A Review on Carrier Frequency Offset (CFO) in OFDM System

Rashi Sharma[1], Neeraj Shrivastava[2]
[1,2] Department of Electronics and Communication
Rustamji Institute of Technology, BSF Tekanpur, Gwalior

Abstract* - With the increase of communications technology, the demands for higher data rate increased quickly. OFDM is a candidate for achieving high data rates in mobile environment because of its multicarrier modulation technique, where a single data stream is transmitted over a number of lower rate subcarriers. The OFDM is one of the techniques for Parallel transmission. In this Paper, we address basic OFDM. The main attractive property of OFDM is that it's inherently resilient to multipath reflections because of its long symbol time. However, this comes at the cost of a relatively high sensitivity to CFO. One of the major drawbacks for OFDM system is Carrier frequency offset (CFO). The OFDM systems are sensitive to the frequency synchronization errors in the form of CFO, because it can cause the ICI which can lead to the frequency mismatched in transmitter and receiver oscillator. In this Paper, a survey on CFO in OFDM system will study. The CFO causes loss of orthogonality between sub-carriers and the signals transmitted on each carrier are not independent of each other. This paper presents, CFO and the influence of Carrier frequency offset in OFDM systems.

***Keywords* - Orthogonal frequency division multiplexing (OFDM), Carrier frequency offset (CFO) and Intercarrier interference (ICI).**

1. INTRODUCTION

Recently, Orthogonal Frequency-Division Multiplexing (OFDM) has received considerable attention. In OFDM systems, the term orthogonal dictates an exact mathematical relationship between the frequencies of the subcarriers. OFDM stands as the prime technology for 4G. It has been adopted or proposed for a number of applications, such as satellite and terrestrial digital audio broadcasting (DAB),digital terrestrial TV broadcasting (DVB), broadband indoor wireless systems, asymmetric digital subscriber line (ADSL) for high bit-rate digital subscriber services on twisted-pair channels, and fixed broad-band wireless access [1]. Important features of OFDM systems include immunity to multipath fading and impulsive noise. Orthogonal frequency division multiplexing (OFDM) is the method of choice for combating frequency selective multipath fading channels, and achieving high spectral efficiency in wireless communication systems. With the aid of sufficient cyclic prefix, inter-symbol interference (ISI) due to multipath fading is completely avoided without the need for complicated equalizers. Since OFDM systems divide the available wide-band amongst a set of orthogonal overlapping sub-carriers, it is supremely susceptible to time and frequency synchronization errors which results in destroying the orthogonality amongst sub-carriers [2], bringing about inter-carrier interference (ICI) which can deteriorate the performance of OFDM systems. The basic principle of OFDM is gaining a wide spread popularity within the wireless transmission community.

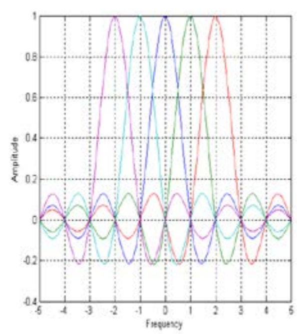

Fig. 1. Multi Carriers of OFDM signal

OFDM requires a high degree of synchronization to maintain sub-carrier orthogonality. OFDM has been adopted by existing and future wireless local area network (WLAN) standards such as IEEE 802.11ac and IEEE 802.11ad [3]. OFDM is a multi-carrier modulation technique. We can see from figure 1. Due to its multicarrier feature, OFDM systems are more sensitive than single-carrier systems to frequency synchronization errors [4]. Orthogonal frequency division multiplexing (OFDM) performance suffers from a pronounced sensitivity against carrier frequency offsets (CFOs) Indeed, the carrier frequency offset (CFO), which models the frequency mismatch between the transmitter and receiver oscillators, gives rise to intercarrier interference (ICI), thereby destroying the orthogonality of the OFDM data. OFDM can easily remove inter-symbol interference (ISI) and can be implemented using the computationally efficient fast Fourier transform (FFT) [5]. Orthogonal Frequency Division Multiplexing (OFDM) is a bandwidth efficient signaling scheme where the orthogonality among the subcarriers should be maintained to a high degree of precision. Since the spectra of the sub-carriers are overlapping, an accurate frequency synchronization technique is needed.

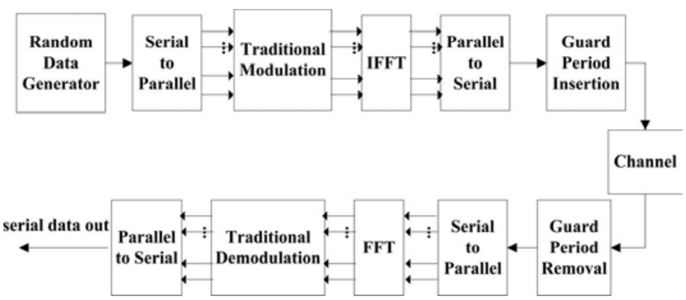

Fig. 2. Block diagram of OFDM System model

The diagram of basic OFDM system is shown in figure 2. In the transmitter, random binary input data sequence is generated. The modulated data is then divided into low data rate streams using serial to parallel conversion. Each parallel stream is then modulated on a separate subcarrier in the allocated spectrum using IFFT. The symbol is modulated onto sub carriers by applying the Inverse Fast Fourier Transform (IFFT). Then cyclic extension is added to make the system robust to multipath propagation. The parallel data is then further converted to serial form using serial to parallel conversion. This serial data is then transmitted over multipath fading channel. The channel can be additive white Gaussian noise (AWGN). The multipath fading channels used for this work are Rayleigh, Rician and Nakagami-m. The receiver performs the reverse operations of the transmitter. After removing the cyclic extension, the signal can be applied to a Fast Fourier Transform (FFT) to recover the modulated values of all subcarriers. The modulated values are then demapped into binary values, and finally de inter-leaving and decoding is performed to get back information bits [5]. CFO can lead to the Inter Carrier Interference (ICI), therefore CFO plays a key role in Frequency synchronization. Basically for getting a good performance of OFDM, the CFO should be estimated and compensated [6]. Lack of the synchronization of the local oscillator signal (L.OSC), for down conversion in receiver with carrier signal contained in received signal causes Carrier Frequency Offset (CFO) and it can cause to degrade the performance of OFDM, which can create the following factors:

- Frequency mismatched in the transmitter and the receiver oscillator.
- Inter Carrier Interference (ICI), and
- Doppler Effect (DE).

Frequency offset occurs due to many sources, such as Doppler shift or frequency mismatch between transmitter and receiver oscillators [7]. The first source of error arises when there is relative motion between transmitter and receiver. In the center of OFDM spectrum the quantity of ICI, in compare with their amount at band edges, is almost double. This increase comes from interfering of subcarriers from both sides on middle ones. If there is differences in transmitter and receiver frequencies oscillator, and also due to Doppler shifts and phase noise, there introduces frequency offset. We can see from figure 3. We recognize frequency offset guide to demur of signal amplitude since the *sinc* functions are shifted and no longer sampled at peak and also orthogonality is lost between subcarrier. Due to this phenomenon there introduces ICI which results in a degradation of whole system performance.

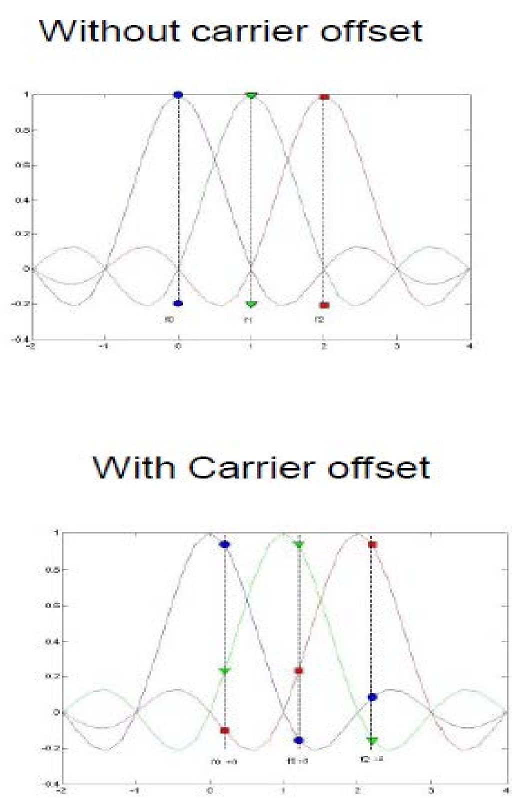

Fig. 3 (b). With Carrier offset

LITERATURE REVIEW

1. In 2001 “Ufuk Tureli” et. al. [1] proposed the performance of a blind CFO estimation algorithm for OFDM communications. Insights obtained from these experiments provided motivation to explore fundamental relationships between estimator performance and multiple system parameters. They proposed sensitivity of new blind CFO estimator against key system parameters in practical implementation.

2. In 2001 “Helmut Bölcskei” [2] proposed a novel algorithm for the blind estimation of symbol timing and CFO in wireless OFDM systems. The method can be applied to pulse shaping OFDM systems with arbitrary time-frequency guard regions, OFDM based on offset QAM. They proposed the use of different subcarrier transmit powers and periodic transmitter precoding to achieve a carrier frequency acquisition range of entire bandwidth of OFDM signal, and a symbol timing acquisition range of arbitrary length.

3. In 2005 “Linling Kuang” et. al. [3] proposed an Acquisition and tracking are two crucial stages necessary to CFO in OFDM systems. In this, by employing rotation property of OFDM data subcarriers, simple time-frequency decision-feedback loop without use of pilot subcarriers is proposed for fine CFO tracking with very low complexity comparable to that of the pilot-subcarrier-aided schemes.
4. In 2005 “Yong Sun” et. al. [4] proposed the design of expectation-maximization multiple-output (MIMO) orthogonal frequency-division multiplexing (OFDM) systems with the presence of carrier-frequency offset (CFO). They proposed a pilot-aided CFO estimation scheme that allows FFT-based fast implementation. Then this CFO estimation is incorporated into the initialization step of iterative receiver.

5. In 2005 “Luca Rugini and Paolo Banelli” [5] proposed an analytical approach to evaluate error probability of OFDM systems subject to CFO in frequency-selective channels, characterized by Rayleigh or Rician fading. By properly exploiting the Gaussian approximation of ICI, they show that BER for an uncoded OFDM system with QAM can be expressed by sum of few integrals, whose number depends on the constellation size. The main weakness is that they consider CFO effects only in AWGN channels.

6. In 2006 “Jungwon Lee” et. al. [6] proposed the effect of the Carrier frequency offset (CFO) on OFDM systems for multipath fading channels. A simple approximate expression for the average SNR is derived. This approximate expression is shown to be an upper bound of the average SNR for flat fading channels and an exact expression for the AWGN channel.

7. In 2007 “Amine Laourine” et. al. [7] proposed a new data-aided CFO estimation scheme for OFDM communications suitable for frequency-selective channels. The proposed method is based on transmission of specially designed synchronization symbol that generates particular signal structure between received observation samples at receiver. The proposed solution offers wide acquisition range with reduced computational load.

8. In 2009 “P. C. Weeraddana” et. al. [8] proposed exact closed form BER or SER expressions for OFDM systems with CFO. Most of published work treats CFO as non-random parameter. But they consider it as a random parameter. The BER performance of BPSK OFDM systems with random CFO is analyzed in cases of AWGN, frequency-flat and frequency-selective Rayleigh fading channels. They proposed new approach in contrast to Gaussian ICI approximation based approaches of existing work.

9. In 2009 “Hung Nguyen-Le” et. al. [9] proposed a pilot-aided joint channel estimation and synchronization scheme for burst-mode OFDM systems. Based on the received signal samples containing pilot tones in the frequency domain, cost function that includes the CFO, SFO and CIR coefficients is formulated and used to develop an accompanying recursive least-squares (RLS) estimation and tracking algorithm. The proposed scheme eliminates need for an IFFT block while reducing number of parameters to be estimated.

10. In 2009 “Hung-Tao Hsieh and Wen-Rong Wu” [10] proposed the STO and CFO estimation are the two main synchronization operations in a packet-based OFDM systems. Recently, researchers have proposed a ML CFO Estimation method. They proposed a new ML method to solve the likelihood function directly and

thereby perform CFO estimation problem. The method generates a closed-form ML solution, and the root finding procedure is not required.

11. In 2010 "A. Al-Dweik" et. al. [11] proposed a low-complexity technique for blind estimation of CFO in the wireless OFDM systems with constant-modulus constellations over frequency-selective Rayleigh fading channels. The proposed technique is totally blind and requires no prior knowledge of channel-state information or the SNR. The proposed estimator, which is denoted as the power difference estimator (PDE), is based on the assumption that channel slowly changes over two consecutive OFDM symbols.
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12. In 2010 "Khairi Ashour Hamdi" [12] proposed a new mathematical analysis for the evaluation of the average signal-to-interference plus noise ratio (SINR) of orthogonal frequency division multiplexing (OFDM) in the presence of carrier frequency offset (CFO). In this paper, they present an indirect method that leads to a new exact simpler expression for the average SINR over Rayleigh multipath fading channels.

13. In 2010 "Hung Nguyen-Le and Tho Le-Ngoc" [13] proposed the deployment of various basis expansion models (BEMs) for pilot-aided joint Carrier frequency offset (CFO) and doubly-selective channel estimation with the Fisher and Bayesian approaches in the SISO-OFDM transmissions. In a particular, the recursive-least-squares (RLS) and maximum likelihood (ML) techniques are used to facilitate the Fisher estimation implementations.

14. In 2011 "Liang Liu" et. al. [14] proposed the system performance of SC-CDMA with FDE is evaluated in terms of the average bit error rate (BER) and SINR obtained through an analytical approach for the downlink transmission over frequency-selective fading channel. The results show that the CFO gives rise to three effects: a net phase rotation, fading-like signal power reduction, and the intercode interferences due to loss of code orthogonality. The number of virtual subcarriers and constellation size is also investigated.

15. In 2014 "Omar Hazim Salim" et. al. [15] proposed Oscillator phase noise (PHN) and CFO can adversely impact performance of OFDM systems, since they can result in the ICI and rotation of signal constellation. They proposed an expectation conditional maximization based algorithm for the joint estimation of the channel, PHN, and CFO in the OFDM systems. They present a signal model for the estimation problem and derive hybrid Cramér-Rao lower bound (HCRB) for joint estimation problem. Next, they proposed an iterative receiver based on an extended Kalman filter.

2. CARRIER FREQUENCY OFFSET

When CFO happens, it causes the receiver signal to be shifted in frequency (δf). As we know the subcarriers (SCs) will sample at their peak, and this can only occur when there is no frequency offset, however if there is any frequency offset, the sampling will be done at the offset point, which is not the peak point. This causes to reduce the amplitude of the anticipated subcarriers, which can result to raise the Inter Carrier Interference (ICI) from the adjacent subcarriers (SCs).

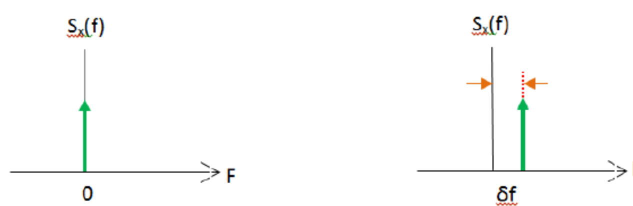

Fig. 4. Frequency offset (δf)

In the presence of CFO, the sampling points in the frequency domain are shifted from the optimal points, therefore, the energy of other symbols spills into the sample of the desired symbol. This interference is known as inter-carrier interference (ICI) [8]. The Carrier frequency offset divided by the subcarrier spacing. When there is the different integer number of cycles in each FFT interval the orthogonality between the subcarrier will be kept, otherwise the subcarriers will not be orthogonal [8]. Therefore we can conclude that the frequency offset will happen when the number of cycle in FFT interval will not be an integer. CFO can put an extra phase factor in each subcarrier.

$$e^{j2\pi\Delta Ft}$$

Two factors can introduce the frequency offset; the first one is the lack of the matching carrier frequency between the receiver oscillator and transmitter oscillator and the second one is due to the Doppler shift. The Doppler shift can be created when there is a relative motion between the transmitter and receiver or both of them. The Doppler Effect is given as follows:

$$f_d = \frac{v.f_c}{c}$$

fd, c and v are respectively Doppler frequency, the speed of light, and the velocity of the moving receiver (i.e. 100 km/h). The normalized CFO (ε) is:

$$\varepsilon = \frac{f_{offset}}{\Delta f}$$

ΔF is the subcarrier spacing; the ε has two portions, one integer (ε_i) and one fractional (ε_f) so:

$$\varepsilon = \varepsilon_i + \varepsilon_f$$

The instability of the oscillators is the one that can cause the mismatch between the transmitter and the receiver oscillator. The factors that can cause this instability are: temperature, humidity, the interference of the other magnetic field (which these factors are categorized as the working environment), the tolerance of the electronic elements and aging. Aging is the frequency change with time while the other factors i.e. working environment, power supply and etc. will be kept constant. By the way, two important factors for oscillator performance are stability and accuracy. Stability shows how well an oscillator can produce the same frequency in a specified interval of time, but the accuracy indicates the offset from the ideal value. Although the frequency errors introduce by the frequency mismatch between the local oscillator in the transmitter and the receiver, nonetheless this frequency mismatch due to the electronics elements tolerances are avoidable. So at all the time there is a difference between the carrier frequencies which has been produced in the receiver side, with the one that has been generated in the transmitted side. This frequency offset is defined as follows:

$$f_{offset} = f_c - f_c'$$

f_C and f_c' are respectively carrier frequency in transmitter and carrier frequency in receiver. With the presence of frequency offset, the sampling cannot be exactly done at center frequencies of subcarriers therefore amplitude of desired subcarriers will be decreased.

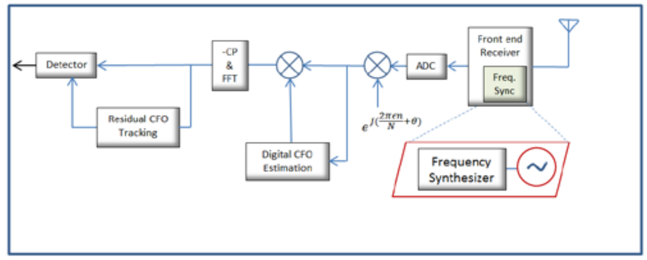

Fig. 5. The block diagram of a typical OFDM receiver with Frequency Synchronization.

The sensitivity of OFDM systems to frequency offset compared with single carrier systems is a major disadvantage [9]. In general, Frequency offset is defined as the difference between the nominal frequency and actual output frequency. In OFDM, the uncertainty in carrier frequency, which is due to a difference in the frequencies of the local oscillators in the transmitter and receiver, gives rise to a shift in the frequency domain. This shift is also referred to as frequency offset. It can also be caused due to the Doppler shift in the channel [9]. The demodulation of a signal with an offset in the carrier frequency can cause large bit error rate and may degrade the performance of a symbol synchronizer. It is therefore important to estimate the frequency offset and minimize/eliminate its impact. In a typical wireless communication system, the signal to be transmitted is unconverted to a carrier frequency prior to transmission. The receiver is expected to tune to the same carrier frequency for down-converting the signal to baseband, prior to demodulation. However, due to device impairments the carrier frequency of the receiver need not be same as the carrier frequency of the transmitter. When this happens, the received baseband signal, instead of being centered at DC (0MHz), will be centered at a frequency $f\delta$, where $f\delta = f_{Tx} - f_{Rx}$

The baseband representation is (ignoring noise),

$y(t) = s(t)e^{\frac{j2\pi f_\delta t}{T}}$, where y(t) is the received signal

s (t) is the transmitted signal and $f\delta$ is the frequency offset. The effect is caused by the CFO reduce the signal amplitude and makes interference between the carriers. The absolute value of CFO is f∈ is either an integer multiple or a fraction of Δf. Now if the f∈ is normalized to the sub carrier spacing Δ_f then normalized CFO of the channel is expressed as,

$$\varepsilon = \frac{f_{\varepsilon}}{\Delta f} = \delta + \in$$

Where δ is an integer and |ϵ|=<0.5, If the CFO occurs then the symbol transmitted on a certain sub carrier k, will shift to another sub carrier $k_s = k + \delta$. The received signal contains samples from this shifted subcarrier, leading to Inter Carrier Interference (ICI).

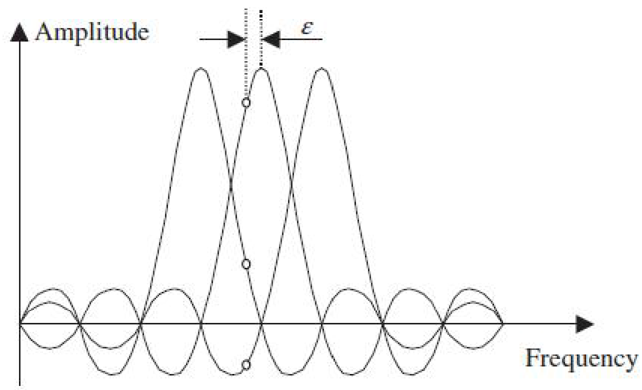

Fig. 6. Inter-carrier interference (ICI) subject to CFO

The OFDM systems are very sensitive to the carrier frequency offset (CFO) and timing [10], therefore, before demodulating the OFDM signals at the receiver side, the receiver must be synchronized to the time frame and carrier frequency which has been transmitted. In order to help the synchronization, the signals that are transmitted, have the references parameters that are used in receiver for synchronization. However, in order the receiver to be synchronized with the transmitter, it needs to know two important factors:

(i) Prior to the FFT process, where it should start sampling the incoming OFDM symbol from.

(ii) How to correct any carrier frequency offset (CFO).

After estimating and correcting the symbol boundaries in the receiver and when the presence of the symbol is detected the next step is to estimate the frequency offset.

3 BASIC CFO MODEL AND TECHNIQUES

In the center of the OFDM spectrum the quantity of the Inter-Carrier Interference (ICI), in compare with their amount at the band edges, is almost double. This increase comes from the interfering of the subcarriers from both sides on the middle ones. However the degradation of the SNR which is introduced by the frequency offset can be given by:

$$D_{freq} \cong \frac{10}{3 ln 10} (\pi \Delta f T)^2 \frac{E_s}{N_o}$$

Where D_{freq}, T, E_b, N_o are in order; frequency offset, symbol duration, energy per bit (for OFDM signal) and one sided noise Power Spectrum Density (PSD).

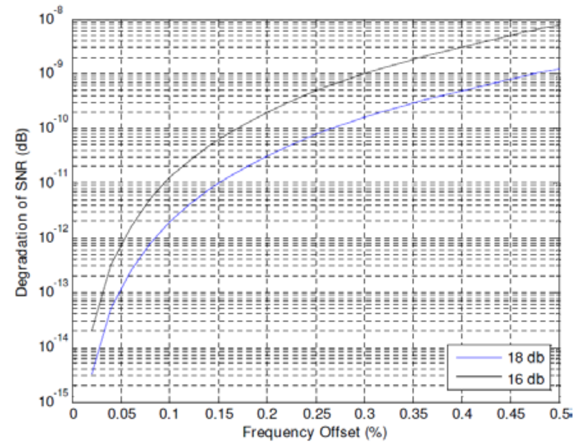

Fig. 7. SNR degradation as a function of the frequency offset

If frequency offset is denoted as Δfc, the OFDM signal generated by the transmitter denoted as s(t) and y(t) is the signal received by the receiver, then

$$s(t) = e^{j\omega t} x(t)$$

$$y(t) = e^{j(\omega - \hat{\omega})t} x(t)$$

$$\Delta\omega = \omega - \hat{\omega} = 2\pi\Delta fc$$

The frequency response of each sub-channel should be zero at all other sub-carrier frequencies [11], i.e., the sub-channels shouldn't interfere with each other. The effect of frequency offset is a translation of these frequency responses resulting in loss of orthogonality between the sub-carriers. CFO can produce Inter Carrier Interference (ICI) which can be much worse than the effect of noise on OFDM systems [12]. That's why various CFO estimation and compensation algorithms have been proposed. For showing the importance of it, it is enough to mention that, by now the researchers have proposed numerous and various CFO estimation and compensation techniques and algorithms, which these methods can generally be categorized into two major branches:

A. Training based algorithm

B. Blind algorithm and Semi-blind algorithm

A. Training based algorithm

The training sequence can be designed the way that can limit the number of computation at the receiver side; therefore in general, these algorithms have a low computational complexity. On the other hand, the negative point of training based algorithm is the training sequences that must be transmitted from transmitter during its transmission [13]. This can cause the reduction of the effectiveness of the data throughput. In this algorithm two repetitive OFDM symbol will be sent. This algorithm works on the base of knowing the start point of the OFDM symbol. This estimation for the small values of CFO is conditionally unbiased.

B. Blind and Semi-blind algorithms

Another algorithm that has been used is called Blind CFO estimation algorithm. In these algorithms by using statistical properties of received signal, CFO will be estimated [14].

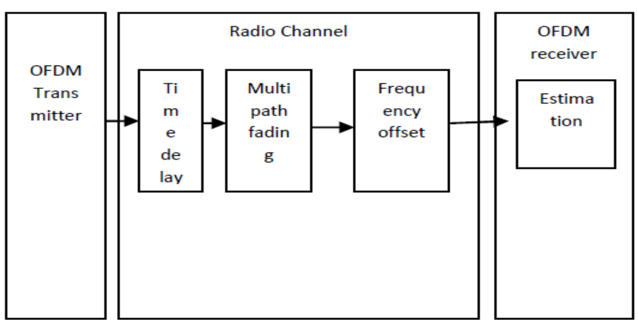

Fig. 8. Blind System Model

Since receiver doesn’t have any knowledge of signal that transmitter has been sending, therefore blind algorithms are considered to have a high computational complexity. Blind estimation is such technique which did not required any training symbol of pilot sub-carriers and performed well in frequency selective channels. This technique has low complexity due to use of minimum number of operations of multiplication and division. The blind detection blind channel estimation based on the cyclic prefix is that this channel estimation concept is standard-compliant and can be applied to all commonly used OFDM systems that use a cyclic prefix. The blind detection without the necessity of pilot symbols for coherent detection is possible when joint equalization and detection is applied [15]. This is possible by trellis decoding of differentially encoded PSK signals where the trellis decoding can efficiently be achieved by applying the Viterbi algorithm. The main design goal of a blind estimation are fast convergence to an operating point where the detection of information symbols is reliable as well as low computational complexity.

4. CONCLUSION

In this paper one major drawback of Orthogonal Frequency Division Multiplexing (OFDM) is considered that is the sensitivity of frequency synchronizations. The effect of Carrier Frequency Offset (CFO) on OFDM is discussed. In this paper, we have described OFDM and basic CFO causes. We start with the basic principle of OFDM and the importance of the study of carrier frequency offset in OFDM systems has been covered. The performance of the OFDM systems is susceptible to degradation when failing to attain perfect time and frequency synchronization. At the end an information framework for carrier frequency offset (CFO) is presented. And a CFO technique using training symbols and blind estimations offered. It’s one of the most common impairments found in a communication system. In OFDM communications, CFO must be estimated and compensated at the receiver to maintain orthogonality. In this paper, the reason of creating CFO and the effects of the CFO on the performance of the OFDM system has been reviewed.

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