Investigating The Effect of The Carrier Frequency Offset(CFO) and Frequency Synchronization on The Performance of The OFDM Wireless Systems

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Abstract
Orthogonal Frequency Division Multiplexing (OFDM) is a modulation schema that due to the high spectral efficiency and the simplicity of the receiver implementation is the most common system for using in broadband communication systems. Although OFDM has been used in numerous wireless communication systems, but two of the main problems that are needed to be considered and investigated is Carrier Frequency Offset (CFO) and OFDM synchronization. CFO ruins the orthogonality between the subcarriers and creates Inter-Carrier Interference (ICI). In brief, CFO and lack of the frequency synchronization in OFDM systems can severely degrade the performance of the OFDM systems. In this paper we review and analyze the effect of the CFO and frequency synchronization in the OFDM systems, and propose an algorithm that can be used for CFO estimation.
Key words:
Carrier frequency offset (CFO), Frequency synchronization, Inter-Carrier Interference (ICI), CFO estimation and compensation, OFDM performance, Frequency Offset, Orthogonal Frequency Division Multiplexing (OFDM)

1. Introduction

Less than 60 years ago the idea of dividing the transmitting data into the number of interleaved bit streams was published by Doelz et al. [1]. After that Chang [2] proposed the basic idea of multicarrier modulation. On the other hand, Weinstein and Ebert [3] are the ones that showed how to use the Discrete Fourier Transform (DFT) for performing the baseband modulation and demodulation. However at the present time, OFDM is the most popular system. Especially in the last few years it has been used in various commercial applications.
Although OFDM has many advantages; but CFO and frequency synchronization has been recognized as two important issues that should be considered for OFDM systems. The effect of CFO can be seen in Figure 1. CFO generates by: Frequency mismatched in the transmitter and the receiver oscillator, the Doppler Effect, and precision limitation of the oscillators. CFO causes inter-carrier frequency offset and mismatch between Digital-to-Analog Converter (DAC) and Analog-to-Digital Converter (ADC) which leads to create sample timing offset (STO) [4]. CFO can also create Inter carrier Interference (ICI) which can cause performance degradation. Due to the problems that CFO causes, many algorithms have been proposed for estimating the CFO by now.

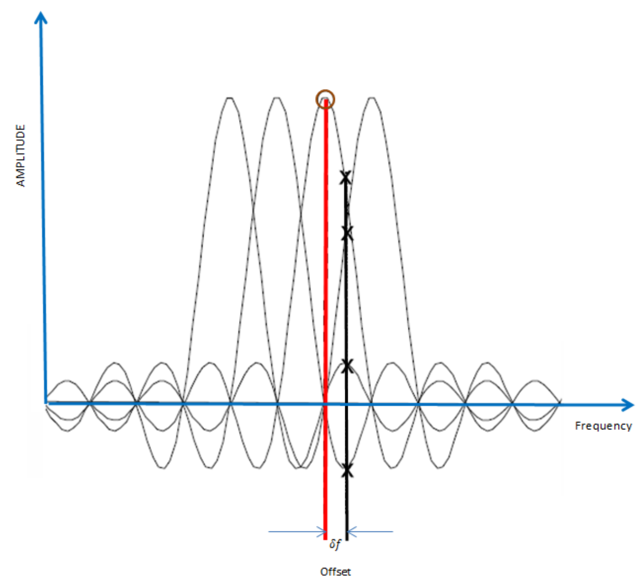

Fig. 1 The impact of frequency offset [5]

To overcome the ICI problem which is the result of the CFO, different methods have been suggested, which some of them that can be mentioned are as follows. One algorithm, which is based on CFO estimation, is using pilot sequences or blind signal processing method. The other one is based on the windowing technique, like Nyquist and Hanning windowing and another approach is ICI self-cancellation. However CFO and frequency synchronization errors have serious effects on the performance of the OFDM systems and no matter which method to be used, the point is: for keeping the orthogonality in OFDM systems the carrier frequency offset should be estimated and compensated at the receiver

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side. When the CFO is estimated a perfect equalizer can be designed to remove the effect of the ICI.
When the orthogonality cannot be kept, the performance of OFDM system will be degraded. In the following parts after a concise review About CFO, we study the major factors that have direct effects on frequency offset and frequency synchronization in OFDM wireless communication systems. On the other hand since using Direct Conversion Receivers (DCR) causes CFO, we briefly study it too.

2. Carrier Frequency Offset (CFO)

In order the receiver to be synchronized with the transmitter; two key factors are needed to be known by the receiver [5]. Firstly the receiver needs to know prior to the FFT process, where it should start sampling the incoming OFDM symbol from and then how to estimate and correct any carrier frequency offset (CFO).

After detecting the symbol and estimating the symbol boundaries in receiver, estimation of the frequency offset starts.
The block diagram of the OFDM transceiver system, including the modulation, digital-to-analog (D/A) converter, channel and noise, the analog-to-digital (A/D) converter, and demodulation is illustrated in figure 2.

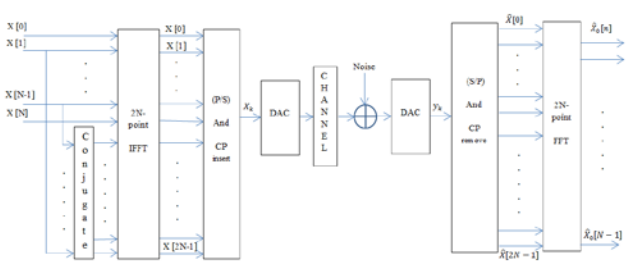

Fig. 2 Block diagram of the OFDM transceiver system

However in case of the presence of the CFO in the received signal to the receiver, the received signal can be states as [6]:

$$[n] = H[n]X(n)\frac{\sin(\pi\varepsilon)}{Nsin(\frac{\pi\varepsilon}{N})}e^{\frac{j\pi\varepsilon(N-1)}{N}} + \qquad (1)$$

$$\sum_{m=0,m\neq n}^{N-1} H[m]X(m)\frac{\sin[\pi(m-n+\varepsilon)]}{Nsin\left[\frac{\pi(m-n+\varepsilon)}{N}\right]}e^{\frac{j\pi(m-n+\varepsilon)(N-1)}{N}}$$

$$+\omega[n]$$

In Eq. (1), ε is the normalized frequency offset. The part two in Eq. (1) is the result of the effect of ICI due to the presence of the frequency offset. As it is can be observed from the Eq. (1) the CFO causes the amplitude of the signal to be degraded by the following factor:

$$\frac{\sin(\pi\epsilon)}{Nsin(\frac{\pi\epsilon}{N})}$$

According the Eq. (1), the shift that the received signal experience is equal to:

$$\theta = e^{j\pi\varepsilon(N-1)/N} \qquad (2)$$

As we know the normalized (ε) CFO has two parts: integer part (ε_i) and fractional par (ε_f) therefore it can be stated as:

$$\varepsilon = \varepsilon_i + \varepsilon_f \qquad (3)$$

The integer part leads to the cyclic shifted in the received signal but the fractional part has the effect on phase distortion and amplitude of the received signal. The figure 3 illustrates a typical block diagram of the OFDM system with the fractional frequency offset estimation, and integer frequency offset estimation for estimating and compensating the effect of CFO in the receiver.

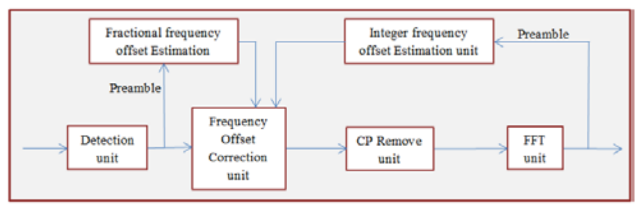

Fig. 3 Structure of an OFDM system with the required units for estimating and compensating CFO

3. Effect of CFO on phase

CFO has also impact on the phase in time domain. The figure 4 shows the effect of phase change due to the CFO. To get the figure 4 we assume there is no interference of noise with the system. The solid line in figure 4 shows the case that the CFO=0, and the dash line shows the effect of CFO when the amount of the CFO in the system is equal to 1.4.

4. Degradation of OFDM systems due to the Carrier Frequency Offset (CFO)

The complex transmitted OFDM signal in a period T at the frequency m/T can be state as [7]:

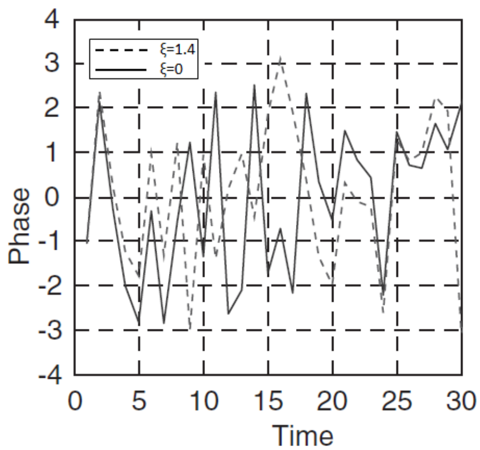

Fig. 4 The effect of CFO (ξ) on phase in the time domain

$$s(t) = \left(\sum_{m=0}^{N-1} a_m e^{\frac{j2\pi mt}{T}}\right) e^{j\theta(t)} \qquad (4)$$

In which a_m is data symbol and the term $\theta(t)$ represents the time varying phase due to the carrier frequency offset between transmitter and receiver.

With an accepted approximation the degradation in terms of dB is defined as follows [7]:

$$D \cong \frac{10}{Ln\,10}\left(\left(1 - {E_0}^2\right) + V_0 \frac{E_S}{N_0}\right) \qquad (5)$$

In which, the signal to noise ratio (SNR) is: E_s/N_0, and V_0 is the variance for others noises and ${E_0}^2$ is the power of the component.

In case of presence the frequency offset (Δf) between the transmitter and receiver, the $\theta(t)$ in Eq. (4) is defined as:

$$\theta(t) = 2\pi\Delta f t + \theta_0 \qquad (6)$$

Therefore the degradation (D) for OFDM is defined as [7]:

$$D \cong \frac{10}{3Ln\,10}\left(\pi N \frac{\Delta f}{R}\right)^2 \frac{E_S}{N_0} \qquad (7)$$

From Eq. (7) it can be observed the degradation for an OFDM is proportional with the square root of the frequency offset and it is also proportional with E_s/N_0. In another word, OFDM is very sensitive to frequency offset and frequency offset can cause severe degradation in OFDM systems.

Figure 5 illustrates the SNR degradation as a function of the frequency offset to the subcarrier spacing. For this illustration we consider two different values for E_s/N_0 which are 18 and 16 db. However the maximum acceptable frequency offset can only happen when the frequency offset is less than one percent of the subcarrier space. As a result, for overcoming to the mentioned problem the frequency synchronization must be used before the FFT.

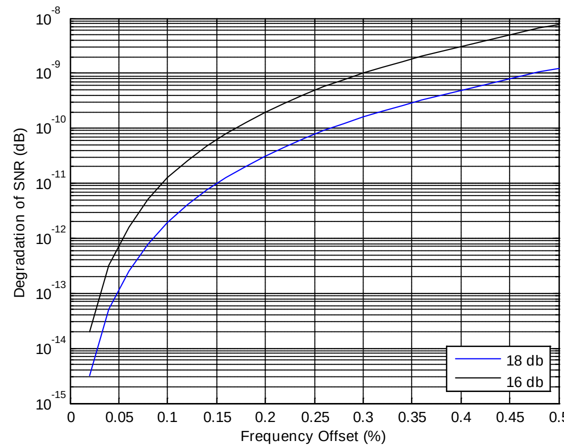

Fig. 5 SNR degradation as a function of the frequency offset

5. Frequency synchronization

The frequency synchronization for OFDM systems can be classified in two methods: data aided and non-data aided. While the data aided uses the pilot symbols for estimation the other one uses Cyclic Prefix (CP) correction.

In wireless OFDM systems, synchronization is the most important issue. In order the receiver regenerate the signal that the transmitter sends, must be synchronized in frequency, time and phase with the transmitter. Since the mobile OFDM systems work in a dynamic environment this is not an easy case. However in the OFDM wireless systems; two reasons that leads to frequency offset between the receiver and transmitter are:

(i) sampling clock mismatch
(ii) misalignment

6. Sampling clock mismatch

The Analog-to-Digital (A/D) in receiver side is responsible for determining the sampling time. A/D does not have always the exact sampling clock; this can cause a relative drift between the receivers sampling respect to the transmitter. This drift which is called Sampling Clock Drift (SCD) (or sampling clock error) reduces the OFDM System performance. The SCE produce the rotation of subcarriers which leads to ICI and finally destroy the orthogonality between the subcarriers. By now many researchers have discussed and evaluated the effect of SCD on OFDM wireless systems [8]. The normalized sampling error can be stated as follows:

$$t_\delta = \frac{T_{RX}-T_{TR}}{T} \tag{8}$$

T_{RX} is received sampling period and T_{TR} is transmit sampling period. The total effect can be shown as [9]:

$$R_{l,k} = exp\left[j2\pi k t_\delta l \frac{T_s}{T_u}\right] X_{l,k} \sin c(\pi k t_\delta) H_{l,k} + W_{l,k} + N_{t_\delta}(l,k) \tag{9}$$

Here $R_{l,k}$ is the received subcarrier, l and k are OFDM symbol index and subcarrier index, $W_{l,k}$ is Additive White Gaussian Noise (AWGN), T_s is total symbol duration, T_u is useful sample duration and $N_{t\delta}$ is additional interference because of the sampling frequency offset. The degradation of OFDM systems due to this effect can be given by [10]:

$$D_n \approx 10\log_{10}\left[1 + \frac{\pi^2}{3}\frac{E_s}{N_0}(kt_\delta)^2\right] \tag{10}$$

As it can be seen from Eq. (10) the degradation performance of OFDM wireless systems increase by the square power of the frequency offset.

7. Performance degradation due to the ISI

The signals that arrive to the receiver; come from the different paths, therefore there is a time delay between them which can cause inter-symbol interference (ISI). ISI causes the degradation performance in the reception of the receiver. Well let's consider the output of the modulator unit in transmitter as:

$$x(t) = \sum_{n=-\infty}^{\infty}\left[\sum_{k=0}^{N-1} d_{n,k} \emptyset_k(t-nT_d)\right] \tag{11}$$

Respectively $T_d, d_{n,k}, N$ are: symbol duration, data symbol and block size, and f_k is k[th] subcarrier frequency where $f_k = f_0 + \frac{k}{T_d}$ $\quad and \quad k = 0,1,\dots,N-1$ and

$$\emptyset_k(t) = \begin{cases} e^{j2\pi f_k t} & t \in [0, T_d] \\ 0 & otherwise \end{cases} \tag{12}$$

Eq. (11) can be stated as follows:

$$x_n(t) = \sum_{k=0}^{N-1} d_{n,k} \emptyset_k(t-nT_d) \tag{13}$$

The transmitted signal can be stated as:

$$s(t) = \sum\left[\sum_{k=0}^{L-1} x_n(k)\delta(t-(nL+k)T_d)\right] \tag{14}$$

L is the data symbol length.

The received OFDM signal considering the AWGN and multipath condition can be presented as follows [11]:

$$r_n(k) = \sum_{i=0}^{L-1} x_n(i)h(k-i) + \sum_{i=0}^{L-1} x_{n-1}(i)h(k+L-i) + v_n(k) \tag{15}$$

If we consider Q=L-N and the length of the multipath channel (L_h) to be as long as the guard interval, therefore the Eq. (15) can be separated and stated in two time intervals as follows:

$$r_n(k) = \tag{16}$$

$$\begin{cases} \sum_{i=0}^{L-1} x_n(i)h(k-i) + \sum_{i=0}^{L-1} x_{n-1}(i)h(k+L-i) + v_n(k) & 0 \le k0 \le Q-1 \\ \sum_{i=0}^{L-1} x_n(i)h(k-i) + v_n(k) & Q \le k \le L-1 \end{cases}$$

As it can be seen; the first interval has the ISI from the previous symbol and desired symbol but the next interval has merely the wanted data symbol. However the good advantage of the OFDM wireless systems is their robustness against the multipath delay spread. Decreasing the effect of ISI can be accomplished by using the long symbol period.

8. Effect of CFO on SNR

The effect of CFO on Signal-to-Noise Ratio (SNR) in OFDM systems was studied by Pollet et al. [12]; the impact of the CFO on the degradation in term of dB is given by:

$$SNR_{loss} = \frac{10}{3ln10}(\pi T f_\delta)^2 \frac{E_s}{N_o} \tag{17}$$

Where T is subcarrier spacing and δf is the frequency offset. Figure 6 illustrates the impact of the sampling offset on the degradation of SNR.

As the figure 6 shows; by increasing the number of subcarriers the degradation of OFDM increases.

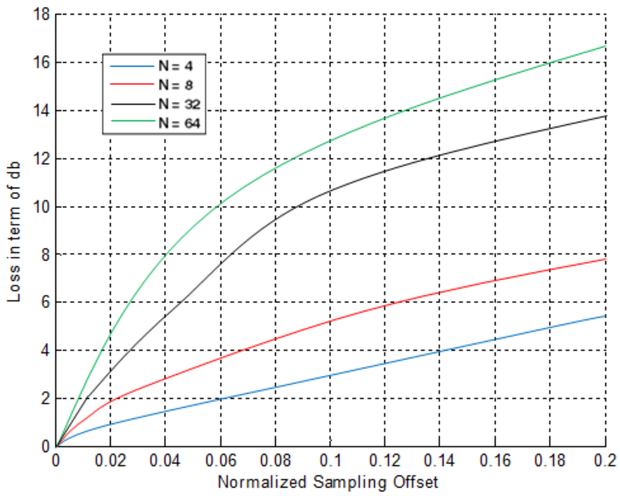

Fig. 6 SNR degradation Versus Sampling offset

9. Effect of CFO on creating ICI

As we mentioned the lack of orthogonality in the received signal to the OFDM receiver, creates carrier frequency offset. CFO introduces the ICI in the system. However Figure 7 illustrates the ICI due to the frequency offset. Figure 7 was created for different values of frequency offset. As it can be seen from figure 7; by increasing the frequency offset ICI increases.

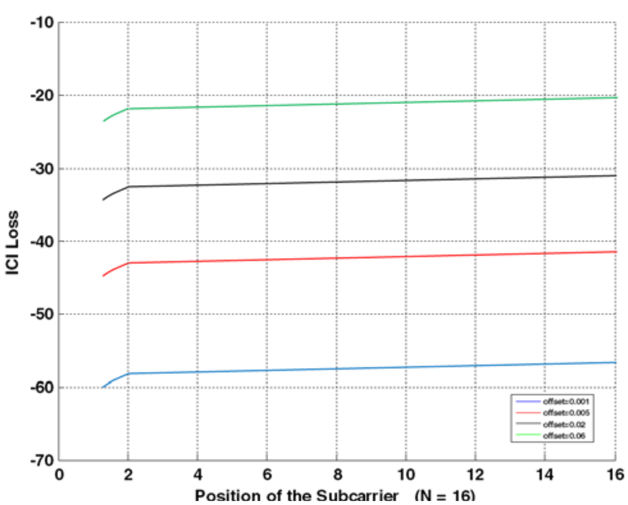

Fig. 7 The overall ICI created by frequency offset

10. The effect of Symbol and Sample Timing Offset

When the data blocks in the input of the FFT in receiver are exactly matched with the ones from the transmitted IFFT block in transmitter, we can claim that we have achieved a perfect synchronization. There is two kind of synchronization: late synchronization and early synchronization. If the synchronization tick comes after the perfect synchronization point it is called the late synchronization which can destroys the orthogonality of the subcarrier and causes ICI. By getting the Cyclic Prefix (CP) enough long we can eliminate the major effects of the early synchronization. It is worth to mention that we must avoid the late synchronization in all the cases however the late synchronization can also cause a chunk of the channel response fall out of the channel estimation window, which can create an additional noise; therefore let's consider an Additive White Gaussian Noise (AWGN) channel which the vector received signal can presented as:

$$y_m = \left[y_{p,m}, \dots, y_{N_c-1,m}, y_{0,m+1}, \dots, y_{p-1,m+1}\right] \qquad (18)$$

After the demodulation via FFT unit it is [13]:

$$\hat{X}_{k,m} = \frac{N_c - P}{N_c} X_{k,m} e^{j2\pi\left(\frac{K}{N_c}\right)P} + \frac{1}{N_c} \sum_{n=0}^{N_c-1-P} e^{-j2\pi(n/N_c)k} \sum_{i=N_d/2;i\neq k}^{N_d/2-1} e^{j2\pi(i/N_c)(n+p)} + \frac{1}{N_c} \sum_{n=N_c-p}^{N_c-1} e^{-j2\pi(n/N_c)k} \sum_{i=N_d/2}^{N_d/2-1} X_{i,m+1} e^{j2\pi(i/N_c)(n+p)} + n_{k,m} \qquad (19)$$

As it is obvious from the Eq. (19), the symbol timing offset can create three effects, which are ISI, ICI and phase rotation.

Carrier Frequency Offset Δf_c (CFO) and Sampling Clock Frequency Offset (SCFO) cause the phase rotation in the received signals which can be stated as:

$$\theta(t) = 2\pi\left(1 + \left(\frac{T_s - T}{T}\right)\right).\Delta f_c t \qquad (20)$$

T_s is actual sampling interval and T is perfect sampling interval. The effect of the phase rotation is:

(21)

$$y_{k,m} = \frac{1}{T}\left\{X_{k,m}\int_0^T e^{j\theta(t)}dt + \sum_{i=0,i\neq k}^{N_c-1} X_{i,m}\int_0^T e^{-j2\pi(k-i/T)t}e^{j\theta(t)}dt\right\} + n_{k,m}$$

Considering the Eq. (21), it is obvious not only the CFO and SCFO destroy the orthogonality between the subcarriers but also they create the OFDM subcarrier symbol rotation and OFDM symbol window drift.

Considering the [14], the degradation of OFDM systems due to the ICI can be stated as follows:

$$D(db) \approx \frac{10}{3\ln 10}\left[\pi\frac{N_c\Delta f_c}{B}\right]^2\frac{E_S}{N_0} \qquad (22)$$

11. The effect of using DCR on CFO

Using Direct Conversion Receivers (DCR) is another case that causes CFO. By now, numerous investigators and researchers have been studied the effects of the In-phase and Quadrature (I/Q) mismatch of the local oscillators (LOSC) in OFDM wireless systems [15, 16, 17]. They have revealed that I/Q mismatch destroys the orthogonality of the subcarriers, which leads the OFDM systems suffer from Inter Carrier Interference (ICI) and CFO. However, since Direct Conversion Receivers (DCR) are very good in cost and power consumption, their popularities are getting more and more.

Although DCRs have some good advantages but they bring a challenging issue which is called In-phase/Quadrature phase (I/Q) imbalance. This issue causes ICI at the received signals which lead to CFO. It is well-known that OFDM systems are sensitive to the CFO, therefore many CFO and I/Q imbalance estimation and compensation methods and techniques have been proposed by now. Some of these techniques assume the perfect timing synchronization, which makes it so hard to accomplish it in practice. To show the impact of I/Q imbalance on the received signal, let's consider the Figure 8, which shows the block diagram of the DCR with I/Q and CFO compensation configuration.

The received RF signals to the DCR receiver antenna can be stated as [18]:

$$rRF(t) = \mathcal{R}\{[s(t)\otimes h(t)].e^{j2\pi f_c t}\} \qquad (23)$$

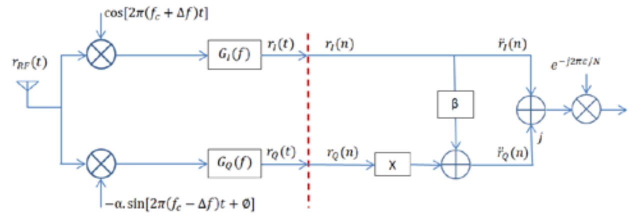

Fig. 8 Block diagram of the DCR with I/Q and CFO compensation configuration

In where $h(t)$, $s(t)$ and f_c in order are: baseband equivalent channel, baseband transmitted signal, and carrier frequency. According to the [18], [19] and [20] the down converted signal at the receiver side can be presented as:

$$r(t) = \{e^{j2\pi\Delta f t}.[s(t)\otimes h(t)]\otimes c_1(t) + \{e^{-j2\pi\Delta f t}.[s^*(t)\otimes h^*(t)]\}\otimes c_2(t) + w(t)\} \qquad (24)$$

In Eq. (24), you can see the presence of the frequency offset (Δf) in the down converted signal at the receiver side, which is surely needed to be estimated and compensated.

12. Model for CFO with proposed algorithm

Figure 9 illustrates the block diagram of the OFDM wireless transceiver system. Let's consider the figure 9 with N subcarriers with the sampling rate $1/T_s$.

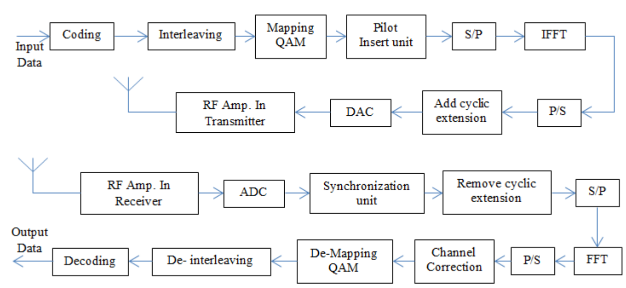

Fig. 9 Schematic diagram of an OFDM transceiver system

Therefore we have:

$$X(n) = W_P S(n) \qquad (25)$$

$$y(n) = [y_0(n)y_1(n)y_2(n) \ldots y_{N-1}(n)]^T \qquad (26)$$

$$y(n) = W_P H s(n) \qquad (27)$$

In where

$$H = \begin{bmatrix} H(1) & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & H(P) \end{bmatrix} \quad (28)$$

After DFT unit we have:

$$W_P^H y(n) = H\left[s_1(n) \ldots s_p(n)\right]^T \quad (29)$$

$$y(n) = EW_P Hs(n)e^{j\varepsilon((N+L)(n-1))} \quad (30)$$

$$E = diag\left(1, e^{j\emptyset}, \ldots, e^{j(n-1)\varepsilon}\right) \quad (31)$$

Here E is carrier offset matrix, W_p is a $N \times P$ matrix, $s(n)$ is data, H is channel response and L is length of cyclic prefix.

$$W_P^H y(n) = W_P^H EW_P Hs(n)e^{j\varepsilon(N+L)(n-1)} \quad (32)$$

Here the CFO (ε) is needed to be estimated. The CFO can be estimated by using the cost function as follows. This method uses the structure of the subcarrier, and has two steps, in step one we take the outputs of the receiver $\{y(n)\}$ and we build a polynomial cost function and step two includes the estimating of the CFO as the phase of the root in unit circle.

Let's consider A=E;

$$E = A = \begin{bmatrix} 1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & A^{N-1} \end{bmatrix} \quad (33)$$

Then the cost function can be stated as follows:

$$P(a) = \sum_{i=1}^{K} \sum_{n=1}^{N_p} \| W_{P+i}^H A^{-1} y(n) \|^2 \quad (34)$$

However when ε=0, in Eq. (34) we do not have any CFO. Figure 10 shows a simple block diagram of an OFDM system that has all the required units for compensating the unwanted effects on the received signal.

Conclusion

The objective of this paper was to investigate the effects of the Carrier frequency offset and frequency synchronization on OFDM systems. In this paper we have studied the source of the creation of the CFO and then we analyzed the effect of CFO and frequency synchronization on OFDM wireless systems and then we proposed an algorithm for estimating the CFO. In real-world the frequency offset cannot perfectly be estimated for the OFDM wireless systems, therefore it always impacts the performance of the OFDM systems. Nonetheless we have an acceptable range of the carrier frequency offset (CFO) which in that range, we can reach to our desired performance for our OFDM wireless system.

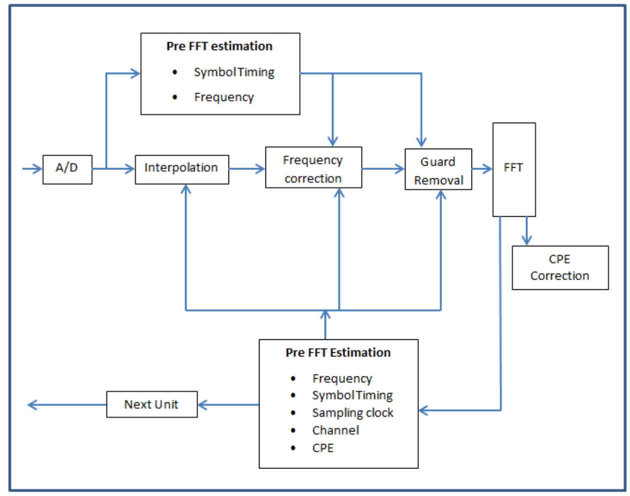

Fig. 10 a simple block diagram of an OFDM receiver

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