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# An Improved Preamble Aided Preamble Structure Independent Coarse Timing Estimation Method for OFDM Signals

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***Abstract*—Timing estimation has been one of the major research issue in orthogonal frequency division multiplexing (OFDM) systems. In the literature there are mainly two types of preamble (data) aided timing estimation methods have been proposed. One type of timing estimation methods that depend on the specific structure of the preamble and the other type of timing estimation methods that work independent of the structure of the preamble. Performance of most of the timing estimation methods, which work independent of the structure of the preamble is severely affected in the presence of carrier frequency offset (CFO). The challenge is to design a preamble structure independent timing metric that should be robust to CFO. In this paper, a data aided coarse (initial) timing estimation scheme for OFDM system is proposed. Proposed timing estimation method is independent of the structure of the preamble and it works better than the other existing methods in the presence of CFO. The algorithm is also capable of using multiple preambles for coarse timing estimation. The performance is compared in terms of probability of erasure, probability of correct estimation and mean square error (MSE) with the existing timing synchronization methods for OFDM systems.**

***Keywords*—Timing synchronization; OFDM; Preamble; carrier frequency offset; Timing metric; MSE; Probability of erasure; Probability of correct estimation.***

## I. INTRODUCTION

A part of this work was presented at ICWMC 2016 conference [1]. The main impairments in a wireless communication system are multipath fading and noise [2]. Multipath fading introduces inter symbol interference (ISI). The major requirements of a digital communication system is to maximize the bit rate, minimize bit error rate, minimize transmit power and minimize transmission bandwidth [2] [3]. Orthogonal frequency division multiplexing (OFDM) has emerged as a powerful technique which meets the above requirements in multipath fading channels [4]. However, OFDM is known to be very sensitive to timing and carrier frequency synchronization errors [5].

Timing and frequency synchronization in OFDM systems can be achieved by either data aided (DA) or non data aided (NDA) method. In data aided method preamble or pilot is transmitted along with data through multipath fading channel for synchronization. It is assumed that preamble or pilot is known to the receiver. Preamble is transmitted separately along with the data in the time domain whereas pilots are inserted within OFDM data in frequency domain. Preamble is used for both timing and frequency synchronization as well as channel estimation, whereas pilots are mainly used for carrier frequency synchronization and channel estimation. In non data aided method [6] [7], cyclic prefix is used for synchronization, it is bandwidth efficient because there is no need of additional information (preamble). The drawback of this method is that it is less accurate because CP is the part of OFDM data and it (CP) is distorted by multipath fading (ISI) [8]. On the other hand, DA method requires additional preambles for synchronization; hence, it is less bandwidth efficient than the NDA method but accuracy is better than the NDA method. In this paper, we focus on the data aided (DA) timing estimation methods. Data aided timing estimation methods proposed in the literature can be broadly classified into two categories:

1) Approaches that depend on the special structure of the preamble [5] [9] [10] [11] [12] [13] [14] [15] [16] [17] [18] [19] [20] [21] [22] [23] [24] [25] [26] [27].
2) Approaches that work independent of the structure of the preamble [28] [29] [30] [31] [32] [33] [34].

Approaches that depend on the special structure of the preamble can be categorized as

1) Approaches that utilize repeated structure of the preamble [5] [9] [10] [12] [15] [18] [20] [22] [26].
2) Approaches that utilize symmetrical correlation of the preamble [11] [13] [16] [17] [21].
3) Approaches that utilize weighted structure of the preamble [14] [23] [24] [25].
4) Approaches that utilize both symmetrical correlation as well as the weighted structure of the preamble [19] [27].

The first data aided timing estimation technique is proposed in the literature by *Schmidl et al.* [5]. In [5], a preamble with two identical halves is used for timing estimation. However, the variance of the timing estimation is large due to timing metric plateau. To reduce the variance of timing estimate a modified preamble structure and new timing metric are proposed by *Minn et al.* [9] [10]. In [9] [10], a preamble with four identical halves with specific sign pattern is used to improve the performance. However, the variance of *Minn's* method is still high in ISI channel. The performance is further improved by *Shi et al.* [12]. Unlike *Minn's* method a preamble with four identical halves with specific sign pattern is used in [12]. In *Minn's* method correlations between the adjacent blocks of the preamble are utilized, whereas *Shi's* method is capable of utilizing correlations between the adjacent blocks as well as correlations between the non adjacent blocks of the preamble.

Differential cross correlation is used in the methods proposed by *Awoseyila et al.* [18] [22], to estimate the timing offset. A preamble with two identical halves is utilized in the methods proposed in [18] [22]. The methods proposed in [5] [9] [10] [12] [15] [18] [22] utilize time domain repeated preamble to estimate the timing offset. The method proposed by *Pushpa et al.* [20] utilize frequency domain repeated preamble to estimate the timing offset. *Park et al.* [11] propose the idea of utilizing symmetrical correlation of the preamble for timing synchronization. Later, the methods proposed by *Kim et al.* [13], *Seung et al.* [16], *Guo et al.* [17], utilize symmetrical correlation with their own preamble structure to estimate the timing offset. Timing metrics proposed in [11] [13] [16] [17] have impulsive shape at the correct timing point, so they give better performance in multipath Rayleigh fading scenario but the drawback of these metrics is they have sub peaks apart from the correct timing point. In order to solve this problem a new timing metric is proposed by *Sajadi et al.* [21]. *Ren et al.* [14] propose the technique of utilizing weighted structure of the preamble for timing synchronization. Later, the methods proposed by *Wang et al.* [23], *Fang et al.* [24], *Silva et al.* [25] utilize different weighted structure of the preamble to estimate the timing offset. *Zhou et al.* [19] propose the idea of utilizing both symmetrical correlation as well as weighted structure of the preamble to estimate the timing offset. Later, a similar type of technique is used in the method proposed by *Shao et al.* [27].

All these methods are dependent on the special structure of the preamble; hence, they cannot work with other preambles and moreover the variance of the timing estimation of these methods is high in multipath fading scenario. *Kang et al.* [28] propose a technique to estimate timing offset that work independent of the preamble structure. In [28], a delayed correlation of the preamble is used for timing synchronization. The performance is further improved by *Hamed et al.* [29] [30]. In [29] [30], all correlation points are utilized without repetition. In [32] [33] [34], a new timing estimation method using a matched filter is proposed, which gives better performance than [28] [29]. All these methods proposed in the literature [28] [29] [30] [32] [33] [34], which work independent of the structure of the preamble, utilize only one preamble for timing synchronization. *Hamed et al.* [31] propose a timing estimation method by utilizing more than one preamble. The main drawback of these methods [28] [29] [30] [31] [32] [33] is that the coarse timing estimation is severely degraded in the presence of carrier frequency offset (CFO). CFO arises due to two reasons, first one is due to frequency mismatch between the local oscillators used in the transmitter and receiver and the another one is due to Doppler shift. CFO causes phase rotation in the samples of the received signal. The phase rotation affects timing synchronization. Here, we propose a new timing estimation method using multiple preambles and we also propose a modified timing estimation method, which is robust to CFO.

This paper is organized as follows. The system model is presented in Section II. The existing timing estimation methods are discussed in Section III. The proposed method is presented in Section IV. The simulation results are given in Section V and finally, the conclusions in Section VI.

## II. SYSTEM MODEL

Fig. 1 shows the typical structure of a OFDM frame in the time domain. An OFDM frame contains preamble, cyclic prefix (CP) and data. The preamble is used for synchronization.

| | | | | | |
|---|---|---|---|---|---|
| $\mathbf{x}_0$ | $\mathbf{x}_1$ | .... | $\mathbf{x}_{M-1}$ | $\mathbf{x}_{cp}$ | $\mathbf{x}_d$ |

Figure 1. OFDM frame structure in the time domain

The $mth$ preamble in the frequency domain can be represented in vector form as follows.

$$\mathbf{X}_m = [X_m\,(0)\ \ X_m\,(1)\ \ ...\ X_m\,(N-1)] \tag{1}$$

where $0 \leq m \leq M-1$. The IFFT of the $mth$ preamble is given by

$$x_m\,(n) = \frac{1}{N}\sum_{k=0}^{N-1} X_m\,(k)\,\mathrm{e}^{j2\pi nk/N}. \tag{2}$$

The $mth$ preamble in the time domain can be represented in vector form as follows

$$\mathbf{x}_m = [x_m\,(0)\ \ x_m\,(1)\ \ ...\ x_m\,(N-1)] \tag{3}$$

where $0 \leq k, n \leq N-1$. Let $\mathbf{X}_d$ denotes the frequency domain data of the OFDM frame. $\mathbf{X}_d$ can be represented in vector form as follows:

$$\mathbf{X}_d = [X_d\,(0)\ \ X_d\,(1)\ \ ...\ X_d\,(N_d-1)]\,. \tag{4}$$

The IFFT of the frequency domain data $\mathbf{X}_d$ is given by

$$x_d\,(n) = \frac{1}{N_d}\sum_{k=0}^{N_d-1} X_d\,(k)\,\mathrm{e}^{j2\pi nk/N_d}. \tag{5}$$

The time domain data $\mathbf{x}_d$ (see Fig. 1) of the OFDM frame can be represented in vector form as follows

$$\mathbf{x}_d = [x_d\,(0)\ \ x_d\,(1)\ \ ...\ x_d\,(N_d-1)] \tag{6}$$

where $0 \leq k, n \leq N_d - 1$. A cyclic prefix $\mathbf{x}_{cp}$ of length $N_g$ is introduced in front of time domain data $\mathbf{x}_d$. The value of the $N_g$ is $L-1$, where $L$ is the number of channel taps. $\mathbf{x}_{cp}$ is given by

$$\mathbf{x}_{cp} = [x_d\,(N_d - N_g)\ \ ...\ x_d\,(N_d-1)]\,. \tag{7}$$

Let $\mathbf{x}_0$ to $\mathbf{x}_{M-1}$ are the preambles of the frame in the time domain. Let the transmitted frame is given by (see Fig. 1)

$$\begin{aligned}\mathbf{x} &= [\mathbf{x}_0\ ..\ \mathbf{x}_{M-1}\ \mathbf{x}_{cp}\ \mathbf{x}_d] \\ &= [x(0)\ x(1)\ ...\ x(MN+N_d+N_g-1)]\,. \end{aligned} \tag{8}$$

Now, $\mathbf{x}$ is transmitted through the frequency selective channel. The channel is assumed to be quasi static and it is fixed for one frame and varies independently from frame to frame. Its impulse response for a given frame can be expressed as:

$$\mathbf{h} = [h(0)\ h(1)\ h(2)\ .....\ h(L-1)] \tag{9}$$

where $L$ is the number of channel taps. The received signal $\mathbf{r}$ in the time domain is given by:

$$r\,(n) = y\,(n)\,\mathrm{e}^{j2\pi n\epsilon/N} + w\,(n) \tag{10}$$

where

$$\begin{aligned} y(n) &= h(n) \star x(n) \\ &= \sum_{l=0}^{L-1} h(l)\, x(n-l) \end{aligned} \qquad (11)$$

where $0 \leq n \leq MN + N_g + N_d + L - 2$ and $w(n)$ is zero mean Gaussian noise sample and $\epsilon$ is the normalized frequency offset. Vector form representation of $\mathbf{r}$ is given by

$$\mathbf{r} = [r(0)\; r(1)\; ...\; r(MN + N_d + N_g + L - 2)]\,. \qquad (12)$$

## III. Existing timing synchronization methods

In this section we describe some of the existing data (preamble) aided timing synchronization methods. In general, the timing metric, which is used for OFDM timing synchronization, is given by

$$G(d) = \frac{|T(d)|^2}{R^2(d)}. \qquad (13)$$

Some authors use another timing metric given by

$$G(d) = \frac{T(d)}{R(d)} \qquad (14)$$

where $T(d)$ is the correlation function, $R(d)$ is the energy of the received signal used for normalization, $d$ is the index of the correlation, where $0 \leq d \leq N-1$. The start of the frame can be estimated by finding the peak of the timing metric (13) or (14).

### A. Schmidl et al. method

The time domain preamble proposed by *Schmidl et al.* [5] is given by

$$\mathbf{x}_{0sch} = \left[\mathbf{A}_{N/2}\, \mathbf{A}_{N/2}\right] \qquad (15)$$

where $\mathbf{A}_{N/2}$ is the sample of length $N/2$. $T(d)$ and $R(d)$ are given by

$$T(d) = \sum_{n=0}^{N/2-1} r^{\star}(d+n)\,.r(d+n+N/2) \qquad (16)$$

$$R(d) = \sum_{n=0}^{N/2-1} |r(d+n+N/2)|^2 \qquad (17)$$

where $N$ is the FFT size. $\mathbf{r}$ is the received signal given by (12) and the timing metric can be calculated using (13).

### B. Minn et al. method

The time domain preamble proposed by *Minn et al.* [9] is given by

$$\mathbf{x}_{0minn} = \left[\mathbf{A}_{N/4}\; \mathbf{A}_{N/4}\; -\mathbf{A}_{N/4}\; -\mathbf{A}_{N/4}\right] \qquad (18)$$

where $\mathbf{A}_{N/4}$ is the sample of length $N/4$. $T(d)$ and $R(d)$ are given by

$$T(d) = \sum_{k=0}^{1} \sum_{n=0}^{N/4-1} r^{\star}(d+n+kN/2)\,. \; r(d+n+kN/2+N/4) \qquad (19)$$

$$R(d) = \sum_{k=0}^{1} \sum_{n=0}^{N/4-1} |r(d+n+kN/2+N/4)|^2 \qquad (20)$$

where $N$ is the FFT size. $\mathbf{r}$ is the received signal given by (12) and the timing metric can be calculated using (13).

### C. Park et al. method

The time domain preamble proposed by *Park et al.* [11] is given by

$$\mathbf{x}_{0park} = \left[\mathbf{A}_{N/4}\, \mathbf{B}_{N/4}\, \mathbf{A}^{\star}_{N/4}\, \mathbf{B}^{\star}_{N/4}\right] \qquad (21)$$

where $\mathbf{A}_{N/4}$ is the sample of length $N/4$. $\mathbf{A}^{\star}_{N/4}$ is the conjugate of $\mathbf{A}_{N/4}$. $\mathbf{B}_{N/4}$ is designed to be symmetric with $\mathbf{A}_{N/4}$. $\mathbf{B}^{\star}_{N/4}$ is the conjugate of $\mathbf{B}_{N/4}$. $T(d)$ and $R(d)$ are given by

$$T(d) = \sum_{n=0}^{N/2-1} r(d-n)\,.r(d+n) \qquad (22)$$

$$R(d) = \sum_{n=0}^{N/2-1} |r(d+n)|^2 \qquad (23)$$

where $N$ is the FFT size. $\mathbf{r}$ is the received signal given by (12) and the timing metric can be calculated using (13).

### D. Ren et al. method

The time domain preamble proposed by *Ren et al.* [14] is given by

$$\mathbf{x}_{0ren} = \left[\mathbf{A}_{N/2}\, \mathbf{A}_{N/2}\right] \circ \mathbf{S} \qquad (24)$$

where $\circ$ is the Hadamard product and $\mathbf{S}$ is the pseudo noise sequence with values +1 or -1. $T(d)$ and $R(d)$ are given by

$$T(d) = \sum_{n=0}^{N/2-1} s(n).s(n+N/2).r^{\star}(d+n)\,.r(d+n+N/2) \qquad (25)$$

$$R(d) = \frac{1}{2} \sum_{n=0}^{N-1} |r(d+n)|^2. \qquad (26)$$

The timing metric can be calculated using (13).

### E. Sajadi et al. method

The time domain preamble proposed by *Sajadi et al.* [21] is given by

$$\mathbf{x}_{0sajadi} = \left[\mathbf{A}_{N/8}\, \mathbf{A}_{N/8}\, \mathbf{A}^{\star}_{N/8}\, \mathbf{A}^{\star}_{N/8}\, \mathbf{A}_{N/8}\, \mathbf{B}_{N/8}\, \mathbf{A}^{\star}_{N/8}\, \mathbf{B}^{\star}_{N/8}\right] \qquad (27)$$

where $\mathbf{A}_{N/8}$ is the sample of length $N/8$. $\mathbf{A}^{\star}_{N/8}$ is the conjugate of $\mathbf{A}_{N/8}$. $\mathbf{B}_{N/8}$ is designed to be symmetric with $\mathbf{A}_{N/8}$. $\mathbf{B}^{\star}_{N/8}$ is the conjugate of $\mathbf{B}_{N/8}$. Two correlation functions $T_1(d)$, $T_2(d)$ and two normalization functions $R_1(d)$, $R_2(d)$ are used in [21]. $T_1(d)$, $R_1(d)$ are given by

$$T_1(d) = \sum_{k=0}^{1} \sum_{n=0}^{N/8-1} r^{\star}(d+n+kN/4)\,. \; r(d+n+kN/4+N/8) \qquad (28)$$

$$R_1(d) = \sum_{k=0}^{1} \sum_{n=0}^{N/4-1} |r(d+n+kN/4+N/8)|^2. \quad (29)$$

$T_2(d)$, $R_2(d)$ are given by

$$T_2(d) = \sum_{n=0}^{N/4-1} r(d-n).r(d+n) \quad (30)$$

$$R_2(d) = \sum_{n=0}^{N/4-1} |r(d+n)|^2. \quad (31)$$

The timing metric proposed in [21] given by

$$G(d) = G_1(d).G_2(d) \quad (32)$$

where $G_1(d)$ and $G_2(d)$ are same as (13) can be calculated using $T_1(d)$, $R_1(d)$ and $T_2(d)$, $R_2(d)$.

### F. Kang et al. method

*Kang et al.* [28] propose a preamble pattern independent technique. In [28], a correlation sequence of preamble $\mathbf{C}$ (CSP) is derived as $\mathbf{C} = \mathbf{x}_0^\star \circ \mathbf{x}_0^n$, where $\circ$ represents the Hadamard product. $\mathbf{x}_0$ is the preamble of length $N$. $\mathbf{x}_0^\star$ is the conjugate of $\mathbf{x}_0$. $\mathbf{x}_0^n$ is the circular shift of $\mathbf{x}_0$ by an amount equal to $n$. The length of the vector $\mathbf{C}$ is $N$. Autocorrelation of $\mathbf{C}$ has an impulsive characteristics at the optimum value of $n$. Let $\mathbf{r}_0^d$ be the vector of length $N$ obtained from the received signal $\mathbf{r}$ starting from index $d$. $\mathbf{r}_0^d$ is given by

$$\begin{aligned} \mathbf{r}_0^d &= \left[r_0^d(0)\, r_0^d(1) \,....\, r_0^d(N-1)\right] \\ &= \left[r(d)\, r(d+1) \,....\, r(d+N-1)\right]. \end{aligned} \quad (33)$$

$T(d)$ is given by

$$T(d) = \text{Re}\left[\left(\mathbf{r}_0^d\right)^\star \circ \mathbf{r}_0^{d,n}\right]\mathbf{p}^T + \text{Im}\left[\left(\mathbf{r}_0^d\right)^\star \circ \mathbf{r}_0^{d,n}\right]\mathbf{q}^T \quad (34)$$

and $R(d)$ is given by

$$R(d) = \left\|\text{Re}\left[\left(\mathbf{r}_0^d\right)^\star \circ \mathbf{r}_0^{d,n}\right]\right\| + \left\|\text{Im}\left[\left(\mathbf{r}_0^d\right)^\star \circ \mathbf{r}_0^{d,n}\right]\right\| \quad (35)$$

where $\left(\mathbf{r}_0^d\right)^\star$ is the conjugate of $\mathbf{r}_0^d$ and $\mathbf{r}_0^{d,n}$ is the circular shift of $\mathbf{r}_0^d$ by an amount equal to $n$ and $0 \le d \le N-1$ and $0 \le n \le N-1$. The vectors $\mathbf{p}$ and $\mathbf{q}$ represent the sign vectors of $\mathbf{C}$ (CSP). The timing metric can be calculated using (14).

### G. Hamed et al. method (M=1)

*Hamed et al.* [29] [30] extend *Kang's* work for timing synchronization. In this works, *Hamed et al.* extend the correlation length upto $N(N-1)/2$, where $N$ is the FFT size. An adjustable correlation sequence of preamble $\mathbf{C}$ (ACSP) is derived without repetition. $\mathbf{C}$ is given by

$$\begin{aligned} \mathbf{C} = \{ & x_0^\star(0)\,x_0(1), x_0^\star(0)\,x_0(2), ..., x_0^\star(0)\,x_0(N-1), \\ & x_0^\star(1)\,x_0(2), x_0^\star(1)\,x_0(3), .., x_0^\star(1)\,x_0(N-1), \\ & ..., x_0^\star(N-2)\,x_0(N-1)\} \end{aligned} \quad (36)$$

where $\mathbf{x}_0$ is the preamble of length $N$. The length of the vector $\mathbf{C}$ (ACSP) is upto $N(N-1)/2$. Let $\mathbf{r}_0^d$ be the vector of length $N$ obtained from the received signal $\mathbf{r}$ starting from index $d$. $\mathbf{r}_0^d$ is given by (33). A sequence $\mathbf{V}^d$ is derived from $\mathbf{r}_0^d$. $\mathbf{V}^d$ is given by

$$\begin{aligned} \mathbf{V}^d = \Big\{ & \left(r_0^d(0)\right)^\star r_0^d(1), \left(r_0^d(0)\right)^\star r_0^d(2), \\ & ..., \left(r_0^d(0)\right)^\star r_0^d(N-1), \left(r_0^d(1)\right)^\star r_0^d(2), \\ & \left(r_0^d(1)\right)^\star r_0^d(3), .., \left(r_0^d(1)\right)^\star r_0^d(N-1), \\ & ..., \left(r_0^d(N-2)\right)^\star r_0^d(N-1)\Big\}. \end{aligned} \quad (37)$$

Length of the vector $\mathbf{V}^d$ is upto $N(N-1)/2$. $T(d)$ is given by [29]

$$T(d) = \text{Re}\left[\mathbf{V}^d\right]\mathbf{p}^T + \text{Im}\left[\mathbf{V}^d\right]\mathbf{q}^T \quad (38)$$

or $T(d)$ is given by [30]

$$T(d) = \mid \mathbf{V}^d \mathbf{C}^H \mid^2. \quad (39)$$

$R(d)$ is given by

$$R(d) = \left\|\text{Re}\left[\mathbf{V}^d\right]\right\| + \left\|\text{Im}\left[\mathbf{V}^d\right]\right\|. \quad (40)$$

The vectors $\mathbf{p}$ and $\mathbf{q}$ represent the sign vectors of $\mathbf{C}$ (ACSP). The timing metric can be calculated using (14). Timing estimation using (39) gives better performance than (38).

### H. Matched filter method

In matched filtering approach [32] [33] the received signal is correlated with a known preamble. $T(d)$ and $R$ are given by

$$T(d) = \sum_{n=0}^{N-1} r^\star(d+n).x_0(n) \quad (41)$$

$$R = \sum_{n=0}^{N-1} \mid x_0(n) \mid^2. \quad (42)$$

Timing metric $G(d)$ is given by

$$G(d) = \frac{\mid T(d) \mid^2}{R}. \quad (43)$$

### I. Hamed et al. method (M=2)

In this work, *Hamed et al.* [31] extend the correlation length upto $N^2$, by utilizing two preambles, where $N$ is the FFT size. In this work, the correlation sequence $\mathbf{C}$ is derived by using two preambles $\mathbf{x}_0$ and $\mathbf{x}_1$. $\mathbf{x}_0$ and $\mathbf{x}_1$ are the preambles of length $N$. Correlation sequence $\mathbf{C}$ is given by

$$\mathbf{C} = \left[\mathbf{C}^0\, \mathbf{C}^1 \,....\, \mathbf{C}^{N-1}\right]. \quad (44)$$

The $nth$ sub vector of vector $\mathbf{C}$ is given by

$$\mathbf{C}^n = \mathbf{x}_0^\star \circ \mathbf{x}_1^n \quad (45)$$

where $\mathbf{x}_0^\star$ is the conjugate of $\mathbf{x}_0$ and $\mathbf{x}_1^n$ is the circular shift of $\mathbf{x}_1$ by an amount equal to $n$ and $0 \le n \le N-1$. Let $\mathbf{r}_0^d$ be the vector of length $N$ obtained from the received signal $\mathbf{r}$ starting from index $d$. $\mathbf{r}_0^d$ is given by

$$\begin{aligned} \mathbf{r}_0^d &= \left[r_0^d(0)\, r_0^d(1) \,....\, r_0^d(N-1)\right] \\ &= \left[r(d)\, r(d+1) \,....\, r(d+N-1)\right]. \end{aligned} \quad (46)$$

Let $\mathbf{r}_1^d$ be the vector of length $N$ obtained from the received signal $\mathbf{r}$ starting from index $d+N$. $\mathbf{r}_1^d$ is given by

$$\begin{aligned}\mathbf{r}_1^d &= \left[r_1^d(0)\, r_1^d(1) \,....\, r_1^d(N-1)\right] \\ &= \left[r(d+N)\, r(d+N+1) \,....\, r(d+2N-1)\right]. \end{aligned} \quad (47)$$

A sequence $\mathbf{Q}^d$ generated from $\mathbf{r}_0^d$ and $\mathbf{r}_1^d$ is given by

$$\mathbf{Q}^d = \left[\mathbf{Q}^{d,0}\, \mathbf{Q}^{d,1} \,....\, \mathbf{Q}^{d,N-1}\right]. \quad (48)$$

The $nth$ sub vector of vector $\mathbf{Q}^d$ is given by

$$\mathbf{Q}^{d,n} = \left(\mathbf{r}_0^d\right)^\star \circ \mathbf{r}_1^{d,n} \quad (49)$$

where $\left(\mathbf{r}_0^d\right)^\star$ is the conjugate of $\mathbf{r}_0^d$ and $\mathbf{r}_1^{d,n}$ is the circular shift of $\mathbf{r}_1^d$ by an amount equal to $n$ and $0 \le d \le N-1$ and $0 \le n \le N-1$. $T(d)$ is given by

$$T(d) = \left| \sum_{j=0}^{\lambda N-1} Q^d(j)\,.C^\star(j) \right| \quad (50)$$

and $R(d)$ is given by

$$R(d) = \sum_{j=0}^{\lambda N-1} \mid Q^d(j) \mid^2 \quad (51)$$

where $0 \le \lambda \le N-1$. The timing metric can be calculated using (14).

Methods $(A)$ to $(H)$ use one preamble $(M = 1)$ for timing estimation. Method $(I)$ use two preambles $(M = 2)$ for timing estimation. Methods $(A)$ to $(E)$ depend on the special structure of the preamble, whereas methods $(F)$ to $(I)$ work independent of the structure of the preamble.

The preamble structure dependent timing metrics proposed in [5] [9] [11] [14] [21] utilize received signal for correlation, whereas the preamble structure independent timing metrics proposed in [28] [29] [30] [31] [32] utilize the correlation between received signal and locally generated reference signal. Timing metrics proposed in [5] [9] [11] [14] [21] are not affected by the CFO because the correlation functions given by (16), (19), (22), (25), (28), (30) are not affected by the CFO [26]. Correlation functions given by (34), (38), (39), (41), (50) are affected due to phase rotation caused by the CFO in the received signal. As a result the correlation peak is destroyed in the presence of CFO. So the timing metrics proposed in [28] [29] [30] [31] [32] are severely affected by the CFO.

## IV. PROPOSED MODEL

The received signal $r(n)$ is used to estimate the start of the frame $\hat{\theta}_t$. It is assumed that the preambles $\mathbf{x}_0, \mathbf{x}_1, ..., \mathbf{x}_{M-1}$ are known to the receiver. We define the correlation function given by

$$T(d) = \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} r^\star(d+n+mN)\, x_m(n) \quad (52)$$

$$R = \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} \mid x_m(n) \mid^2 \quad (53)$$

$$G(d) = \frac{\mid T(d) \mid^2}{M.R} \quad (54)$$

The estimated start of the frame is given by

$$\hat{\theta}_t = \max_d \left[G(d)\right]. \quad (55)$$

Note that in the special case of $M = 1$ in (52), $T(d)$ reduces to

$$T(d) = \sum_{n=0}^{N-1} r^\star(d+n)\, x_0(n). \quad (56)$$

It is equivalent to the method proposed in [32], which is a matched filtering approach using one preamble. The performance of the proposed timing metric (54) is severely degraded in the presence of CFO. Hence, we propose a modified timing metric which performs better than (54) in the presence of CFO. Let the frequency offset $\epsilon$ lie within $[-I, I]$. We divide the interval $[-I, I]$ into $B$ sub intervals. The length of the each sub interval is 0.1. The modified correlation function $T_{CFO}(d)$ is given by

$$T_{CFO}(d) = \sum_{p=1}^{p=P} \left\{ \left| \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} r^\star(d+n+mN)\, x_m(n)\, \mathrm{e}^{(j2\pi(i(p))(n+mN)/N)} \right|^2 \right\} \quad (57)$$

where $i(p)$ takes equally spaced points within the interval $[-I, I]$. The spacing between two successive points is 0.1. $i(p)$ is defined as

$$i(p) = -I + (p-1)\,0.1 \quad (58)$$

$$i(P) = I \quad (59)$$

where $1 \le p \le P$ and $P = B+1$. The estimated start of the frame is given by

$$\hat{\theta}_t = \max_d \left[T_{CFO}(d)\right]. \quad (60)$$

From (58) and (59) we have

$$\begin{aligned} i(P) &= -I + (P-1)\,0.1 \\ &= I \\ \Rightarrow \frac{2I}{0.1} &= P-1 \\ \Rightarrow 20I+1 &= P. \end{aligned} \quad (61)$$

From (61), it is clear that in the proposed method the computational complexity is high as the range of CFO increases because as the value of $I$ increases, the value of $P$ is also increases. Note that in the special case of $M = 1$ in (57) $T_{CFO}(d)$ becomes

$$T_{CFO}(d) = \sum_{p=1}^{p=P} \left| \sum_{n=0}^{N-1} r^\star(d+n)\, x_0(n)\, \mathrm{e}^{(j2\pi(i(p))n/N)} \right|^2. \quad (62)$$

Now, (62) is the proposed timing estimation method using one preamble, which is independent of the structure of the preamble. Note that (62) gives better performance than (56) in the presence of CFO.

The advantages of the proposed method in (62) using one preamble ($M = 1$) over the matched filtering approach in (56) are:

1) Use of exponential term in (62) to compensate the phase rotation caused by CFO. The phase rotation caused by CFO destroys the correlation peak in match filtering operation given in (56).
2) Averaging the cross correlation over the interval $[-I, I]$ improves the performance of the proposed timing metric (62) in the presence of CFO.

### A. Probability of erasure

If the estimated start of the frame $\hat{\theta}_t$ satisfies the condition $1 \leq \hat{\theta}_t \leq L$ then the frame is processed further, otherwise frame is discarded and considered as an erasure. Let $F1$ be the total number of frames that is considered as erasure and $F2$ be the total number of frames that is transmitted. The Probability of erasure (PE) is given by

$$PE = \frac{F1}{F2}. \quad (63)$$

### B. Mean square error

Let the number of detected frames be given by

$$F = F2 - F1. \quad (64)$$

The mean squared error (MSE) of the detected frames is given by

$$MSE = \frac{\sum_{f=0}^{F-1} \left(\theta_{tf} - \hat{\theta}_{tf}\right)^2}{F} \quad (65)$$

where $\theta_{tf}$ is the time index corresponding to the maximum absolute value of the channel impulse response for the $f^{th}$ detected frame given by

$$\theta_{tf} = \arg\max\left(\text{abs}\left(\mathbf{h}_f\right)\right) \quad (66)$$

where $\mathbf{h}_f$ is the channel impulse response for the $f^{th}$ detected frame and $\hat{\theta}_{tf}$ is the estimated start of the $f^{th}$ detected frame.

### C. Probability of correct estimation

Let $F3$ be the total number of frames for which $\hat{\theta}_t = \theta_t$, then the probability of correct estimation $P(\hat{\theta}_t = \theta_t)$ is given by

$$P(\hat{\theta}_t = \theta_t) = \frac{F3}{F2} \quad (67)$$

where $\theta_t$ is the time index corresponding to the maximum absolute value of the channel impulse response for a given frame, given by

$$\theta_t = \arg\max\left(\text{abs}\left(\mathbf{h}\right)\right) \quad (68)$$

where $\mathbf{h}$ is the channel impulse response for a given frame and $\hat{\theta}_t$ is the estimated start of that frame.

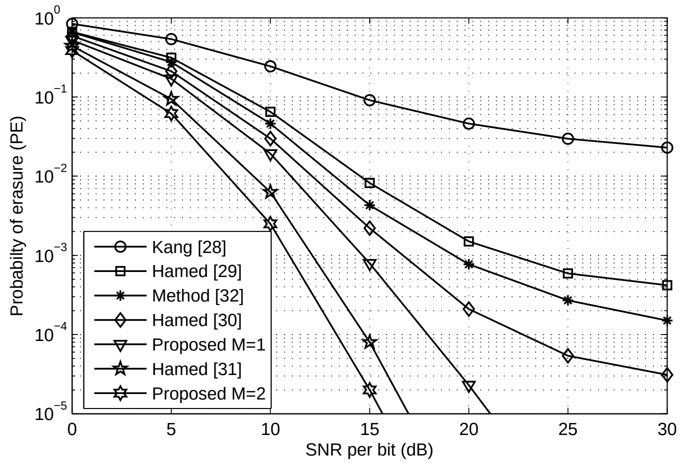


Figure 2. Probability of erasure of different estimators using randomly generated preamble in the presence of CFO [(M=1,2), I=0.5]

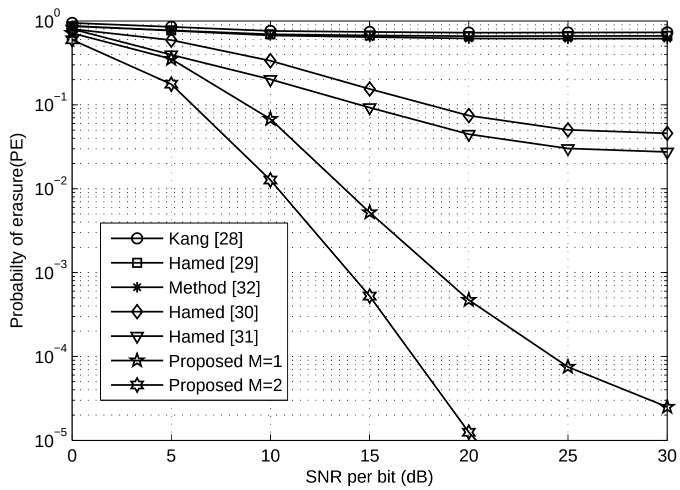


Figure 3. Probability of erasure of different estimators using randomly generated preamble in the presence of CFO [(M=1,2), I=32]

## V. SIMULATION RESULTS AND DISCUSSION

In this section, the performance of the proposed method is compared with the major existing timing synchronization methods [28] [29] [30] [31] [32], which work independent of the structure of the preamble. Matlab simulation is performed for performance comparison. We have assumed $N$=64 and performed the simulations over $5\times10^5$ frames. QPSK signaling is assumed. A frequency selective Rayleigh fading channel is assumed with $L = 5$ path taps and path delays $\mu_l = l$ for $l = 0, 1, ..., 4$. The channel has an exponential power delay profile (PDP) with an average power of $\exp(-\mu_l/L)$. The CFO takes random value within the range $[-I, I]$ and it varies independently from frame to frame. For the methods presented in [29] [30], we have considered all the available correlation points without repetition, i.e., $N(N-1)/2$=2016 and for the method presented in [31], we have considered all the available

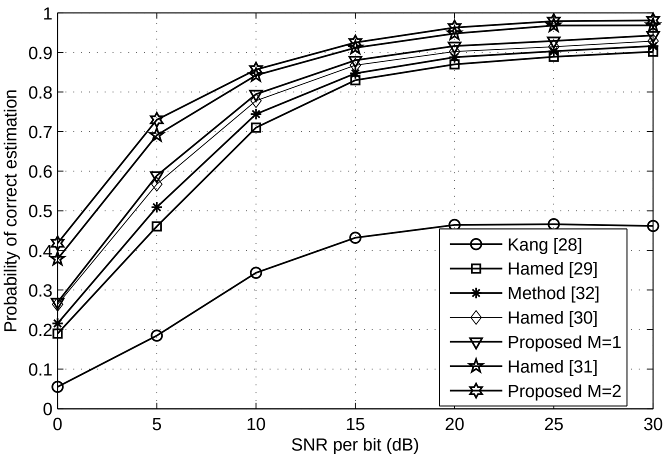


Figure 4. Probability of correct estimation of different estimators using randomly generated preamble in the presence of CFO [(M=1,2), I=0.5]

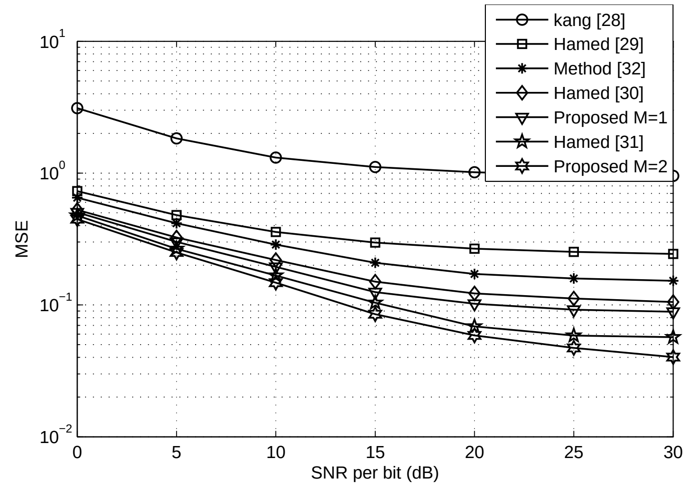


Figure 6. Timing MSE of different estimators using randomly generated preamble in the presence of CFO [(M=1,2), I=0.5]

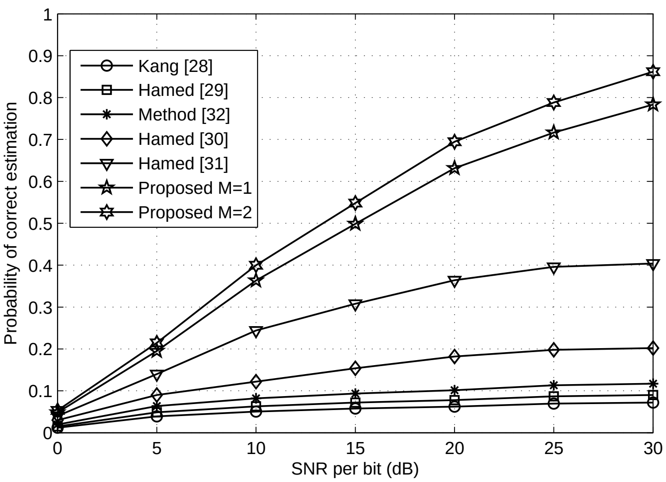


Figure 5. Probability of correct estimation of different estimators using randomly generated preamble in the presence of CFO [(M=1,2), I=32]

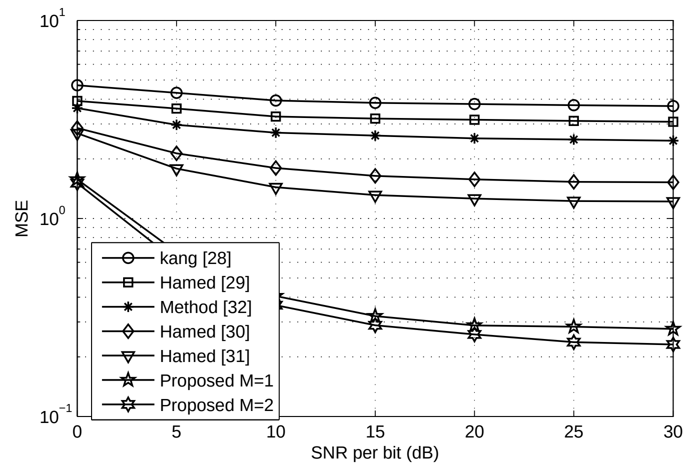


Figure 7. Timing MSE of different estimators using randomly generated preamble in the presence of CFO [(M=1,2), I=32]

correlation points utilized by two preambles, i.e., $N^2$=4096. In order to compare with [28] [29] [30] [32], we consider $M$=1 and to compare with [31], we consider $M$=2. Methods proposed in [28] [29] [30] [31] [32] give satisfactory results when the range of CFO is within $\pm 0.5$, i.e., $I = 0.5$, beyond that the performance starts degrading. So, for performance comparison, we consider the value of $I$ is 0.5 another value of $I$ is considered as 32 for simulation because the whole range of CFO of the OFDM system is within $\pm N/2$, i.e., $I = N/2 = 32$.

The SNR per bit is defined as [34]

$$\begin{aligned} \text{SNR per bit} &= \frac{E\left[\mid H(k)\, X_m(k) \mid^2\right]}{E\left[\mid W(k) \mid^2\right]} \\ &= \frac{E\left[\mid H(k) \mid^2\right] E\left[\mid X_m(k) \mid^2\right]}{E\left[\mid W(k) \mid^2\right]} \end{aligned} \tag{69}$$

where $X_m(k)$ is the $mth$ preamble in the frequency domain, $H(k)$ is the frequency response of the channel and $W(k)$ is the FFT of the noise. In the case of uniform power delay profile of the channel [34]

$$\begin{aligned} E\left[\mid H(k) \mid^2\right] &= E\left[H(k)\, H^\star(k)\right] \\ &= 2L\sigma_f^2 \end{aligned} \tag{70}$$

Hence, the SNR per bit in decibels becomes

$$\text{SNR per bit}\ (dB) = 10\ \log_{10}\left(\frac{2L\sigma_f^2}{N\sigma_w^2}\right) \tag{71}$$

In the case of exponential power delay profile of the channel

$$\begin{aligned} E\left[\mid H(k) \mid^2\right] &= E\left[H(k)\, H^\star(k)\right] \\ &= 2\sigma_f^2 \sum_{l=0}^{L-1} \exp\left(-\mu_l/L\right) \end{aligned} \tag{72}$$

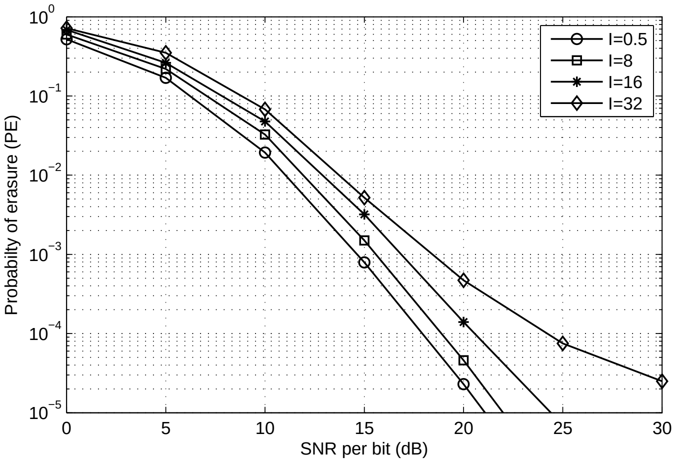


Figure 8. Probability of erasure of proposed estimator using randomly generated preamble for different values of I [(M=1)]

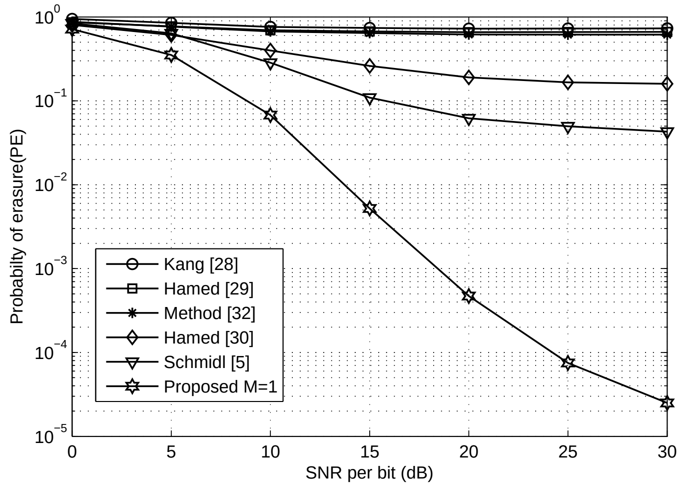


Figure 10. Probability of erasure of different estimators using Schmidl's preamble in the presence of CFO [M=1, I=32]

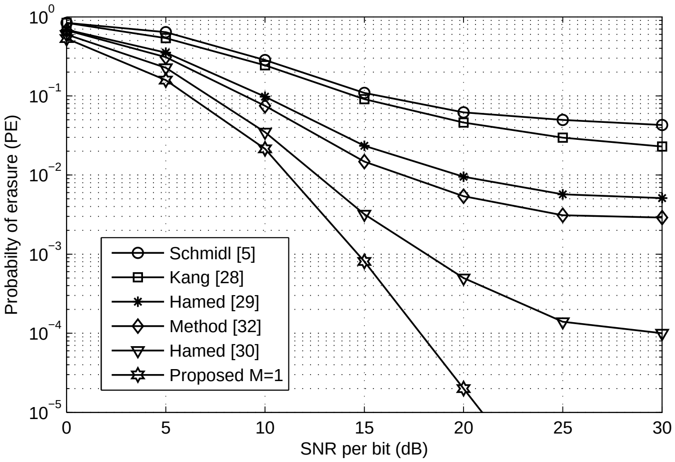


Figure 9. Probability of erasure of different estimators using Schmidl's preamble in the presence of CFO [M=1, I=0.5]

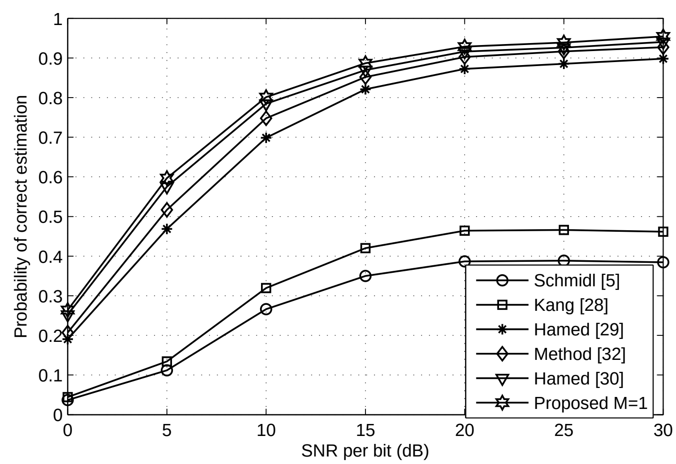


Figure 11. Probability of correct estimation of different estimators using Schmidl's preamble in the presence of CFO [M=1, I=0.5]

Hence, the SNR per bit in decibels becomes

$$\text{SNR per bit}\ (dB) = 10\ \log_{10}\left(\frac{2\sigma_f^2 \sum_{l=0}^{L-1} \exp\left(-\mu_l/L\right)}{N\sigma_w^2}\right) \tag{73}$$

where $\sigma_f^2$ and $\sigma_w^2$ are the fade and noise variance. In Matlab simulation, probability of erasure (63), probability of correct estimation (67), timing MSE (65) performance of the existing methods as well as of the proposed method are shown for different values of SNR per bit. Random preamble and preambles proposed in [5] [9] [11] [14] [21] are considered for simulation.

In Figs. 2 to 7, probability of erasure, probability of correct estimation and timing MSE of the proposed method are compared with major existing timing synchronization methods in the presence of CFO using a randomly generated preamble. Random preamble means preamble with no repetition. One randomly generated preamble ($M$=1) is used for the methods in [28] [29] [30] [32] and the proposed method and two randomly generated preambles ($M$=2) are used for the method in [31] and the proposed method. Figs. 2, 4 and 6 show the performance comparison considering $I = 0.5$. Figs. 3, 5 and 7 show the performance comparison considering $I = N/2 = 32$. It is observed that there is a major performance degradation of the methods proposed in [28] [29] [30] [31] [32] using random preamble when the CFO increases (large value of $I$). It is also observed that the proposed method performs better than the existing methods in the presence of large range of CFO. Note that in the presence of CFO ($I \neq 0$) with $M = 1$ in the proposed method, there is a significant improvement in the performance as compared to method presented in [32]. It is also observed that the proposed method performs better especially in high SNR per bit. Fig. 8 shows the probability of erasure of the proposed estimator considering different values of $I$ (different range of CFO). It is observed that the proposed

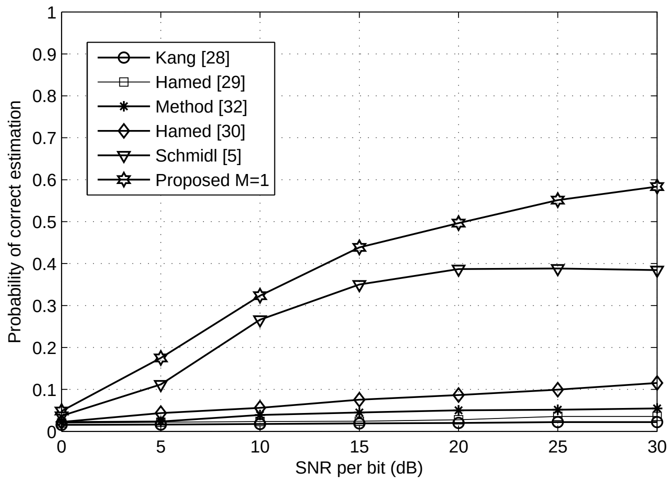


Figure 12. Probability of correct estimation of different estimators using Schmidl's preamble in the presence of CFO [M=1, I=32]

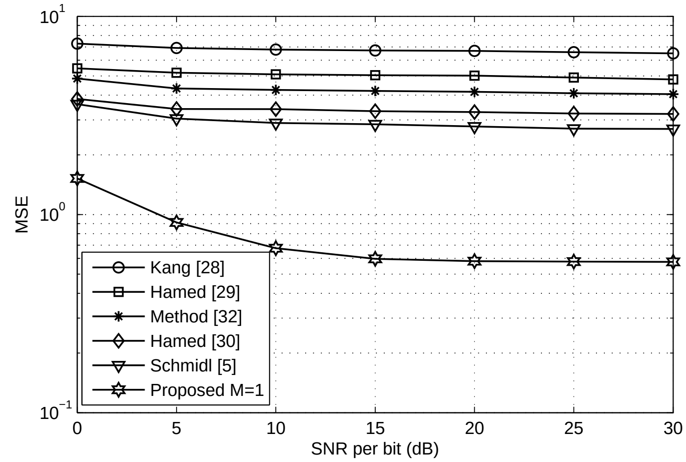


Figure 14. Timing MSE of different estimators using Schmidl's preamble in the presence of CFO [M=1, I=32]

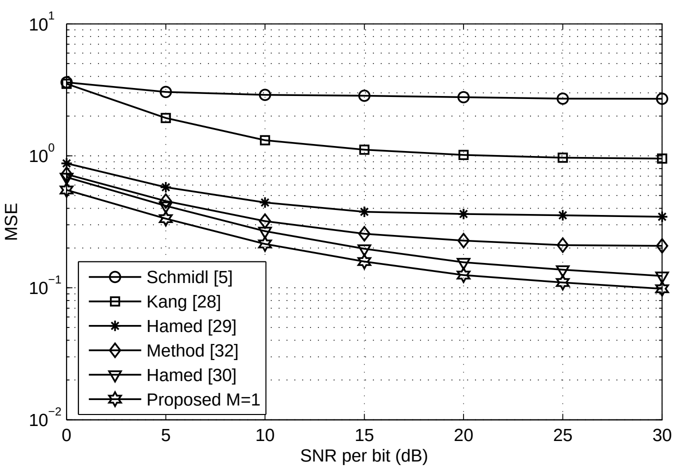


Figure 13. Timing MSE of different estimators using Schmidl's preamble in the presence of CFO [M=1, I=0.5]

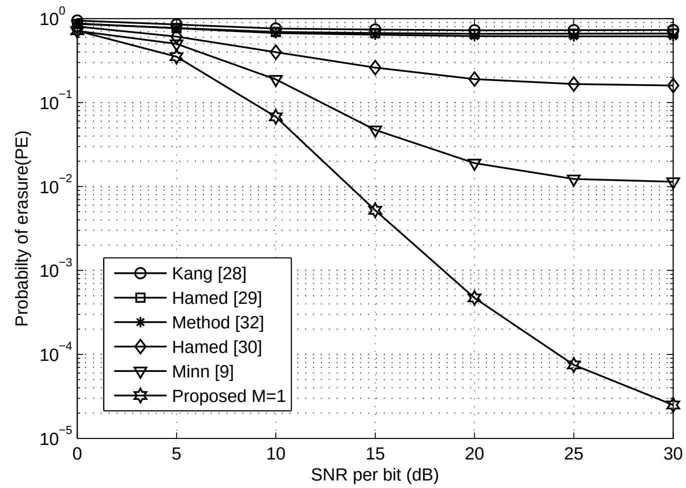


Figure 15. Probability of erasure of different estimators using Minn's preamble in the presence of CFO [M=1, I=32]

method gives satisfactory result even when the range of CFO increases.

In order to compare with the timing estimation methods that depend on the specific structure of the preamble, *Schmidl's* preamble [5] is considered. In Figs. 9 to 14, probability of erasure, probability of correct estimation and timing MSE of the proposed method are compared with the major existing timing synchronization methods using *Schmidl's* preamble [5] considering $M = 1$. Figs. 9, 11 and 13 show the performance comparison with $I = 0.5$. Figs. 10, 12 and 14 show the performance comparison with $I = N/2 = 32$. Like random preamble case, it is also observed that there is a major performance degradation of the methods proposed in [28] [29] [30] [32] using Schmidl's preamble when the CFO increases (large value of $I$). Hence, from the simulation results (as shown in Figs. 9 to 14), it is clear that the timing metrics proposed in [28] [29] [30] [32] are affected by the CFO whereas the timing metric propsed in [5] is not affected by the CFO. It is again concluded that the proposed timing metric is more robust to CFO as compared to methods in [28] [29] [30] [32].

In Figs. 15 to 22, probability of erasure and timing MSE of the proposed method are compared with the major existing timing synchronization methods using other preambles. In Figs. 15 to 16, *Minn's* preamble [9] is used with $M = 1$. In Figs. 17 to 18, *Park's* preamble [11] is used with $M = 1$. In Figs. 19 to 20, *Ren's* preamble [14] is used with $M = 1$. In Figs. 21 to 22, *Sajadi's* preamble [21] is used with $M = 1$. We assume $I = 32$. From simulation results it is observed that the proposed method gives better performance using other preambles. Figs. 23 to 24 show the performance comparison by using both *Schmidl's* and *Minn's* preamble with $M = 2$. Figs. 25 to 26 show the performance comparison by using both *Park's* and *Ren's* preamble with $M = 2$. We assume $I = 32$. From Figs. 23 to 26, we find that the proposed method gives the best performance. In Table 1, computational complexity of the proposed estimator along with existing estimators are given. Computational complexity mainly consists of complex calculations and real calculations. Most of the preamble structure independent methods require both complex and real calculations while the proposed method only require complex calculations, which is high as compared to other methods but the proposed method gives better performance.

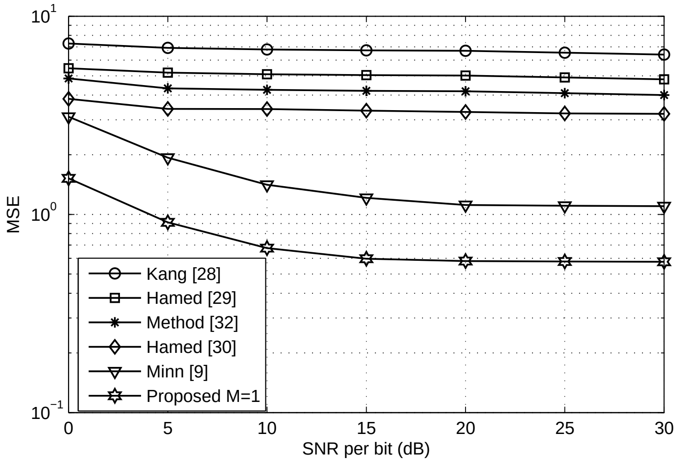


Figure 16. Timing MSE of different estimators using Minn's preamble in the presence of CFO [M=1, I=32]

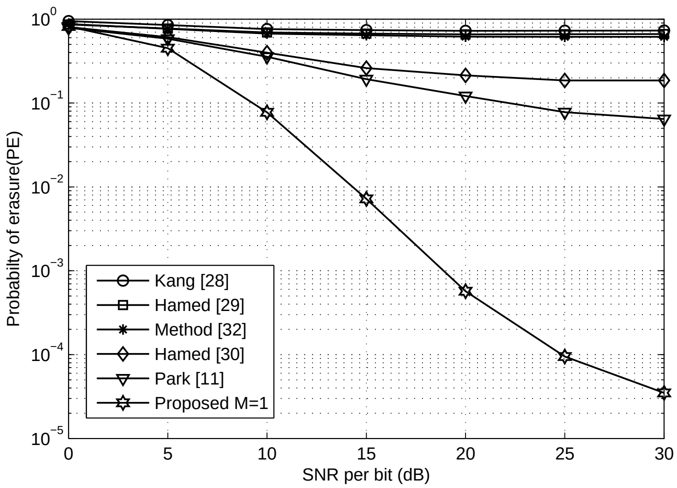


Figure 17. Probability of erasure of different estimators using Park's preamble in the presence of CFO [M=1, I=32]

## VI. CONCLUSION

In this paper, different data aided timing estimation methods are explained and compared. Both preamble structure dependent as well as preamble structure independent timing estimation methods are discussed. It is concluded that preamble structure dependent timing estimation methods perform better than preamble structure independent methods in the

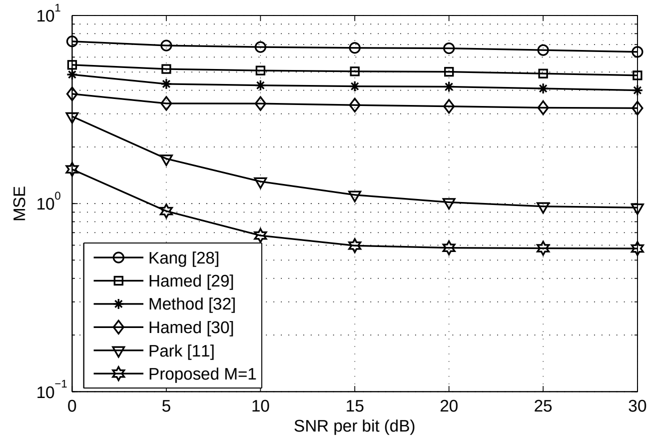


Figure 18. Timing MSE of different estimators using Park's preamble in the presence of CFO [M=1, I=32]

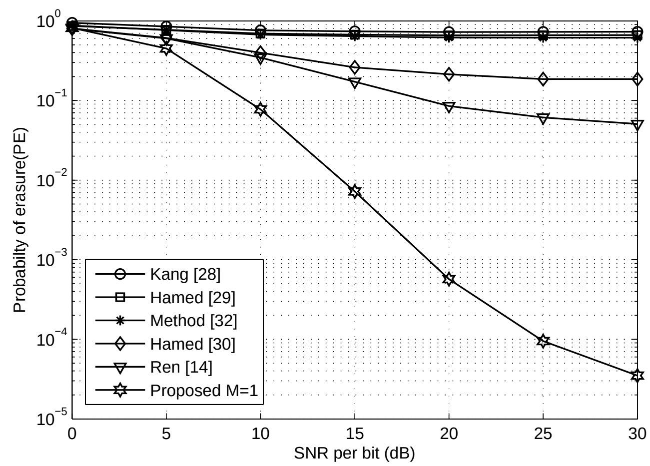


Figure 19. Probability of erasure of different estimators using Ren's preamble in the presence of CFO [M=1, I=32]

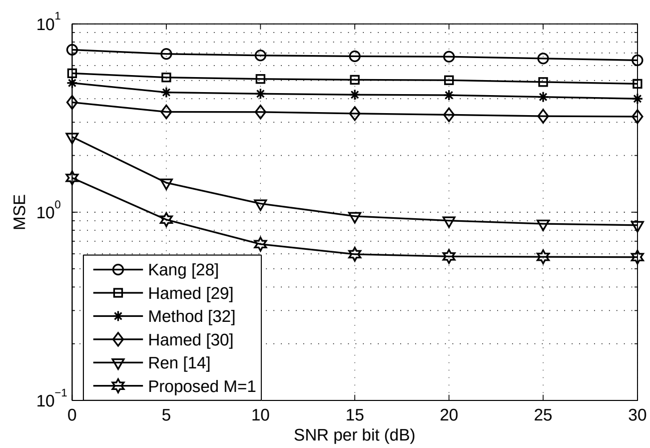


Figure 20. Timing MSE of different estimators using Ren's preamble in the presence of CFO [M=1, I=32]

TABLE I: COMPUTATIONAL COMPLEXITY

| Sl. No. | Method | Complex multiplications | Complex additions | Complex divisions | Real multiplications | Real additions | Real divisions |
|---|---|---|---|---|---|---|---|
| I | Schmidl [5] | $N(N+2)$ | $N(N-2)$ | $N$ | 0 | 0 | 0 |
| II | Minn [9] | $N(N+2)$ | $N(N-2)$ | $N$ | 0 | 0 | 0 |
| III | Kang [28] | $N^2$ | 0 | 0 | $2N^2$ | $N(3N-1)$ | $N$ |
| IV | Hamed [29] | $0.5N^2(N-1)$ | 0 | 0 | $N^2(N-1)$ | $(1.5N^2-1.5N-1)N$ | $N$ |
| V | Hamed [30] | $N(N^2-N+1)$ | $N(0.5N^2-0.5N-1)$ | 0 | 0 | $0.5N^2(N-1)$ | $N$ |
| VI | Method [32] | $N^2$ | $N(N-1)$ | $N$ | 0 | 0 | 0 |
| VII | Hamed [31] | $3N^3$ | $N(2N^2-2)$ | 0 | 0 | 0 | $N$ |
| VIII | Proposed M=1 | $PN(2N+1)$ | $N(NP-1)$ | 0 | 0 | 0 | 0 |
| IX | Proposed M=2 | $PN(4N+1)$ | $N(2NP-1)$ | 0 | 0 | 0 | 0 |

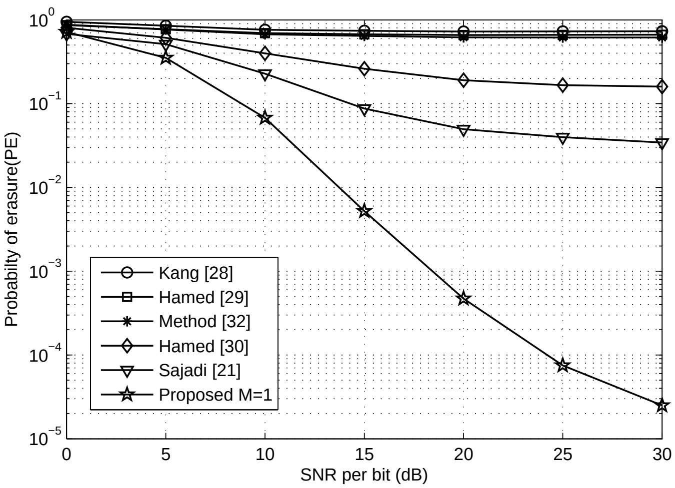


Figure 21. Probability of erasure of different estimators using Sajadi's preamble in the presence of CFO [M=1, I=32]

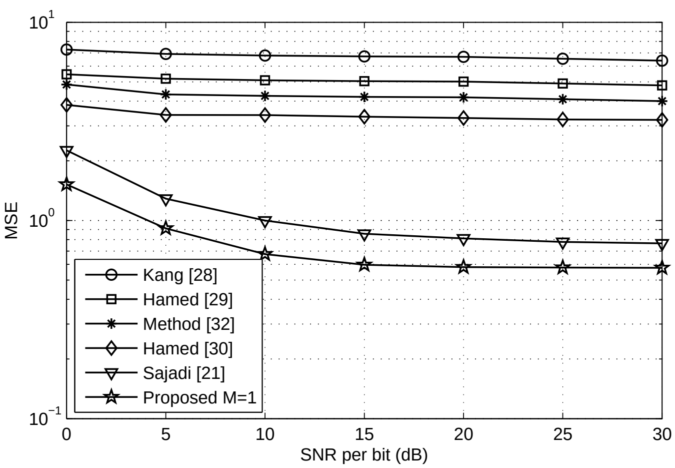


Figure 22. Timing MSE of different estimators using Sajadi's preamble in the presence of CFO [M=1, I=32]

presence of CFO. A new timing estimation method, which is independent of the structure of the preamble, is proposed. A timing estimation method using multiple preambles is also proposed. The performance of the proposed method along with existing methods are investigated in the presence of CFO. Performance is investigated in the presence of different range of CFO. It is observed that the proposed method is robust to CFO. Computational complexity of different estimators are also explained. It is observed that the proposed method performs better than the existing methods in the presence of CFO at the cost of increased computational complexity.

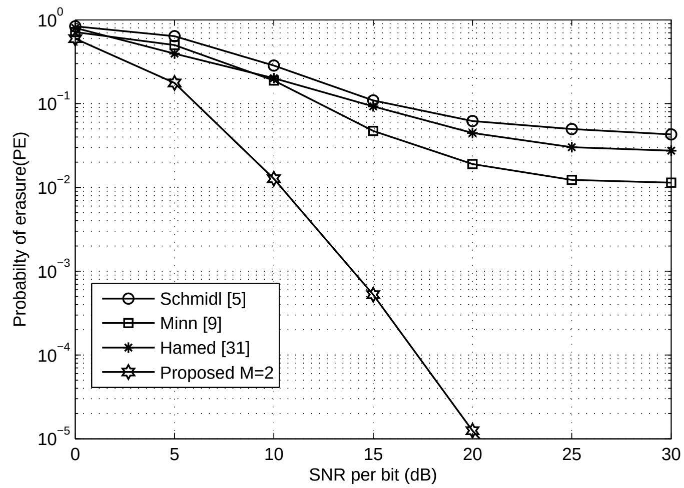


Figure 23. Probability of erasure of proposed estimator using Schmidl's and Minn's preamble in the presence of CFO [M=2, I=32]

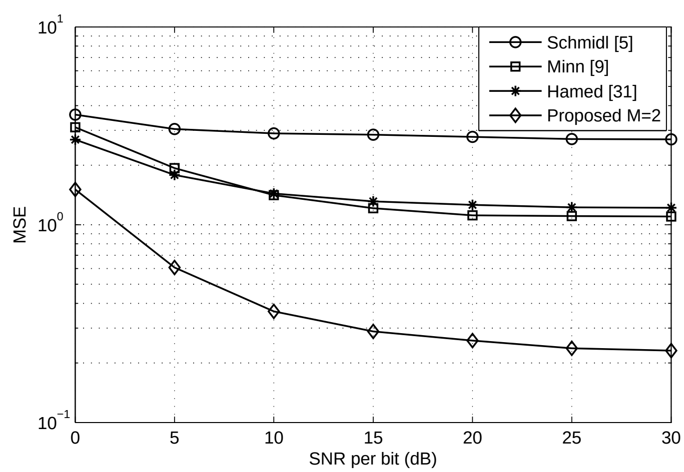


Figure 24. Timing MSE of proposed estimator using Schmidl's and Minn's preamble in the presence of CFO [M=2, I=32]

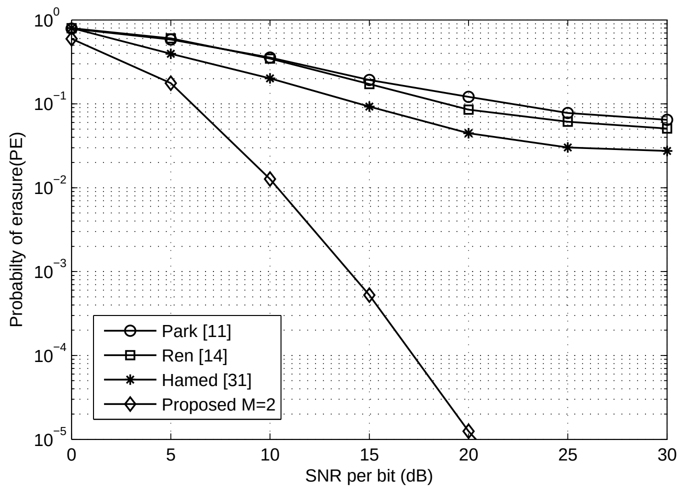


Figure 25. Probability of erasure of proposed estimator using Park's and Ren's preamble in the presence of CFO [M=2, I=32]

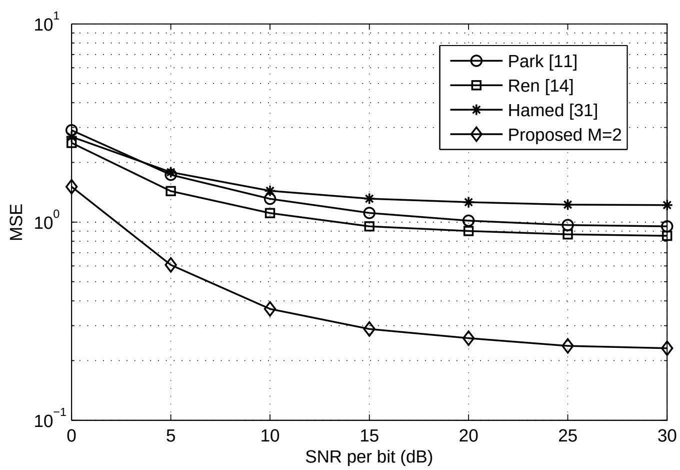


Figure 26. Timing MSE of proposed estimator using Park's and Ren's preamble in the presence of CFO [M=2, I=32]

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