe owns special features in time and frequency domain. There are some methods that utilized cyclic prefix (CP) [6]. And there are some methods exploited features of preamble [7]–[12].

In this paper, we propose a metric method that do timing synchronization and can estimate CFO by knowing preamble in receiver. The proposed method has high performance even in low SNR. The following sections of this paper are organized as follows: in Sect. 2, the system model and the conjugate symmetry character of BPSK-OFDM symbol are described. In Sect. 3, we present the existing methods. In Sect. 4, we introduce our proposed algorithm. In Sect. 5, simulation results are demonstrated and finally the conclusion is given in Section 6.

II. THE SYSTEM MODEL AND THE CONJUGATE SYMMETRY CHARACTER OF BPSK-OFDM SYMBOL

OFDM system could be considered as the one of frequency division multiplex (FDM) technique that is achieved by subdividing the available bandwidth into multiple channels. The system is obtained by using parallel data transmission. Then, each parallel data transmission is modulated by different carrier frequencies using phase shift keying (PSK) or quadrature amplitude modulation (QAM), i.e., an OFDM signal contains a sum of subcarriers that are PSK or QAM modulation.Also, OFDM can be treated as a modulation technique with the view of the relation between input and output signals. To reduce the complexity of OFDM modem implementation, the fast Fourier transform (FFT) is employed to replace the banks of sinusoidal generator and the demodulation significantly. In general, an OFDM system at least contains the function of parallel transmission, signal mapping and IFFT/FFT.

Figure 1 illustrates the block diagram of the baseband, discrete-time FFT-based BPSK-OFDM systems model. Each parallel data is mapped with BPSK scheme and, then, those data are modulated by an IFFT on N-parallel subcarriers. The resulting OFDM symbol extended with a cyclic prefix is serially transmitted over a discrete-time channel. The receiver performs the inverse process of the transmitter, the data are retrieved by a FFT and then, demapped with BPSK to obtain the estimated data [13].

Without timing offset, the baseband discrete-time transmitted signal $s_i(k)$ is as [14]:

$$s_i(k) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} x_{i,n} e^{j\frac{2\pi}{N}nk}, \quad 0 \le k \le N-1 \qquad (1)$$

Where N denotes the IFFT window size, $s_i(k)$ represents the kth sample of the ith OFDM symbol, and $x_{i,n}$ represents the nth subcarrier in the ith symbol interval. In (1), $x_{i,n}$ is

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F. Rahbari is with the Department of Electrical Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran (e-mail: Fahimeh.rahbari@gmail.com).

H. R. Bakhshi is with the Department of Electrical Engineering, Shahed University, Tehran, Iran (e-mail: Bakhshi@shahed.ac.ir).

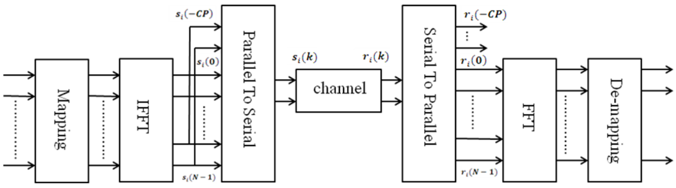

Fig. 1. The model of baseband, discrete-time BPSK-OFDM system [13].

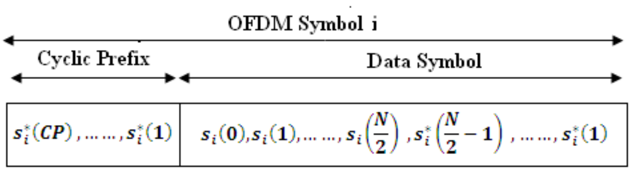

Fig. 2. The structure of BPSK-OFDM symbol with the conjugate symmetry character [13].

a real value when BPSK mapping is used. The equations of the IFFT output have the following characters:

$$real(s_i(k)) = real\left(\frac{1}{\sqrt{N}}\sum_{n=0}^{N-1} x_{i,n}e^{j\frac{2\pi}{N}nk}\right) =$$

$$= \frac{1}{\sqrt{N}}\sum_{n=0}^{N-1} x_{i,n}\cos\left(e^{j\frac{2\pi}{N}nk}\right)$$

$$image(s_i(k)) = image\left(\frac{1}{\sqrt{N}}\sum_{n=0}^{N-1} x_{i,n}e^{j\frac{2\pi}{N}nk}\right) =$$

$$= \frac{1}{\sqrt{N}}\sum_{n=0}^{N-1} x_{i,n}\sin\left(e^{j\frac{2\pi}{N}nk}\right)$$

$$real(s_i(N-k)) = real\left(\frac{1}{\sqrt{N}}\sum_{n=0}^{N-1} x_{i,n}e^{j\frac{2\pi}{N}n(N-k)}\right) =$$

$$= \frac{1}{\sqrt{N}}\sum_{n=0}^{N-1} x_{i,n}\cos\left(e^{j\frac{2\pi}{N}nk}\right)$$

$$image(s_i(N-k)) = image\left(\frac{1}{\sqrt{N}}\sum_{n=0}^{N-1} x_{i,n}e^{j\frac{2\pi}{N}n(N-k)}\right) =$$

$$= -\frac{1}{\sqrt{N}}\sum_{n=0}^{N-1} x_{i,n}\sin\left(e^{j\frac{2\pi}{N}nk}\right) \qquad (2)$$

Where $real(x)$ and $image(x)$ denote the real part and image part of complex number (x). In (2), it is the character for the real and image part of BPSK-OFDM symbol. Also, it can be expressed in (3).

$$s_i(N-k) = s_i^*(k), \quad k \neq 0 \ or\ \frac{N}{2} \qquad (3)$$

Where $*$ indicates the complex conjugate. It is clear in (3) that $s_i(k)$ and $s_i(N-k)$ have the character of conjugate symmetry. Both $s_i(k)$ and $s_i(N-k)$ are belonged to the i-th OFDM symbol. Hence, it is called as the conjugate symmetry character of BPSK-OFDM symbol. With this character, the structure of BPSK-OFDM symbol with cyclic prefix could be written as that in Fig. 2. Before demodulating the received OFDM signal, the receiver has to make the symbol and frequency synchronization.

Thus, the receiver should remove the cyclic prefix. However, the synchronization should be done to remove the prefix. Once, timing information provided by the synchronization algorithm, one could exactly remove the prefix and, then, use FFT to extract the transmitted data. Hence, synchronization is the most important work in the OFDM system [14]. The first symbol of the downlink transmission is the preamble. The preamble of OFDMA mode in WiMAX has size of 2048 in time domain, which makes use of boosted BPSK modulation with specific pseudo-noise (PN) code [1]. According to 802.16e standard, preamble symbol have the following properties:

1) Preamble data is transmitted on every 3rd subcarrier in frequency domain, with two other subcarriers carrying zeros.
2) Preamble data is modulated by BPSK in frequency domain, so its IFFT output has conjugate symmetry property.
3) Uniquely identified each segment in each cell.

In this paper we concentrate on preamble symbol. n-th sample of received signal is given by:

$$r(n) = e^{\frac{j2\pi\epsilon n}{N}}\sum_{l=1}^{L} h(l)s(n-l) + v(n); \quad -N_g \leq n \leq N-1 \qquad (4)$$

Where ϵ and $v(n)$ are the carrier frequency offset normalized to the subcarrier spacing and zero mean complex AWGN respectively. $h(l)$ represents the channel impulse response and l is the index for the multipath. N_g denotes cyclic prefix length.

III. SYNCHRONIZATION ALGORITHMS

In this section, we will have a short review on three methods for downlink in OFDMA based systems.

A. *Tejas Bhatt Method*

In [10], Tejas Bhatt exploited the conjugate symmetry property of the preamble symbol. The conjugate symmetry correlation can be expressed as:

$$x_{cs}(d) = \sum_{n-1}^{\frac{N}{2}-1} r\left(d+\left(\frac{N}{2}\right)-n\right) \times r\left(d+\left(\frac{N}{2}\right)+n\right) \qquad (5)$$

$$M(d) = \qquad (6)$$

$$= \frac{|X_{cs}(d)|^2}{\sum_{n=1}^{\frac{N}{2}-1}\left|r\left(d+\left(\frac{N}{2}\right)-n\right)\right|^2 \times \sum_{n=1}^{\frac{N}{2}-1}\left|r\left(d+\left(\frac{N}{2}\right)+n\right)\right|^2}$$

$$d_{start} = \arg\max_{d}(M(d)) \qquad (7)$$

Where, $M(d)$ represents the normalized $X_{cs}(d)$, d_{start} denotes the start of the preamble symbol (except CP). In the Figs. 3 and 4, clearly, the highest peak denotes the start of the

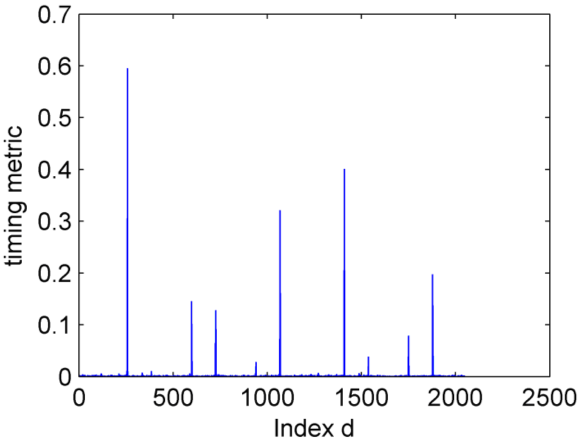

Fig. 3. Tejas Bhatt timing metric at SNR=-5 dB (CFO $2\pi\epsilon$ =1.5 normalized by subcarrier spacing) and AWGN channel.

preamble, The symbol conjugate symmetric correlation affords an effective estimate of start of the preamble symbol, however, in hostile environment with low SNR and surplus frequency offset, it does not have a good performance.

B. Huang Method

In [12] a new timing synchronization method was proposed, giving an effective estimate of start of the preamble symbol, and it reduces the influences of great noise and carrier frequency offset (CFO).

For OFDMA preamble as shown in Fig. 5, the size of FFT is not divisible by 3 ($N = 2048$) and hence, the preamble in the time domain will not be periodic. But, OFDMA preamble consists of three blocks (A, B, and C) with length of 682 in time domain , as shown in Fig. 6, that are not similar to each other, but have good cross correlation. Blocks A, B, and C begin from 0 to 681, 682 to 1363, and 1366 to 2047 respectively. Huang used the cross correlation between block A, B and C and proposed a coarse timing metric.

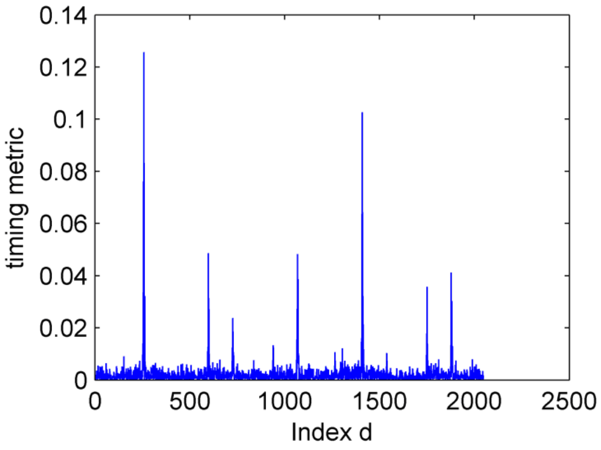

Fig. 4. Tejas Bhatt timing metric at SNR=-5 dB (CFO $2\pi\epsilon$ =1.5) and Rayleigh multipath channel.

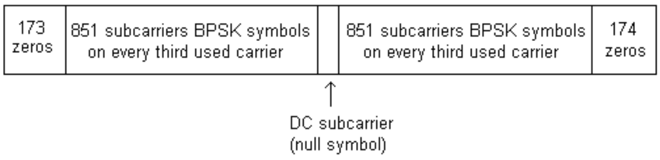

Fig. 5. Frequency description of preamble in OFDMA mode.

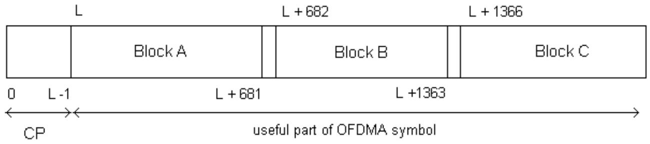

Fig. 6. Time domain structure for the preamble in OFDMA mode of WMAN.

For fine timing synchronization, Huang proposed an improved method, taking advantage of ratio of energy between the high and low energy part in preamble. The first half of preamble ranges from the 2-th sample to the 1024-th sample (except the first sample), which and the second half are symmetrical with the 1025-th sample in terms of amplitude. In Fig. 7, there are two peaks, the first is the 683-th sample, the second is the 1367-th sample of preamble, which obviously are symmetrical with the 1025-th point [12].

Some samples around the two peaks also have relatively high amplitude. In other words, the two peaks and their around samples own much higher energy than other samples in the preamble, which is a useful property. Therefore, Huang proposed a metric as below [12]:

$$M(d) = \frac{|X_{cs}(d)|}{W(d)} \tag{8}$$

$$X_{cs}(d) = \sum_{n=\frac{(Q-1)}{2}-10}^{\frac{(Q-1)}{2}+10} r\left(d+\left(\frac{N}{2}\right)-n\right) \times r\left(d+\left(\frac{N}{2}\right)+n\right) \tag{9}$$

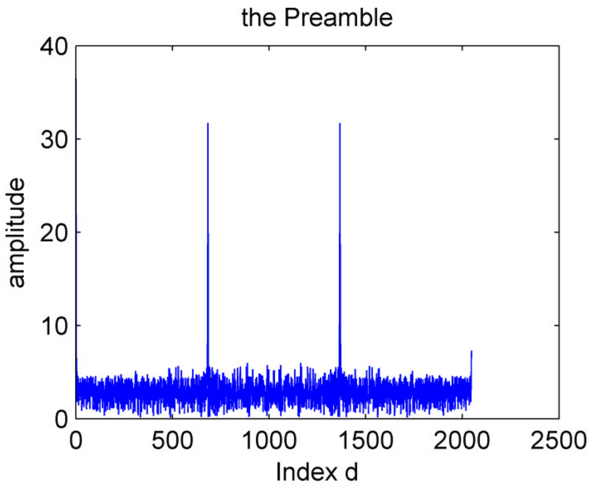

Fig. 7. Amplitude of the time-domain preamble.

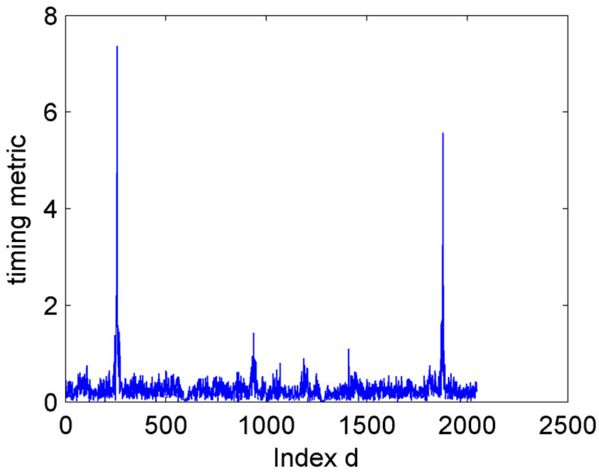

Fig. 8. Huang timing metric at SNR=-5 dB (CFO $2\pi\epsilon$ =1.5 normalized by subcarrier spacing) and AWGN channel.

$$W(d) = \sum_{n=\frac{(Q-1)}{2}-10}^{\frac{(Q-1)}{2}+10} r(d+n) \times r^*(d+n) \qquad (10)$$

$$d_{start} = \arg\max_d (M(d)) \qquad (11)$$

Where $Q = floor(N/3)$. In Figs. 8 and 9 the highest peak denotes the start of preamble.

C. Salbiyono Method

Salbiyono proposed initial timing synchronization by observing a conjugate symmetry property of preamble sequences [11]. The proposed timing metric was given by:

$$P(d) = \sum_{n=1}^{\frac{N}{2}-1} r(d+n) \times r(d+N-n) \qquad (12)$$

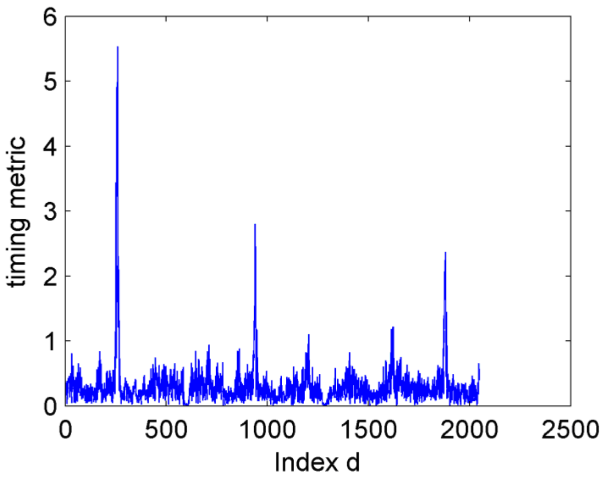

Fig. 9. Huang timing metric at SNR=-5 dB (CFO $2\pi\epsilon$ =1.5) and Rayleigh multipath channel.

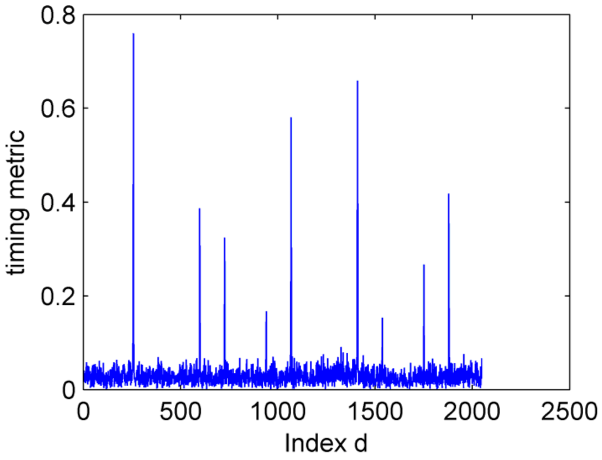

Fig. 10. Salbiyono timing metric at SNR=-5 dB (CFO $2\pi\epsilon$ =1.5 normalized by subcarrier spacing) and AWGN channel.

Where N is the size of FFT, and $r(.)$ is the received signal. The estimation of the preamble symbol can be obtained by:

$$d_{start} = \arg\max_d (P(d)) \qquad (13)$$

Conjugate symmetry correlation does not return a “plateau” but several sharp peaks with highest peak denoting the start of preamble (Figs. 10 and 11).

D. Reddy Method

The Reddy algorithm is one of the most important algorithms that the receiver knows the preamble. The Reddy algorithm is presented for timing and frequency synchronization in this section . The Reddy timing metric uses the cross correlation between block A, B and C in the preamble . Reddy timing metric is given by [3]:

$$M(d) = \frac{|P(d)|^2}{(R(d))^2} \qquad (14)$$

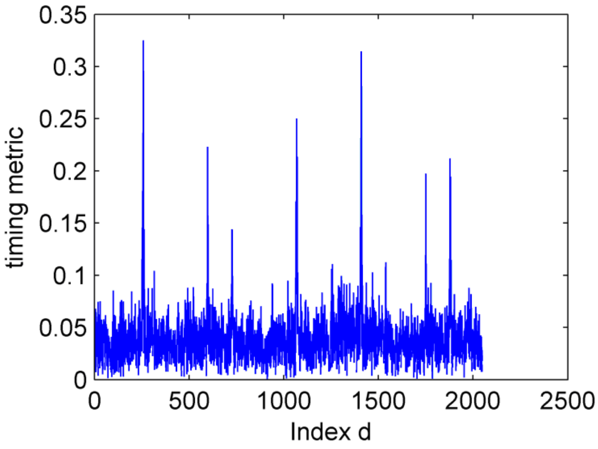

Fig. 11. Salbiyono timing metric at SNR=-5 dB (CFO $2\pi\epsilon$ =1.5) and Rayleigh multipath channel.

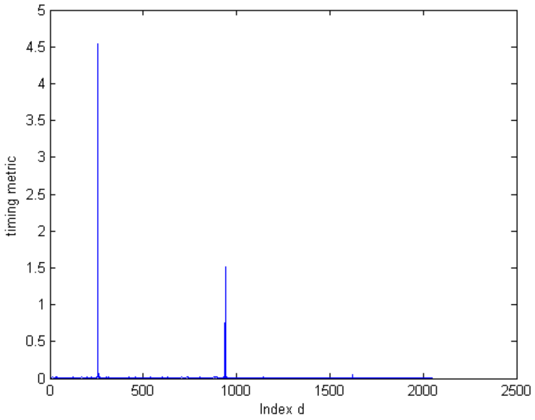

Fig. 12. Reddy timing metric at SNR=-5 dB, $2\pi\epsilon$ =1.5 and AWGN channel.

Where

$$P(d) = \sum_{n=0}^{Q-1} (r(n+d)\times s(n+N_g))^* \times (r(n+d+M)\times s(n+N_g)) \tag{15}$$

and

$$R(d) = \sum_{n=0}^{Q-1} \left| r(n+d+M) \right|^2 \tag{16}$$

A^* means conjugate A and $Q = floor(N/3)$. If $M = Q$, correlation between blocks A and B and if $M = 2Q+2$, correlation between blocks A and C will be considered. Figs. 12 and 13 indicates timing metric with $2\pi\epsilon$=1.5 and SNR=-5 dB for Reddy algorithm.

IV. PROPOSED METHOD

By knowing the preamble in receiver, we propose a timing metric that has good performance even in low SNR and use it to estimate the CFO. The proposed timing metric is given by:

$$M(d) = \frac{|M_1(d)||M_2(d)|}{R(d)} \tag{17}$$

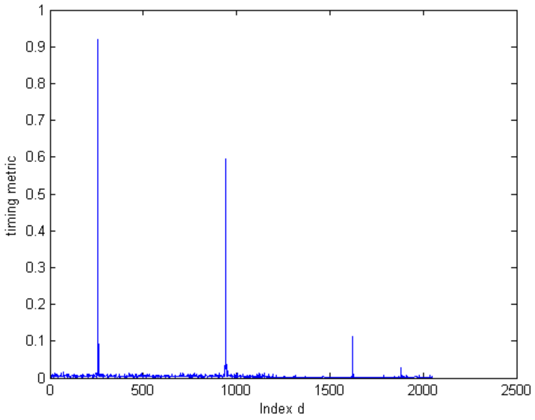

Fig. 13. Reddy timing metric at SNR=-5 dB, $2\pi\epsilon$ =1.5 and Rayleigh multipath channel.

$$d_{opt} = \arg\max_{d}(M(d)) \tag{18}$$

where

$$M_1(d) = \sum_{n=1}^{\frac{N}{2}-1} r(d+n+1) \times s^*(n+N_g+1) \tag{19}$$

and

$$M_2(d) = \sum_{n=1}^{\frac{N}{2}-1} r(N+d-n+1) \times s^*(N+N_g-n+1) \tag{20}$$

and

$$R(d) =$$

$$= \left(\sum_{n=1}^{\frac{N}{2}-1} |r(d+n+1)|^2 \right) \times \left(\sum_{n=1}^{\frac{N}{2}-1} |r(d+n+1)|^2 \right) \tag{21}$$

In this metric, conjugate symmetry correlation between blocks from received preamble and save preamble will be considered. The index of maximum of metric shows the start of symbol. Figs. 14 and 15 indicates timing metric with $2\pi\epsilon$=1.5 and SNR=-5 dB for proposed algorithm.

Conjugate symmetry correlation does not return a “plateau” but several sharp peaks with highest peak denote the start of preamble. As shown in Figs. 14 and 15, highest peak denotes the start of preamble regardless the length of cyclic prefix. By selecting the maximum of metric as beginning of symbol, we use this index d_{opt} to estimate CFO. CFO estimator is given by:

$$\hat{\epsilon} = \angle(M_1(d_{opt})M_2(d_{opt})) \tag{22}$$

$\angle$ means measured angle. In fixed WiMAX, we have CFO because of the change in environment and mismatching between transmitter and receiver oscillators. Thus CFO is smaller than subcarrier spacing. But if the CFO be larger than subcarrier spacing, we compensate the fractional part of CFO by multiplying the received signal by $e^{\frac{-j2\pi\hat{\epsilon}n}{N}}$. We find the integer part of CFO by regarding to the guard bands in frequency domain: each integer part of CFO causes the frequency shift of OFDM subcarriers as many as subcarrier spacing. Therefore, by knowing the guard bands in frequency domain, we can compensate the integer part of CFO.

V. SIMULATION RESULTS

The performance of proposed algorithm will be examined in this section, and it would be compared with 2 other metrics that were explained in sect.3 (T.Bhatt , Salbiyono and Reddy).OFDM system with 2048 subcarriers and 256 samples for CP and Rayleigh multipath channel with 8 paths by power of each path equal 0, -1, -2, -3, -4, -5, -6, and -7 in dB, is considered. Fig. 16 indicates comparison estimation of CFO ($2\pi\epsilon$=1.5) in various SNR between three algorithms by mean square error (MSE) criterion. Based on Fig. 16, the proposed algorithm has the better performance than the other algorithms.

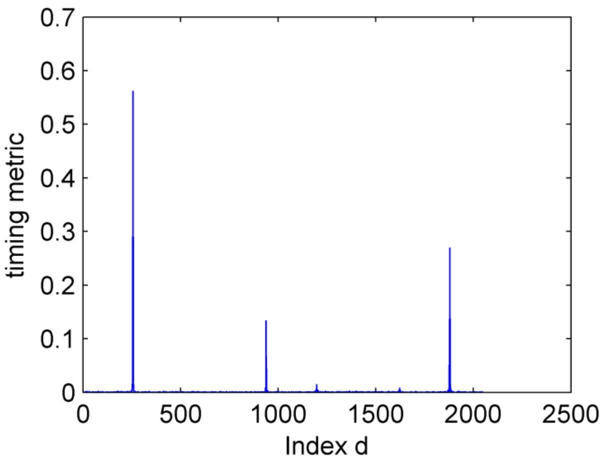

Fig. 14. Proposed timing metric at SNR=-5 dB, $2\pi\epsilon$=1.5 and AWGN channel.

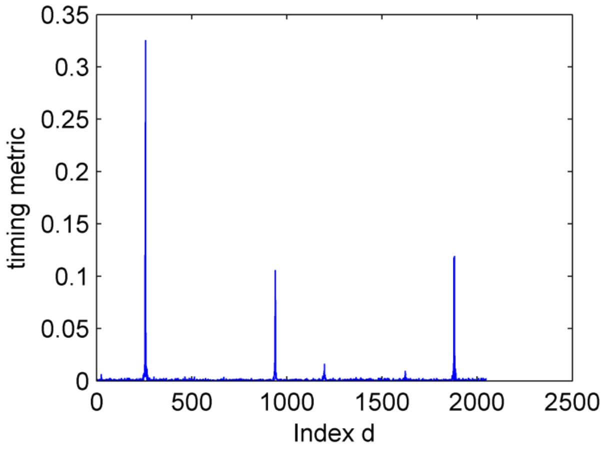

Fig. 15. Proposed timing metric at SNR=-5 dB, $2\pi\epsilon$ =1.5 and Rayleigh multipath channel.

VI. CONCLUSION

In this paper, we have proposed a timing synchronization algorithm, which is suitable for downlink OFDMA 802.16e and can be used for CFO estimation. The special structure of OFDMA makes it hard to use most of present methods for its synchronization. Our new metric has a sharp impulse in correct point without any near sub peaks and has a good functionality without any complexity. We compare the performance of the proposed algorithm with Reddy, T.Bhatt and Salbiyono algorithms. Simulation results indicate that the proposed algorithm has high performance even in low SNR in multipath fading channel.

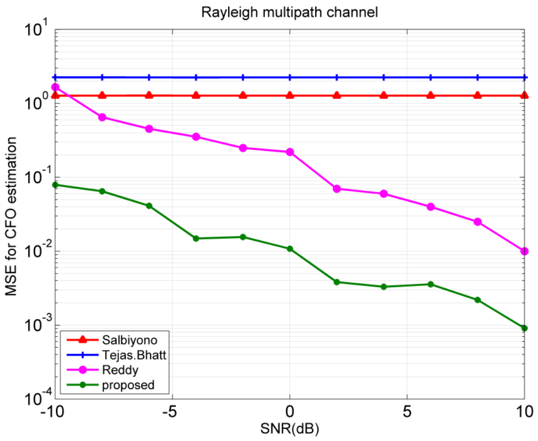

Fig. 16. Comparison between MSE for CFO estimation in Salbiyono, Tejas Bhatt, Reddy and proposed method with various SNR and $2\pi\epsilon$=1.5 in Rayleigh multipath channel.

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