# Suppression of Synchronization Errors in OFDM Based Carrier Aggregation Systems

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**Abstract:** **Orthogonal Frequency Division Multiplexing or OFDM can be defined as a digital multi-carrier modulation scheme that splits the whole channel into different orthogonal sub-channels. OFDM can also be used as the air interface technique for Long Term Evolution (LTE), which has high sensitivity .OFDM delivers high frequency efficiency that helps to increase sturdiness against fading and Inter Symbol Interference (ISI). Orthogonal Frequency Division Multiplexing or OFDM is sensitive to synchronization errors due to multi-path fading, Doppler shift and variability of oscillator. In this paper, Carrier Aggregation (CA) is defined by 3GPP, the 3$^{rd}$ Generation Partnership Project in order to support wide-bandwidth transmission. There are two challenging problems in OFDM. They are Carrier Frequency Offset (CFO) and Sampling Time Offset (STO). However, discontinuous carrier aggregation scenario' synchronization problem is determined and CAZAC algorithm (Constant Amplitude Zero Auto-Correlation)is proposed to reduce synchronization error, Carrier Frequency Offset or CFO and Sampling Time Offset (STO).In addition, pre-coder design is used to enhance Bit Error Rate (BER) performance and to reduce the Mean Square Error Value (MSE).In this paper, a block type pilot pattern error suppression algorithm is proposed to decrease errors of synchronization in Carrier Aggregation Systems (CA). The results of simulation show that it can considerably enhance the performance of the system and has a smooth performance when synchronization errors vary.**

**Keywords**: Orthogonal Frequency Division Multiplexing (OFDM), Carrier Aggregation (CA), weighted Constant Amplitude Zero Auto-Correlation (CAZAC), Carrier Frequency Offset (CFO), and Sampling Time Offset (STO).

## I. INTRODUCTION

For the next generation mobile communication system, Orthogonal Frequency Division Multiplexing or OFDM technology became the essential technology due to its high bandwidth efficiency, robust capability to resist inter carrier interference and anti-channel interference. As OFDM system is a multi-carrier modulation system, it would be very sensitive to its synchronization errors. However, estimation of synchronization is an important part of the OFDM system. In OFDM technology, the given channel is portioned into many orthogonal sub channels in frequency domain. One subcarrier modulates every sub channel and all sub-carriers are transported in parallel. The guard interval or cyclic prefix is inserted among the sub-carrier in frequency domain in order to guarantee the orthogonal of sub carrier. The interference among the OFDM symbols can be removed by inserting guard interval or CP. However, OFDM system is sensitive to frequency and time offset. The good performance of the OFDM system can be determined by noticing the synchronization of time and frequency. The synchronization of OFDM involves the carrier frequency synchronization, the timing synchronization and sampling clock synchronization .In addition, the timing synchronization involves synchronization of symbol and frame synchronization. The frame synchronization is used to find out the starting position of the data packet where as frame synchronization is used to determine the starting position of OFDM symbols. Synchronization is an essential task for any digital communication system. The transmitted data cannot be recovered without using precise synchronization algorithms. In OFDM systems, timing and carrier frequency offset are the challenging problems. They arose when they are combined with other multi access techniques such TDMA, FDMA, and CDMA.

**Definition of OFDM:** Orthogonal Frequency Division Multiplex (OFDM) system can be defined as a multicarrier communication system that contains orthogonal subcarriers. **Basic Principle of OFDM:** The basic principle of OFDM is to divide a high data rate sequence into a number of low rate sequences that can be transmitted simultaneously over a series of sub-carriers. Carrier aggregation is used to support more number of users than OFDM. **Definition of Carrier Aggregation:** Carrier Aggregation is a technique that aggregates various component bands into an overall wider bandwidth and is proposed to support wide bandwidth

transmission in LTE-Advanced standard. It also provides flexibility in spectrum assignment. But, the OFDM system is sensitive to synchronization errors such as Sampling Time Offset (STO) and Carrier Frequency Offset (CFO).The orthogonal among sub-carriers would be broken by inaccurate synchronization. They receive Inter Carrier Interference (ICI) into received signal that leads to serious performance degradation. In non-continuous CA scenario, signals that are transmitted on various component such as a timing synchronization algorithm was discussed but CFO compensation method was not considered. These CFO compensation methods are proposed in [5-14].In addition, frequency synchronization methods are divided into two groups. The first one is feedback method that increases the transmission overhead and possibly caused outdated estimation in time-varying scenario. Another method is to attain synchronization using signal processing at the receiver without the help of a control channel. Successive Interference Cancellation or SIC and Parallel Interference Cancellation or PIC methods were raised in 8-10. The received signals are differentiated as reliable and unreliable groups. The signals of reliable group can be detected directly whereas unreliable signals can be detected after the cancellation of the Multiple Access Interference (MAI) effects due to the reliable signals .Inverse interference matrix was discussed in 11-13. Multiple CFO estimation is not possible in practical system. Our previous algorithms proposed in 12-13 did not consider timing set .All the above methods that are mentioned above are applied in non continuous CA system. There are few papers about the synchronization problems in CA system. This project mainly focuses on the synchronization problems in non-continuous CA system. It also proposed a block type pilot based synchronization errors suppression algorithm. Use the correlation of the pilot block to estimate the STO and estimation of interference is followed after STO estimation. Now, in this stage, pilot blocks are used to estimate the ICI components directly. Inverse matrix method is used to suppress the components. This method can be easily extended to the other systems as block type pilot is a common pilot pattern in wireless communications.

## II. SYSTEM MODEL

The simplified block diagram showcased in the figure 1 illustrates the orthogonal frequency division multiplexing (OFDM) that is based on non-continuous carrier aggregation i.e. non continuous CA system.
Now, we have to assume a case that is without loss of generality. For example, K component bands are utilized in this communication system. The carrier frequency of the $k^{th}$ component band is denoted as $f_c^{\ k}$ and the subcarrier amount of the $k^{th}$ component band is $N_k$. Here we assume the vector $\mathbf{d}_k=[d^k_{\ 0},d^k_{\ 1},..............d^k_{\ Nk-1}]^T$ $(k=1, 2, 3 ..., K)$ denotes the transmitted data on the $k^{th}$ component band. Then the output of the $N_k$-IFFT is

$$s^k(n) = 1/\sqrt{N_k}\sum_{i=0}^{N_k-1}d^i_k e^{j2\pi in/N_k} \qquad (1)$$

Rx
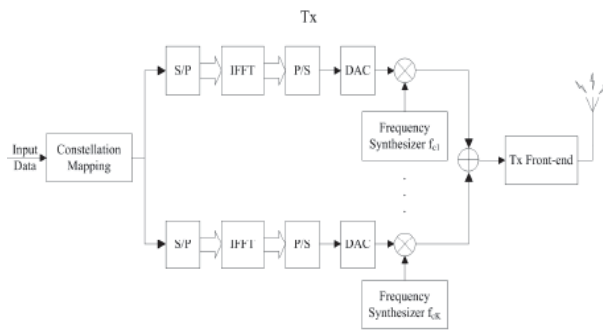

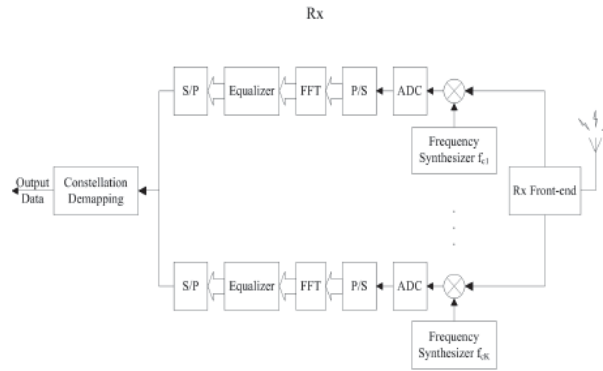
Figure 1: Block diagram of OFDM based non-continuous CA system

With the help of the carrier frequency $f_c^k$, the base band signal would be modulated to the transmission band. However, at the up-converter, carrier frequency can be generated by the transmitter frequency synchronizer.

Here we take, every signal experiences as a frequency selective fading channel with the time domain impulse response $h^k(n)$ (k=1, 2, 3 …K).

So, the signal received is the superposition of signals from all active component bands and can be written as

$$r(t) = \sum_{k=1}^{K} (s^k(t).e^{j2\pi f_c^k t}) \otimes h^k(t) + v^k(t) \qquad (2)$$

Where $\otimes$ denotes convolution and $V^k(t)$ is the AWGN on the $k^{th}$ component band.

Through $N_k$-FFT processing, the output of the $l^{th}$ subcarrier on the $k^{th}$ component band is

$$Y_l^k = d_l^k H_l^k \qquad (3)$$

Where $H_l^k$ denotes the frequency domain that is channel response of the $k^{th}$ component band.

### III. INFLUENCE OF SYNCHRONIZATION ERRORS

Many STOs and CFOS should be introduced into the received signals in order to start the influence of inaccurate synchronization. Moreover, CFO and STO of the $k^{th}$ component band are indicated as $\Delta f_e^k$ and $\Delta t_e^k$ respectively.

The CFOs and channel fading corrupted time domain signal, after transmitted through fading channels can be written as

$$r(t) = \sum_{k=1}^{K} (s^k(t).e^{j2\pi(f_c^k + \Delta f_e^k)t}) \otimes h^k(t) + v^k(t)_{t+n\Delta t_e^k} \qquad (4)$$

Various bands can be separated by sufficient bandwidth for non-continuous CA. The interference between them can be negligible. The STO corrupted received signal can be written as

$$r^k(n) = \frac{1}{\sqrt{N_k}} \sum_{i=0}^{N_k-1} d_i^k H_i^k p_i^k e^{\frac{j2\pi(ni+n\varepsilon_k+\varepsilon_k\delta_k)}{N_k}} + v^k(n+\delta_k) \qquad (5)$$

Where $T_s = T/N_k$ is the sampling period, T indicates the symbol period, $\varepsilon_k$ and $\delta_k$ denote the normalized CFO and STO respectively as, after FFT,

$$Y_l^k = d_l^k H_l^k p_l^k Q_0^k + \sum_{\substack{i=0 \\ i \neq l}}^{N_k-1} d_i^k H_i^k p_i^k Q_{i-l}^k + v^k \qquad (6)$$

Where $Q_l^k = \dfrac{1}{N_k} \sum_{n-0}^{N_k-1} e^{\frac{j2\pi n(L+\varepsilon_k)}{N_k}} e^{\frac{j2\pi\varepsilon_k\delta_k}{N_k}}$ denotes the interference factor and $V_l^k$ denotes AWGN. Obviously, we can attain the matrix expressed frequency domain signal vector according to the above equation

$$\mathbf{Y}_v^k = Q_M^K P_M^K R_v^k + \mathbf{V}_k \qquad (7)$$

Where $\boldsymbol{R_v^k} = [\boldsymbol{R_0^k, R_1^k \ldots\ldots\ldots R_{N_k-1}^k}]^{\mathrm{T}}$ ($R_1^k = d_1^k H_1^k$) denotes the received signal vector distorted by channel fading, $\mathbf{P_M^k} = \mathrm{diag}(p_0^k, p_1^k, \ldots\ldots p_{Nk-1}^k)$ denotes the phase rotation matrix caused by STO and

$$Q_M^k = \begin{bmatrix} Q_0^k & Q_1^k \cdots\cdots & Q_{N_k-1}^k \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ Q_{-(N_k-1)}^k & Q_{-(N_k-2)}^k \cdots\cdots & Q_0^k \end{bmatrix} \qquad (8)$$

denotes the ICI matrix caused by CFO. The components of diagonalized characters in k $Q_M^k$ are the CPE (Common Phase Error) components and the other components represent the ICI from the corresponding subcarriers.

## IV. SYNCHRONIZATION ERRORS SUPPRESSION ALGORITHM

In Synchronization errors suppression algorithm section, we will consider the proposed block type pilot based synchronization errors suppression algorithm. Here we use the pilot pattern that is weighted CAZAC sequence. Let us assume, L be any positive integer that is larger than one and M to be any number, that is relatively prime with L.

Here is an example of weighted CAZAC sequence, that is given as

$$\begin{cases} c_M(n) = e^{\frac{j2\pi M}{L}(n+\frac{n+l}{2})}, n = 0,1..L-1, L\,is\,odd \\ c_M(n) = e^{\frac{j2\pi M}{L}(n+\frac{n^2}{2})}, n = 0,1...L-1, L\,is\,even \end{cases} \qquad (9)$$

and the circular auto-correlation of weighted CAZAC sequence is

$$\sum_{n=0}^{L-1} c_M(n) c_M(n+\tau)_{\mathrm{mod}\,L} = \begin{cases} L, \tau = 0 \\ 0, \tau \neq 0 \end{cases} \qquad (10)$$

## A) STO Estimation Algorithm

In this section, let us discuss the proposed frequency domain STO estimation algorithm to attain the STO between the practical sampling time and optimum sampling time.

Special weighted CAZAC sequence should be used to implement this algorithm. Pilots that are spaced by half sub carriers should satisfy the following requirement.

$$P_l^k = \pm P_{l+N_k/2}^k \qquad (11)$$

Where $P_l^k$ denotes the pilot transmitted on the $l^{th}$ subcarrier of the $k^{th}$ component band. In OFDM system, since the amount of subcarrier is always an even number, we can acquire the expression of $P_l^k$ as

$$P_l^k = e^{j2\pi M/N_k(l+l^2/2)}, l = 0,1..............N_k - 1 \qquad (12)$$

In order to satisfy the above requirement, we just need to set M as an odd and $N_k$ as a multiple of 4 (in this scenario, M is naturally relatively prime In OFDM system) to attain high speed FFT/IFFT. Subcarrier amount is usually set as exponential times of 2. As a result, the above requirement can be achieved by just set M as an odd number. Therefore

$$\begin{cases} P_l^k = P_{l+N_k/2}^k, if\ l\ is\ odd \\ P_l^k = -P_{l+N_k/2}^k; if\ l\ is\ even \end{cases} \qquad (13)$$

In this situation, the $l^{th}$ received pilots can be expressed as

$$P^k(l) = P_l^k H_l^k p_l^k Q_0^k \qquad (14)$$

We suppose the frequency domain channel response has already been estimated. Then the correlation can be calculated as follows

$$\eta = e^{j\pi\delta_k} \sum_{i=0}^{\frac{N_k}{2}-1} \left| P^k(l) \right|^2 \left| Q_0^k \right|^2 \qquad (15)$$

Therefore, the STO of the $k^{th}$ component band can be obtained from the phase of $\eta$ as

$$\delta_k = \arctan(\frac{Im(\eta)}{Re(\eta)})/\pi \qquad (16)$$

Since the variation range of arc tan(x) is (-π/2, π/2), the estimation range is (-0.5, 0.5), which fully covered the available value of STO.

**B) Interference Suppression Algorithm**

Now, we perform interference estimation after STO estimation. And then restrain the imprecise synchronization. As estimating CFOs is fairly difficult to get accurate results, we directly estimate the interference components with the help of the received pilot block .Now, the ICI matrix can be reconstructed by using simple mapping method. Then we can overturn interferences by using inverse matrix method and ultimately develops performance of the system.

From the expression of $Q_L^k$ we can obtain that

$$Q_{-L}^k = Q_{N_k-L}^k \qquad (17)$$

Therefore, the ICI matrix $Q_M^k$ can be rewritten as

$$Q_M^k = \begin{bmatrix} Q_0^k & Q_1^k & \cdots & Q_{N_k-1}^k \\ Q_{N_k-1}^k & Q_0^k & \cdots & Q_{N_k-2}^k \\ \vdots & \vdots & \ddots & \vdots \\ Q_1^k & Q_2^k & \cdots & Q_0^k \end{bmatrix} \qquad (18)$$

We can see that the matrix $Q_M^k$ is a circulated matrix with only $N_k$ different components. Therefore, equation (7) can be written as

$$Y_v^k = R_M^k Q_v^k + V_k \quad (19)$$

Where $Q_v^k = [Q_0^k, Q_1^k .......Q_{N_k-1}^k]^T$ and

$$R_M^k = \begin{bmatrix} R_0^k p_0^k & R_1^k p_1^k & \cdots & R_{N_k-1}^k p_{N_k-1}^k \\ R_1^k p_1^k & R_2^k p_2^k & \cdots & R_0^k p_0^k \\ \vdots & \vdots & \ddots & \vdots \\ R_{N_k-1}^k p_{N_k-1}^k & R_0^k p_0^k & \cdots & R_{N_k-2}^k p_{N_k-2}^k \end{bmatrix} (20)$$

We can consider equation (19) as an equations set and the $N_k$ components in $Q_M^k$ as the unknown values. The $Q_M^k$ matrix can be reconstructed, if we can estimate these $N_k$ values by explaining these equations.

CFO interferences can be gained by multiplying the inverse $Q_M^k$ matrix with the received signal. The pilots are known to receive as STO has already been estimated. $R_M^k$ can be calculated easily.

Obviously, $R_M^k$ is a full rank matrix. Thus, $(R_M^k)^{-1}$ can be easily constructed and $Q_M^k$ which contains the $N_k$ components can be easily estimated by using the following equation is as shown below:

$$\widetilde{Q}_v^k = (R_M^k)^{-1}.Y_v^k = Q_v^k + (R_M^k)^{-1}.V_k \qquad (21)$$

Now, the interference matrix $Q_M^k$ can be reconstructed from the estimated $\widetilde{Q}_v^k$. Therefore, the synchronization errors can be easily suppressed by LS (Least Square) method as

$$Y_{\sup pressed}^k = R_v^k + (P_M^k)^H [(\widetilde{Q}_M^k)^H \widetilde{Q}_M^k]^{-1} (\widetilde{Q}_M^k)^H V_k \quad (22)$$

Therefore, we can use parallel process to restrain the inexact synchronization on each band.
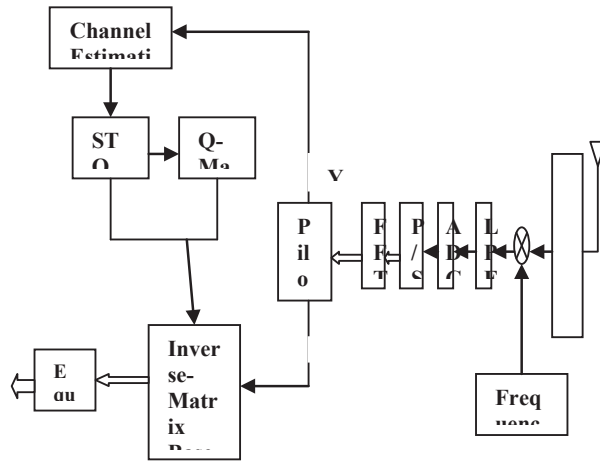
Figure 2: Block diagram of synchronization errors suppression algorithm

The block diagram of the suppression algorithm is shown in Figure 2. The whole process can be illustrated as follows:

1) When a symbol arrives at the receiver, we have to detect whether this symbol is a pilot symbol: If yes, go to step 2 or else go to step 5.

2) Perform channel estimation.
3) Do STO estimation under the aid of channel estimation.
4) Execute Q matrix estimation with the help of channel estimation results and STO estimation results.
5) Perform inverse-matrix based suppression algorithm.
6)

## V. STIMULATION RESULTS

Table 1: Simulation Parameters

| Baud Rate | 9600 symbols/second |
|---|---|
| Modulation Type | 16 QAM |
| Component Carriers | 4 |
| FFT size | 256 |
| Cyclic prefix length | 16 |
| Number of Sub Carriers | 256 |
| Channels | AWGN, Pedestrian-B(Ped-B) |

In figure 3, we can see the performance of the Mean Square Error or MSE of proposed STO estimation algorithm. The results can be estimated in AWGN and ITU Ped-B scenarios.
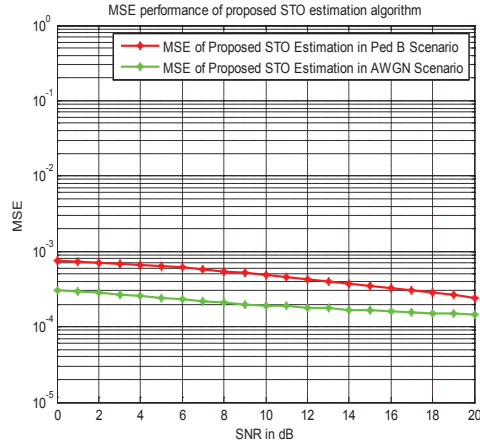
Fig.3 MSE performance of the proposed STO estimation algorithm

This shows that the MSE of the proposed algorithm can be reduced to $10^{-4}$ level that is a fairly small value. We can achieve smooth performance when synchronization errors vary.

The algorithm proposed in 11 as comparison and selected 5, 10, and 50 as the bandwidth of the banded matrix. The BER performance in AWGN channel can be shown in figure 4 and the BER performance can be seen in Ped-B channel in figure 5.

When we compare the stimulation results, we can see that the performance will be degraded seriously due to the co effects of CFO and STO. When we use the banded matrix suppression method, small errors flow phenomenon occurs in high SNR region.

The Bit Error Rate (BER) can be reduced for the proposed system and hence it enhanced the performance of the system.
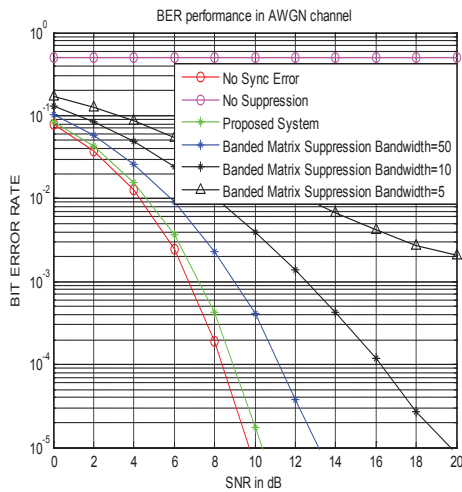




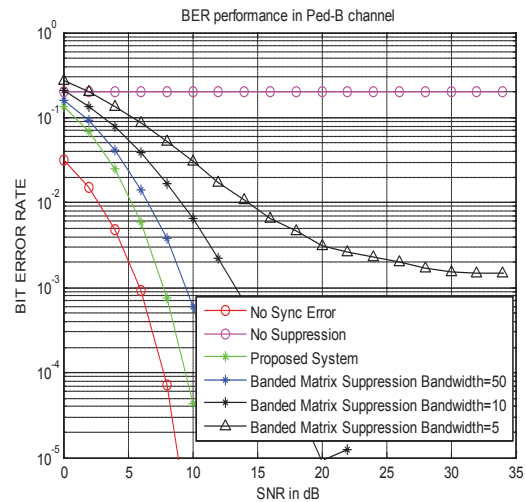Figure 4:  BER performance in AWGN channel          Figure 5:  BER Performance in Ped-B Channel

## VI. CONCLUSION

In this project work, we focus on the problems of synchronization in non-continuous CA OFDM systems. We proposed a novel block type based synchronization errors suppression algorithm.

Distinct to other STO estimation algorithms, the proposed method develops a special weighted CAZAC sequence. It denotes the rule of interference self cancellation and can improve the estimation accuracy.
The proposed algorithm could directly estimate the interference components not including the estimation of CFO. Therefore, the system complexity can be reduced.

According to the results of simulation, the proposed algorithm could considerably develop the performance of the system and attain smooth performance $10^{-4}$ level which is a fairly small value.

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