Journal of Expert Systems (JES)
Vol. 1, No. 2, 2012

www.worldsciencepublisher.org

Time Offset Estimation for OFDM Using MATLAB

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Abstract -- OFDM systems use efficiently the broad spectrum thus meeting the current requirements of new standards laid down by 3GPP. Along with the high data rates, it also competes with other mechanisms providing a good link quality. However, it suffers with Sample Time Offset (STO) and Carrier Frequency Offset (CFO) which must be taken care of at the receiver end. In the current work, effects of STO are studied and correspondingly different precautionary schemes are employed in the receiver to overcome it. These schemes are compared with the help of simulations done on MATLAB.

Keywords – OFDM; 3GPP; Sample Time Offset; MATLAB

1. Introduction

OFDM is one of the emerging techniques for transmitting at higher data rates. This is possible due to the use of multiple carriers thereby dividing the data into smaller chunks. In addition to data rate, this satisfactorily reduces interference; decreasing bit error rates. As a trade-off to this improved performance, it is computationally much more expensive [1].

Systems using OFDM have successfully met the requirements laid down by LTE-A systems. Mobile devices particularly cause problems in achieving the prescribed rates due to their changing position and velocity. These things distinguishes mobile from fixed user and to avail these fantastic advantages, synchronization is required. To use the sine wave for transmission, its parameters of phase and frequency are changed. To prevent the unnecessary change by environment, synchronization should be performed.

DSP technology is now mature enough to implement the OFDM using IFFT/FFT with low cost. Even further synchronization doesn't costs a lot. In general, the timing offset differs a bit in OFDM systems. It faces Sample Time Offset and Symbol Time Offset (STO) [2]. The former is the case with all single-carrier transmission. But as OFDM groups number of samples into one entity called sample; the STO comes to play.

Changing position means the changing distance between transmitter and receiver. Let's say for any transmitter-receiver distance R; the phase offset $\Delta\emptyset$ in the electromagnetic wave of frequency f_c with wavelength $\boldsymbol{\lambda}$ is given by

$$\Delta\emptyset = 2\pi\frac{R}{\lambda} \ldots (1)$$

Apart from this changing position the phase change can occur due to change in estimated and real position of OFDM signal, which is discussed later in more detail. More precisely, the time difference between expected and real symbol position is called STO denoted by □ and in the above case $\eta = \Delta\emptyset$.

These issues are faced in every system but the effect is slight different in the case of OFDM. It is resistant to STO. This is because of the inherent structure of OFDM. It has the guard interval which is the redundancy of modulated samples before or after every symbol or just the zero appending. But this guard interval separates the one symbol from another thereby suppressing the adverse effects of STO but this doesn't mean it is free of STO and some mechanism is required for complete STO free system [3].

In the absence of synchronization simple phase distortion can be removed but once the ISI occurs it can't be removed. So, better estimate is the only way to recover the data error free. The estimation can be done in time domain; using cyclic prefix or training symbols. The equivalent problem can be tackled in frequency domain too. Every method has its own pros and cons and must be adopted depending on the situation and resources.

2. Effects of STO

An OFDM symbol to be sent by a transmitter constitutes of IFFT of modulated symbols, virtual carriers and guard interval. Guard interval, at both
start or at end, is the key to ISI removal. This technique is much efficient but has its limitations in particular scenarios.

This depends on the position of estimated symbol with respect to the real one. The potentially unlimited situations are categorized into four shown in Fig.1.

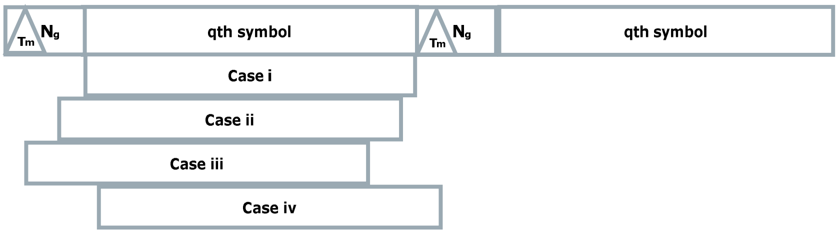

Figure 1. Four different STO scenarios

The symbol q is the actual symbol received and case (i) to (iv) are the different estimates of received symbols. The multipath effect occurs causing the symbol to spread shown in Fig.1 as T_m. The case (i) assumes the perfect situation; the actual and estimated symbol coincides resulting in perfect data retrieval without any interference what so ever [4].

Case (ii) tells estimates the symbol before the actual one yet the q^{th} symbol starts before the lagged channel response of last $(q\text{-}1)^{th}$ symbol. No overlapping of actual symbols is done thus no ISI. Let's consider the N point received sample y in frequency domain.

$$Y_q[k] = \frac{1}{N}\sum_{n=0}^{N-1} x_q[n+\eta]\, e^{-j2\pi nk/N}$$

Where $x_q[n] = \sum_{n=0}^{N-1} X_l[n]\, e^{j2\pi nk/N}$ is the usual IFFT and putting the value of $x_l[n+\eta]$ in the above equation yields.

$$= \frac{1}{N}\sum_{n=0}^{N-1}\left\{\sum_{m=0}^{N-1} X_q[m]\, e^{j2\pi(n+\eta)m/N}\right\} e^{-j2\pi nk/N}$$

$$= \frac{1}{N}\sum_{m=0}^{N-1} X_q[m]\, e^{-j2\pi m\eta/N} \sum_{n=0}^{N-1} e^{j2\pi\frac{m-k}{N}n} \ldots (2)$$

Here the first summation gives $X_q[k]$ and second summation can be thought of

$$\sum_{n=0}^{N-1} e^{j2\pi\frac{m-k}{N}n} = e^{j\pi\frac{m-k}{N}n} * \frac{\sin[\pi(k-m(k-m))]}{\sin[\pi(k-m)/N]}$$

$$= \begin{Bmatrix} N \; for\; k = m \\ 0 \; for\; k \neq m \end{Bmatrix},$$

thus putting its value in Eq.2 results

$$Y_q[k] = X_q[k]\, e^{-j2\pi k\eta/N} \ldots (3)$$

It is clear from Eq.3 that the interference is not faced in this case. There is only a phase offset directly proportional to STO and carrier index k. Its effect is shown in Fig.2 and the effect can be compensated by a single-tap filter.

OFDM symbol in case iii experiences ISI along with ICI because the symbol is estimated prior to the end of lagged channel response of $(q-1)^{th}$ channel response. Its mathematical form is the same as case (ii); but the fact that □ is now very large. For the last case the estimated signal is a little later than the actual one. So the signal, $y_q[n]$ given at the input of FFT block in OFDM hierarchy is $x_q[n]$ and some part of $x_{q+1}[n]$. $y_q[n]$ is more specifically written as

$$y_q[n] = \begin{Bmatrix} x_q[n+\eta] & for\; 0 \le n \le N-1-\eta \\ x_{q+1}[n+2\eta-N_g] & for\; N-\eta \le n \le N-1 \end{Bmatrix}$$

Taking the FFT of a received signal

$$Y_q[k] = \frac{1}{N}\sum_{n=0}^{N-1} x_q[n+\eta]\, e^{-j2\pi nk/N} + \sum_{n=N-\eta}^{N-1} x_{q+1}[n+2\eta-N_g]\, e^{-j2\pi nk/N}$$

$$= \sum_{n=0}^{N-1-\eta} \frac{1}{N}\left\{\sum_{m=0}^{N-1} X_q[m]\, e^{j2\pi(n+\eta)m/N}\right\} e^{-j2\pi nk/N} + \sum_{n=N-\eta}^{N-1} \frac{1}{N}\left\{\sum_{m=0}^{N-1} X_{q+1}[m]\, e^{j2\pi(n+2\eta-N_g)m/N}\right\} e^{-j2\pi nk/N} \ldots (4)$$

$$= \frac{1}{N}\sum_{p=0}^{N-1} X_q[m]\, e^{j2\pi m\eta/N} \sum_{n=0}^{N-1-\eta} e^{j2\pi\frac{m-k}{N}n} + \frac{1}{N}\sum_{m=0}^{N-1} X_{q+1}[m]\, e^{-j2\pi m(2\eta-N_g)/N} \sum_{n=N-\eta}^{N-1} e^{j2\pi\frac{m-k}{N}n}$$

$$Y_q[k] = \frac{N-\eta}{N} X_q[m]\, e^{-j2\pi m\eta/N} + \sum_{m=0,m\neq k}^{N-1} X_q[m]\, e^{j2\pi m\eta/N} \sum_{n=0}^{N-1-\eta} e^{j2\pi\frac{m-k}{N}n}$$

$$+\frac{1}{N}\sum_{m=0}^{N-1} X_{q+1}[m]e^{j2\pi m(2\eta-N_g)/N}\sum_{n=N-\eta}^{N-1} e^{j2\pi\frac{m-k}{N}n}$$

The last term in Eq.4 corresponds that the orthogonality has been destroyed resulting in ICI in this case. The third term of second summation of n implies that the ISI also occurs due to next $(q+1)^{th}$ symbol. Thus this is the worst case of all and resulting in complete failure of the communication system [5].

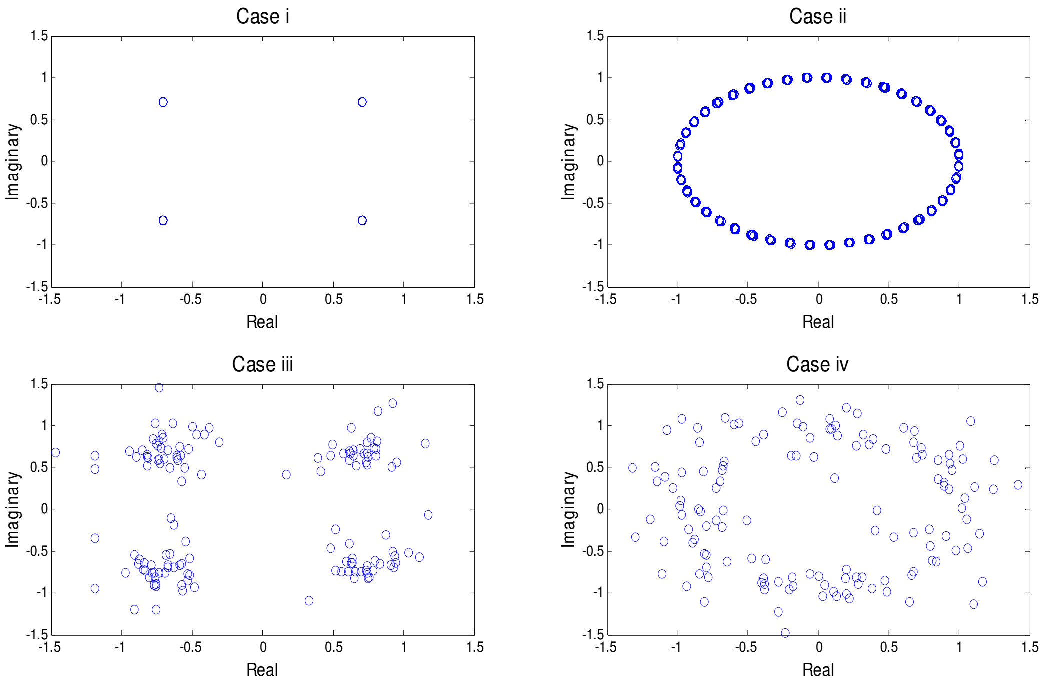

Figure 2. Received Constellations for different cases of STO

3. STO Estimation Techniques

As explained earlier that STO estimation is crucial for OFDM to work properly. General STO estimation techniques in practice are taken into account one by one. Their main classification is estimation in time and frequency domain.

3.1 Time Domain Estimation

First consider an OFDM symbol in time domain; every symbol has an effective data in a span of T_u seconds with N_u symbols. Along with useful data, it has a guard interval of N_g bits over the time T_g seconds. This estimation is done by the use of Cyclic Prefix (CP) or Training Symbol (TS).

3.1.1. STO Estimation using CP

CP is nothing but the replica of actual symbols among the N_g symbols. This replication can be used effectively to be more than just the guard interval. This replication implies similarity between guard interval and effective data. Exploiting the fact that guard interval comes at the start of the symbol; symbol start can be pointed accurately. Consider two windows of exactly N_g symbol size spaced N_u symbols apart demonstrated in figure 3. The similarity in windows is checked continuously and when one window covers whole of the CP, the similarity is maximized thus perfect indication of symbol start [6].

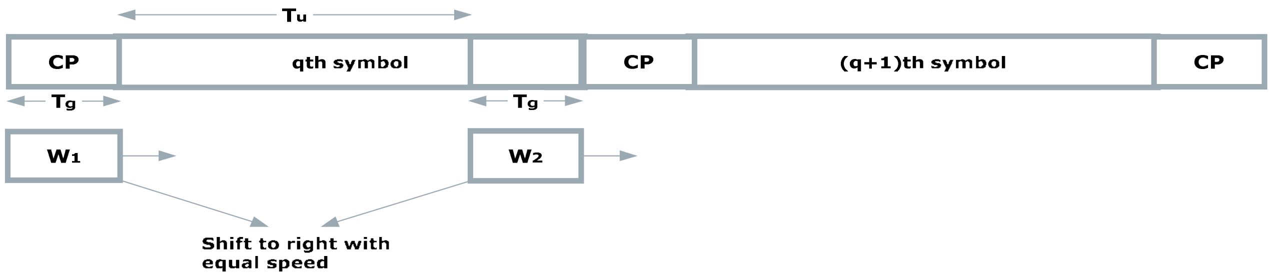

Figure 3. CP estimation using windows depicting symbol start

The symbol start is given by minimizing the difference or maximizing the correlation. These are shown in Eq.5 and Eq.6 respectively.

$$\eta = \min\left\{\sum_{j=\eta}^{N_g-1+\eta} \left|y_q[n+j] - y_q[n+N+j]\right|\right\} \ldots (5)$$

$$\eta = \max\left\{\sum_{j=\eta}^{N_g-1+\eta} \left|y_q[n+j] * y_q^*[n+N+j]\right|\right\} \ldots (6)$$

These approaches are very much simpler but are vulnerable to Carrier Frequency Offset which is often accompanied by STO. CFO free technique is:

$$\eta = \min\left\{\sum_{j=\eta}^{N_g-1+\eta} \left|y_q[n+j] - y_q^*[n+N+j]\right|^2\right\} \ldots (7)$$

3.1.2. STO Estimation using Training Symbol

CP based approach suffers from multi path effect. Although use of TS increase the overhead but it overcomes multi path. STO estimation is same as that in STO; the only difference lies in windowing which now maximizes correlation between TSs [7]. In addition to STO, CFO can be estimated from this technique.

3.2. Frequency Domain STO Estimation

STO directly meant phase shift proportional to subcarrier frequency. So, STO can be estimated by the phase difference between adjacent symbols provided that $x_q = x_{q+1}$ and $H_q \approx H_{q+1}$. For all k, $Y_q[k]Y_q^*[k+1] \approx |X_1[k]|^2 e^{j2\frac{\pi\eta}{N}}$ and STO from this relation comes out to be

$$\eta = \frac{N}{2\pi}\min\left\{\sum_{k=1}^{N_g-1} Y_q[k] * Y_q^*[k-1]\right\} \ldots (8)$$

Another approach for finding STO is to use a delayed channel response obtained by the use of $Y_q[k]$ and $X_q^*[k]$ as

$$\eta = max\left|y_q'[n]\right|$$

Where

$$y_q'[n] = IFFT\left\{Y_q[k]X_q^*[k]e^{j2\pi\eta\frac{k}{N}}\right\}$$

$$= \frac{1}{N}\sum_{k=0}^{N-1} Y_q[k]X_q^*[k]e^{j2\pi\eta\frac{k}{N}}e^{j2\pi n\frac{k}{N}}$$

$$= \frac{1}{N}\sum_{k=0}^{N-1} H_q[k]X_q[k]X_q^*[k]e^{j2\pi(\eta+n)\frac{k}{N}}$$

$$y_q'[n] = h_q[n+\eta] \ldots (9)$$

Last result is obtained considering $X_q[k] = 1$ for simplicity [8]. It can be seen from Eq.9 that the shift caused by STO can be evaluated as the frequency drift in channel due to STO.

4. Simulation Results

Time Domain Estimation techniques are employed using Eq.6 and Eq.7. As stated earlier, the purpose is to find the maximum in case of correlation and minimum for difference in Eq.6 and Eq.7 respectively. Fig.4 shows dotted vertical line as actual STO. It is clear from figure that correlation technique doesn't give satisfactory results in the presence of CFO but the mean square difference is not affected by it.

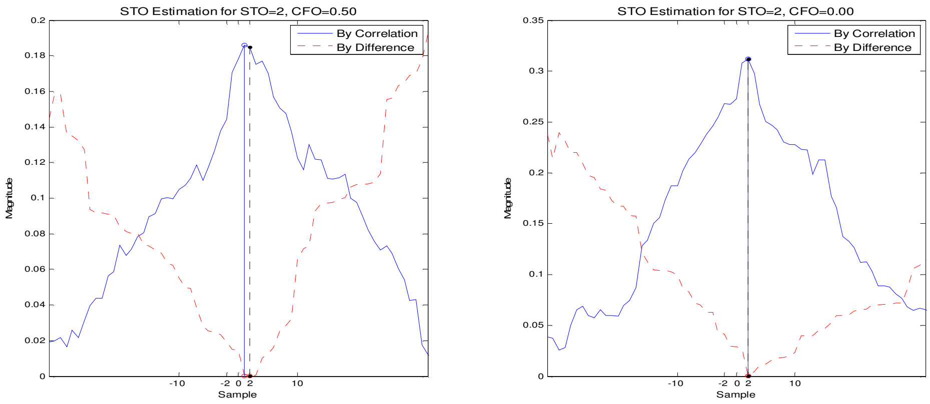

Figure 4. Effect of CFO on Correlation Technique

In addition to these, frequency STO estimation technique can also be implied. It is much more accurate than the previous ones. It can be seen graphically in Fig.5 as the difference between the actual channel response and delayed channel response caused by STO. In this particular case STO is set to be 10.

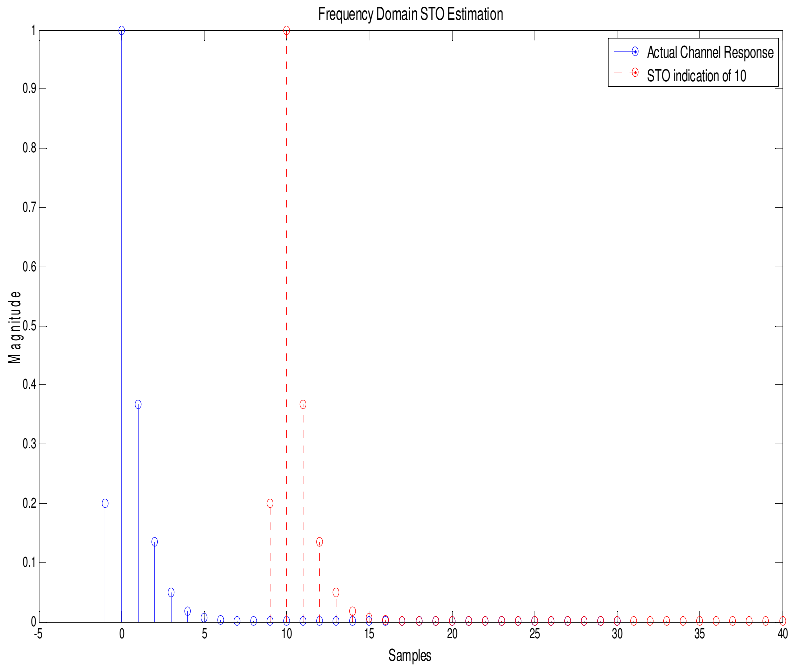

Figure 5. Frequency Domain STO Estimation

5. Conclusion

OFDM is very popular communication technique nowadays which provides high data rates at the cost of higher complexity especially in synchronization. Without synchronization, even OFDM can't outperform other simple communication schemes. Different STO estimation techniques are discussed with their merits and demerits explained. It was seen that Frequency Domain STO Estimation is most accurate.

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Vitae

Waqar Aziz, Ebtisam Ahmed, Ghulam Abbas, are students of B.E Electrical Engineering at Institute of Space Technology, Islamabad, Pakistan. Currently they are working on their Final Year Project “Design and Implementation of MIMO-OFDM System using USRP”. They have already published 3 International Journal Papers from their work related to Final Year Project.

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