Robust synchronization for OFDM employing Zadoff-Chu sequence

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***Abstract*—Zadoff-Chu (ZC) sequences have been proposed for time synchronization of OFDM systems due to their ideal correlation properties. In this paper, we examine the performance of ZC sequence based time synchronization in the presence of large carrier frequency offsets (CFOs). We show that the performance of synchronization in the presence of integer frequency offsets (IFOs), is dependent on the root index of the ZC sequence and some sequences may fail entirely in the presence of IFOs. We develop the conditions to choose such root indices for which inter symbol interference can be avoided for a given maximum IFO. We then design a preamble based on the selected ZC sequences to perform timing synchronization as well as IFO estimation. We also propose a scheme to further enhance the performance of time synchronization through the estimated IFOs. The performance of the proposed algorithms is evaluated through simulation results.**

I. Introduction

Synchronization in OFDM systems is usually a two-fold process. Time synchronization is performed to determine the index of the starting point of the OFDM symbol in the receiver operating window while carrier synchronization involves estimation and compensation of carrier frequency offsets (CFOs) between the oscillators of the transmitter and the receiver. Cyclic prefix (CP) is appended at the beginning of each OFDM symbol which absorbs the spill of the preceding OFDM symbol into the current symbol due to multi-path channel. The length of the CP is always longer than the maximum excess delay of the channel and therefore, some samples towards the end of the CP are inter symbol interference (ISI) free, as shown in Fig. 1. If initial time synchronization can locate the start of the symbol within this ISI free sample region, ISI and inter carrier interference (ICI) due to wrong timing can be avoided [1]. Fine time and carrier synchronization [2], [3] usually follows initial time and carrier synchronization to fine tune the timing and CFO estimates.

As time synchronization usually precedes carrier synchronization, it should be robust to CFOs. In cellular communications, one should expect large CFOs on the downlink for a mobile user (MU) when it attempts to synchronize itself with the base-station. For example, at a carrier frequency of 2.4 GHz, a clock with 10 ppm (parts per million) accuracy can cause a CFO of 24 kHz or normalized CFO of 1.6 sub-carrier spacing (Δf) in long term evolution (LTE) [4], for which $\Delta f = 15$ kHz. Therefore, time synchronization on the downlink should be able to handle fractional as well as integer CFOs. Once downlink synchronization has been achieved, CFOs on the uplink can only be caused by Doppler effect or residual downlink synchronization errors and are therefore, usually a fraction of the sub-carrier spacing.

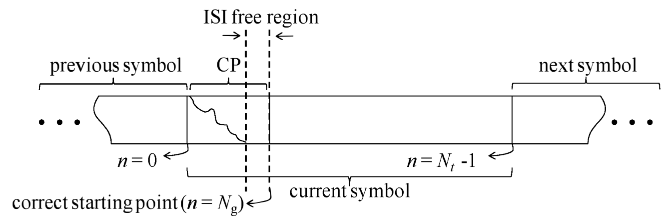

Fig. 1. Interference due to multi-path channel and ISI-free region

Data aided synchronization in OFDM is either based on the autocorrelation of the received signal [2], [5] or its cross-correlation with the local copy of the transmitted signal [6]. Auto-correlation based approaches use preambles with repetitive parts [5] and are robust to multi-path and CFOs but exhibit a higher variance of timing estimate due to presence of the CP. Various methods have been proposed in order to reduce this variance, e.g. [2], [7]. Cross-correlation based approaches provide more accurate time synchronization and lower probability of miss and false detection when there is no CFO, as shown in [6], [3]. However, these approaches perform poorly in the presence of integer CFOs and thus, may not be suitable for initial downlink synchronization. Hence, cross-correlation based methods are usually applied for fine time synchronization as in [3] which assumes that initial time synchronization and CFO estimation and compensation has already been performed.

Recently, Zadoff-Chu (ZC) sequences [8] have been employed in LTE and LTE-Advanced standards [4], both for uplink and downlink synchronization. ZC is a complex exponential sequence given by,

$$x[n] = e^{\pm j \frac{\pi}{N} u \left(n^2 + n(N \bmod 2)\right)}, \quad 0 \leq n \leq N-1 \qquad (1)$$

where N is the length of the sequence, u is the root index relatively prime to N. Circular shifted copies of ZC sequences are uncorrelated from each other [8] which makes them excellent candidates for time synchronization.

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In this paper we propose a downlink initial time synchronization method using ZC sequence. We design a training sequence with two OFDM symbols each with a cyclic suffix (CS) in addition to the CP, which enables robust time synchronization in the presence of integer CFOs. CS based preamble has been proposed earlier for fine time synchronization and channel estimation in [3]. However, [3] does not address the problem of initial time synchronization with CFOs. Instead, it uses [5] for initial time and carrier synchronization. We show that all ZC sequences are not suitable for initial downlink synchronization. This is because the index of the peak of the cross-correlation shifts from its correct position in the presence of integer CFOs which degrades time synchronization performance or may even result in complete failure. The amount of shift depends on the length of the sequence, its root index and the CFO. We show that only some ZC sequences with certain root indices can be used for initial time synchronization. Using those sequences, we design a preamble for which the shifted peak still lies with in the ISI-free region for a certain maximum CFO. We then propose a method to estimate the integer CFOs and correspondingly refine the timing of the received symbol in order to minimize the timing estimation error. In this way, we are able to take advantage of the ideal cross-correlation properties of ZC sequence even in the presence of integer CFOs and thus, make the ZC sequence a suitable candidate for initial downlink synchronization.

II. System Model

Consider the base-band equivalent model of an OFDM downlink system with N sub-carriers, sub-carrier spacing of Δf, sampling rate of $F_s = N\Delta f$ and a CP of N_g samples. The transmission occurs in the forms of frames with Q OFDM symbols in each frame. A ZC sequence is used as a preamble with in each frame in order to facilitate frame detection and synchronization. The n^{th} sample of the transmitted preamble is given as,

$$x[n] = e^{j\frac{\pi}{N}u(n-N_g)^2}, \quad 0 \le n \le N_t - 1 \tag{2}$$

where $N_t = N + N_g$ is total number of samples in each OFDM symbol. We assume N to be even but similar expressions and derivations can be carried out for odd N as well.

Let us assume that the preamble is received with a delay of d samples and a normalized integer CFO of f_I. The n^{th} sample of the received preamble can then be written as,

$$y[n] = e^{j\frac{2\pi}{N}f_I n}\alpha x[n-d] + w[n], \tag{3}$$

where $w[n]$ is the n^{th} additive white gaussian noise (AWGN) sample. Here we assume a flat fading channel with attenuation $\alpha \sim \mathcal{CN}(0, \sigma_h^2)$ where σ_h^2 is the average power of the channel. It will be shown later that the proposed method can be applied to frequency selective channel as well as fractional CFOs.

III. Correlation with the ZC sequence

In order to perform frame detection and initial time synchronization, the receiver calculates a timing metric by performing a cross-correlation $r[k]$ of the received signal samples with the local copy of the ZC sequence,

$$r[k] = \sum_{n=0}^{N-1} y[n+k]e^{-j\frac{\pi}{N}un^2}, \tag{4}$$

where k is the lag of the correlation. The start of the frame is estimated as

$$\hat{d} = \arg\max_k |r[k]|, \tag{5}$$

where $|\cdot|$ denotes the absolute value. Using (2) and (3), (4) can be written as,

$$\begin{aligned} r[k] = &\sum_{n=0}^{N-1} e^{j\frac{2\pi}{N}f_I(n+k)}\alpha e^{j\frac{\pi}{N}u(n+k-N_g-d)^2}e^{-j\frac{\pi}{N}un^2} \\ &+ \sum_{n=0}^{N-1} w[n+k]e^{-j\frac{\pi}{N}un^2} \quad d \le k \le d+N_g. \end{aligned} \tag{6}$$

Note that $d \le k \le d+N_g$ is the ISI free region for a flat fading channel in which linear correlation in the equation above is same as the circular correlation because the samples in the CP are the same as the last N_g samples of the preamble. The above equation can then be simplified as,

$$\begin{aligned} r[k] = &\alpha e^{j\frac{\pi}{N}u(k-N_g-d)^2}e^{j\frac{2\pi}{N}f_I k}\sum_{n=0}^{N-1} e^{j\frac{2\pi}{N}(u(k-N_g-d)+f_I)n} \\ &+ \sum_{n=0}^{N-1} w[n+k]e^{-j\frac{\pi}{N}un^2} \quad d \le k \le d+N_g. \end{aligned} \tag{7}$$

In the noiseless case,

$$|r[k]| = \left|\alpha \sum_{n=0}^{N-1} e^{j\frac{2\pi}{N}(u(k-N_g-d)+f_I)n}\right| \tag{8}$$

The summation in the equation above is equal to zero for all values of k except when $u(k-N_g-d)+f_I = mN$ where m is any integer. At that point, a peak is observed in the timing metric as $|r[k]|$ achieves its maximum value, i.e., $N|\alpha|$. So, the estimate of the start of the frame $\hat{d}$ is given as,

$$\hat{d} = \{k | u(k-N_g-d)+f_I = mN\}. \tag{9}$$

In the absence of CFO, i.e., $f_I = 0$, the condition in (9) is satisfied for $m = 0$ and $k = d+N_g$ which is the true starting point of the preamble. However, for a non zero f_I, the above condition is not satisfied for the correct k and therefore, the peak of the timing metric shifts away from the correct starting position. The amount of shift depends on the value of N, N_g, f_I and u. For example, with $N = 2048$, $N_g = 144$, $f_I = 1$ and $u = 15$, (9) is satisfied for $m = 2$ and $k = d+N_g+273$ which is no longer within the ISI free region.

Proposition: Let k_i denote the index of the peak of the timing metric for $f_I = i$, where i is an integer. If $\exists\, k_1 \; | u(k_1 - N_g - d)+1 = m_1 N$, then $k_{i+1} = k_i + (k_1 - N_g - d)$ satisfies $u(k_{i+1} - N_g - d) + i + 1 = m_{i+1}N$ with $m_{i+1} = (i+1)m_1$.

Proof: $k_2 = k_1 + (k_1 - N_g - d)$ satisfies the above

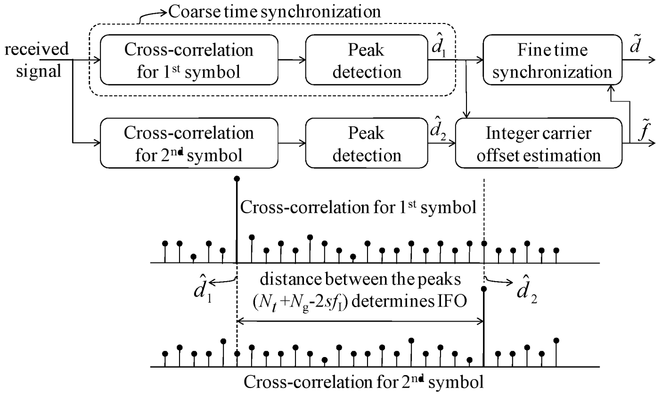

Fig. 2. Block diagram of the proposed synchronization scheme

proposition as,

$$\begin{aligned} u(k_2 - N_g - d) + 2 &= u(k_1 + (k_1 - N_g - d) - N_g - d) + 2 \\ &= 2u(k_1 - N_g - d) + 2 \\ &= 2m_1N = m_2N \end{aligned}$$

Similarly,

$$\begin{aligned} &u(k_{i+1} - N_g - d) + i + 1 \\ &= u(k_i + (k_1 - N_g - d) - N_g - d) + i + 1 \\ &= u(k_i - N_g - d) + i + m_1N \\ &= u(k_{i-1} - N_g - d) + i - 1 + 2m_1N \\ &\quad\vdots \\ &= u(k_1 - N_g - d) + 1 + im_1N = (i+1)m_1N \qquad (10) \end{aligned}$$

A similar proposition holds for $k_{i-1} = k_i - (k_1 - N_g - d)$.

Hence, the peak of the timing metric shifts left or right from the correct location by a fixed amount s, where $s = k_1 - N_g - d$, with each unit increase or decrease in the integer CFO respectively, and the value of s depends on the value of u, N and N_g. If $f_{\max}$ is the maximum absolute integer CFO that can be observed in a system, the peak of the timing metric will lie in the range $[d + N_g - sf_{\max}, d + N_g + sf_{\max}]$. The main idea behind the proposed preamble is to use those values of the root index u which result in the minimum s so that the shifted peak still lies within the ISI free region for a given N_g and $f_{\max}$. The selection of u which results in an appropriate s will be discussed later while the fact that each k_i is unique has been proved in the appendix.

IV. Preamble Design

In this section we describe the proposed preamble design and synchronization algorithm. The block diagram is shown in Fig. 2. In order to deal with both left and right shifts in the location of the peak, we introduce a cyclic suffix (CS) of N_g samples in addition to the CP. Thus, we extend the preamble in (2) to,

$$\tilde{x}[n] = e^{j\frac{\pi}{N}u(n-N_g)^2} 0 \le n \le N_t + N_g - 1 \qquad (11)$$

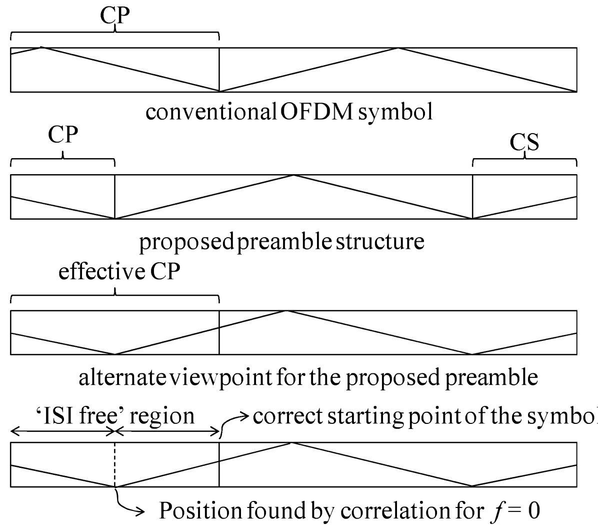

Fig. 3. Structure of the proposed preamble

This modified preamble can also be viewed as a preamble with extended CP as shown in Fig. 3. Since the overall structure remains the same, cross-correlation as in (4) still results in the condition (9) but the ISI free region is extended to $d \le k \le d + 2N_g$. The correct starting point in the proposed preamble is $d + 2N_g$ whereas the peak of the timing metric for $f_I = 0$ is still at,

$$\hat{d} = d + N_g. \qquad (12)$$

It creates a bias of N_g samples in the timing estimate. However, it also allows us to locate the start of preamble within the ISI free region both for positive and negative integer CFOs for a certain $f_{\max}$. If $k_1 = d + N_g + s$, the peak of the timing metric shifts by $\pm s$ samples for each unit increase or decrease in f_I respectively and thus we can locate the preamble within the ISI free region for $f_{\max} = \left| \lfloor \frac{N_g}{s} \rfloor \right|$. Note that the CS has been introduced in the preamble only and the rest of the OFDM symbols in the frame contain only the CP.

A. Finding the root index

The next question is which value of the root index $-(N-1) \le u \le N-1$ should be used so that it is relatively prime to N and also satisfies,

$$u(k_1 - N_g - d) = m_1N - 1. \qquad (13)$$

One would also like to choose a u which gives the minimum possible s, as it would result in a higher $f_{\max}$ that the timing estimation can handle for a given N_g. The simplest choice for u is ± 1 so that $k_1 = d + N_g \mp 1$ or $|s| = 1$. It is minimum possible value of s as well which results in the maximum $f_{\max} = N_g$ for a flat fading channel. Otherwise, any factor of $m_1N - 1$ which is relatively prime to N can be used as u. However one should use the largest possible u in order to make s smallest as $u(k_1 - N_g - d) = us = m_1N - 1$. Thus, we can always find a u so that the peak of the timing metric lies with in the ISI free region for a certain $f_{\max}$ and N_g. This allows us to use cross-correlation for initial time synchronization even in the presence of integer CFOs.

B. Integer CFO estimation and refind time synchronization

The proposed preamble gives a bias in the timing estimate as discussed in the previous section. This bias can be removed once we know the integer CFO. If the estimate of the integer CFO is $\hat{f}_I$, the timing estimate can be corrected as,

$$\tilde{d} = \hat{d} + N_g - \hat{f}_I s. \tag{14}$$

In order to estimate the integer CFO, we propose a further extension in the preamble design . This extension is based on the fact that if $-u$ is used instead of u in a ZC sequence, the value of s will be changed to $-s$. This means that if $\tilde{x}^*[n]$, is used as the preamble instead of $\tilde{x}[n]$ as in (11), the peak of the timing metric will shift by the same amount s but in opposite direction as compared to the peak resulting from the use of $x[n]$. This drives us to design a preamble with two consecutive OFDM symbols, one with a ZC sequence as in (11) followed by another symbol containing the conjugate of the ZC sequence in the first symbol. We perform two separate correlations in order to detect the two symbols. The first correlation is denoted by $r_1[k]$ which is the same as in (4) with $\hat{d}_1$ same as in (5) while, the second correlation is given as,

$$r_2[k] = \sum_{n=0}^{N-1} y[n+k] e^{j\frac{\pi}{N}un^2}, \tag{15}$$

with

$$\hat{d}_2 = \arg\max_k |r_2[k]|. \tag{16}$$

For $f_I = 0$, $\hat{d}_1 = N_g + d$ while $\hat{d}_2 = 2N_g + d + N_t$ and thus $d_2 - d_1 = N_t + N_g$. On the other hand, for a non-zero integer f_I, $\hat{d}_1 = N_g + d + sf_I$, while $\hat{d}_2 = 2N_g + d + N_t - sf_I$ and $d_2 - d_1 = N_t + N_g - 2sf_I$ and we can estimate the integer CFO as,

$$\hat{f}_I = \frac{(N_t + N_g - \hat{d}_2 + \hat{d}_1)}{2s}. \tag{17}$$

As a result, this modified preamble containing two concatenated ZC sequences, allows us to estimate the coarse timing ($\hat{d}_1$), integer CFO ($\hat{f}_I$) and consequently refined timing ($\tilde{d}$) through (14).

C. Effect of fractional CFO and multipath channel

In this section we show that the proposed time synchronization is robust to the presence of fractional CFOs and multipath channel. Note that (8) holds not only for integer CFOs but for any real CFO. Simplifying (8) further, for a real CFO f, we get,

$$|r[k]| = \left| \alpha \frac{\sin\left(\pi(u(k - N_g - d) + f)\right)}{\sin\left(\frac{\pi}{N}(u(k - N_g - d) + f)\right)} \right| \tag{18}$$

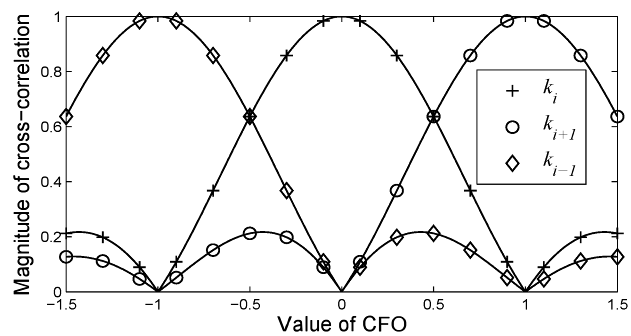

Fig. 4. Effect of fractional CFO on the time synchronization, with $f_I = 0$

Let us express the CFO as $f = f_I + f_F$ where f_I and $|f_F| \leq 0.5$ are the integer and fractional parts of f respectively. We describe the effect of fractional offsets with the help of Fig. 4, in which we show how the absolute value of $\frac{r[k]}{N}$ changes with f, for for three different values of k, i.e., $k_i = d + N_g + is$, $k_{i+1} = d + N_g + (i+1)s$ and $k_{i-1} = d + N_g + (i-1)s$. As the timing estimate is the value of k for which $r[k]$ is maximum, Fig. 4 shows that k_i will be chosen as the start of the OFDM symbol when $f_I = i$ and $-0.5 < f_F < 0.5$. Similarly $k_{i\pm1}$ will be chosen as the OFDM symbol start index when $f_I = i \pm 1$ and $-0.5 < f_F < 0.5$. The only ambiguity lies when $f_F = \pm 0.5$ and $f_I = i$ because, the value of $r[k]$ will be the same for k_i and $k_{i\pm1}$. However, the probability of getting $f_F = \pm 0.5$ is 0 and therefore, there will always be one maximum. Thus, the timing estimation is not disturbed by the presence of fractional offsets.

The discussion in the previous sections is based on a flat fading channel. However, the proposed method can be applied to a multipath channel as well. In the case of multipath channel, the cross-correlation will detect the strongest path of the channel and if the channel remains constant for two consecutive OFDM symbols, the path detected by the two correlations, used for IFO estimation, will be the same and thus the IFO estimation will not be affected by multipath. However, the presence of multipath will shrink the ISI free sample region which will consequently reduce the maximum CFO that the time synchronization can handle. However, the maximum CFO in practical systems is usually limited up to 3,4 sub-carrier spacings and if the s is small enough, we will still be able to detect the peak in the ISI free region, as will be demonstrated in the simulation results.

V. Simulation results

We evaluate the performance of the proposed time synchronization scheme through Monte Carlo simulations and compare it with existing approaches, in this section. The simulation parameters are as follows: $N = 2048$, $N_g = 144$, $\Delta f = 15$ kHz and modulation scheme is quadrature phase shift keying (QPSK) for the data symbols. Each frame consists of $Q = 4$ symbols in which the middle two symbols contain the proposed preamble. The length of CP and CS for the proposed preamble is 72 samples each so that the extended

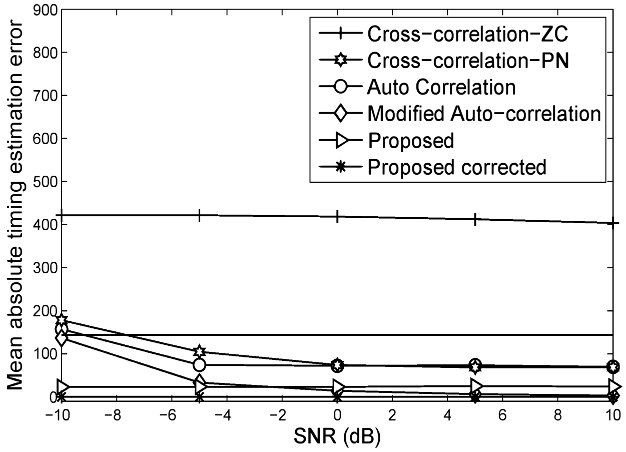

Fig. 5. Timing estimation error comparison for flat fading channel

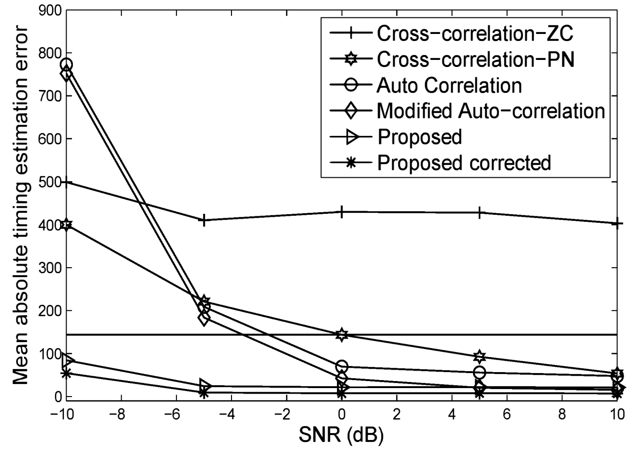

Fig. 6. Timing estimation error comparison for pedestrian 'B' channel

CP is equal to N_g. The value of root index is $u = 1365$ so that $s = 3$. We evaluate the performance for three different channel profiles, i.e., (*a*) flat fading channel, (*b*) pedestrian 'B' channel [9], and (*c*) vehicular 'A' channel [9]. In each scenario, we simulate the performance of the proposed method with and without integer offset estimation and refinement. We compare the performance of the proposed preamble with three different timing estimation methods. *i.* autocorrelation based timing estimation [5], *ii.* cross-correlation based timing estimation using a ZC sequence with $u = 25$ and *iii.* cross-correlation based timing estimation using a PN sequence [6]. A modification of autocorrelation based timing estimation is also simulated in which the timing metric is averaged over N_g samples in order to reduce the ambiguity due to CP. We call it the *modified autocorrelation*. The CFO is modeled as a uniform random variable, i.e. $f \sim \mathcal{U}[-4, 4]$. As Δf is 15 kHz, it is equivalent to having a clock with 25 ppm accuracy at a carrier frequency of 2.5 GHz. As practical cellular communications devices have clocks with accuracy of about 10 ppm or higher, the simulated setup mimics a worst case scenario. It is emphasized that f is a real number for each simulation trial so it contains integer as well as fractional offsets. However the error for IFO estimation is calculated using the integer part of CFO only.

A. Timing offset estimation

Case (*a*) *Flat fading channel*: Fig. 5 shows the mean absolute timing estimation error for flat fading channel. The value of the CP is also shown for reference. The proposed preamble shows better performance than the rest of the schemes with and without IFO estimation. However, the proposed method without IFO estimation shows a bias of about 72 samples as expected while the proposed method with IFO estimation and correction of timing estimate shows perfect performance for the simulated SNR range. The ZC sequence with $u = 25$ shows poor performance because the shifted peak due to CFO does not lie in the ISI free region. Cross-correlation with PN sequence also shows an error floor because the magnitude of cross-correlation peak is reduced for integer CFOs which effects time synchronization performance. Autocorrelation based estimation also shows an error floor because of ambiguity within the CP while the modified autocorrelation has comparable performance to the proposed scheme at higher SNRs. The figure shows that the proposed preamble gains significant performance improvement in timing estimation especially at very low SNRs like -10 dB.

Cases (*b & c*) *Pedestrian 'B' and vehicular 'A' channels*: Fig. 6 and 7 show the performance of the proposed scheme in multi-path channels, i.e., Pedestrian 'B' and Vehicular 'A' channel respectively. The performance of each scheme is affected by the multi-path. However, the performance degradation in autocorrelation based schemes and cross-correlation with PN and ZC sequence with $u = 25$ is much more than the proposed scheme especially at low SNRs. The figure shows that the proposed scheme gives significant advantage in low SNR regimes when others schemes fail to perform successful timing estimation. It also shows the ineffectiveness of conventional cross-correlation methods in the presence of IFOs. These methods can perform successfully for fractional CFOs only which is not usually the case for downlink transmissions.

All these simulation results show the effectiveness of the proposed preamble and IFO estimation and correction method. The proposed scheme outperforms the existing approaches and can detect the start of the symbol for very low SNRs.

B. IFO estimation

We also evaluate the performance of IFO estimation using the proposed preamble with $u = 273$. Fig. 8 shows the normalized mean square error (MSE) for IFO estimation for the three channel profiles described above. The proposed method performs best for a flat fading channel and shows some degradation for multipath channels. However, the performance for multipath channels approaches the flat fading channel as SNR increases.

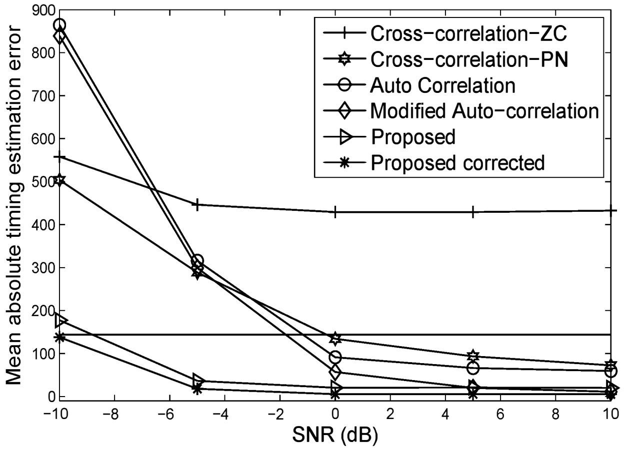

Fig. 7. Timing estimation error comparison for vehicular ‘A’ channel

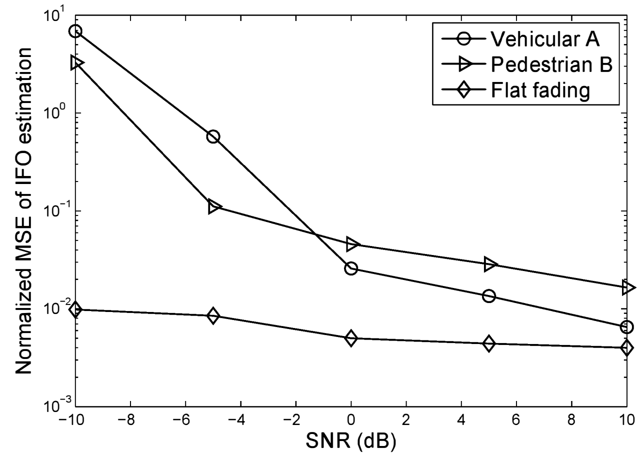

Fig. 8. Normalized MSE of IFO estimation, $E\left[\left|\hat{f}_I - f_I\right|^2\right]$

VI. Conclusions

In this paper we have presented a new method to perform robust time synchronization in the presence of integer carrier frequency offsets using ZC sequences. We have shown that only specific ZC sequences can be employed for time synchronization when we have IFOs. We have demonstrated the dependence of ZC sequence based cross-correlation on the IFOs and shown how this dependence helps us to design efficient preamble which can perform successful time synchronization. We have developed a new scheme to estimate the IFO and consequently improve the time synchronization significantly. Our simulations confirm the effectiveness of the proposed schemes and allows time synchronization and detection in very low SNR regions.

Appendix; uniqueness of peak location k_i

Let us suppose that there exists a k_{i1} such that

$$u(k_{i1} - N_g - d) + i = m_{i1}N \tag{19}$$

for some integer m_{i1} while k_{i1} lies in the ISI free region, i.e., $d \leq k_{i1} \leq d + 2N_g$, and $N_g < N$ which is usually the case. Now assume there exists another k_{i2} such that

$$u(k_{i2} - N_g - d) + i = m_{i2}N \tag{20}$$

for the same i but some integer m_{i2}. Then,

$$u(k_{i2} - k_{i1}) = (m_{i2} - m_{i1})N \tag{21}$$

or

$$\frac{u}{N} = \frac{m_{i2} - m_{i1}}{k_{i2} - k_{i1}} \tag{22}$$

As u is relatively prime to N, the minimum possible value of $(k_{i2} - k_{i1})$ is $\pm N$ or $k_{i2} = k_{i1} \pm N$. So, k_{i2} cannot lie in the ISI-free region and outside ISI free region, linear correlation is no more equal to the circular correlation and hence (9) does not apply.■

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