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A Comprehensive Review: Techniques of CFO Estimation and Mitigation in OFDM

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Abstract

Increasing demand in high data rate applications find key interest in a multicarrier transmission technique termed orthogonal frequency division multiplexing (OFDM). The progress in the generation of wireless communication reaches the 4th generation which imparts the benefits of OFDM. The enhancement in the utility of the bandwidth in an efficient way is made successful by means of OFDM. Besides, being a promising candidate for multipath delay spread, this kind of multiplexing are sensitive to carrier frequency offsets (CFO). A historical perspective of CFO is presented and the effects of frequency synchronization errors are reviewed. A comprehensive review on the range of solutions proposed for estimation and compensation of CFO are discussed. In addition, the future research directions are forecasted.

Keywords: Carrier frequency offsets; CFO estimation; CFO compensation; Inter carrier interference; Orthogonal frequency division multiplexing

INTRODUCTION

Rapid adoption of smartphones and other emerging mobile data services leads to an increasing data rate. OFDM is a transmission method that achieves a high data rate of 100 Mbps. OFDM is a good aspirant for high data rate communication (4th generation (4G) and next generation wireless communication). In addition, OFDM exhibits better spectral efficiency than conventional techniques. It is a multicarrier transmission (MC), where the entire bandwidth is divided into number of orthogonal sub-carriers (Singh & Sahu, 2015). In communications, orthogonal defines the uncorrelation of two signals over a symbol interval. The preserved orthogonality of the subcarriers results in null interference. However, the OFDM system is sensitive to frequency errors caused by frequency mismatch between the local oscillators in transmitter and receiver (Paul 1994; Jean, 1999; Sesia et al., 2011). This frequency mismatch is labelled as CFO that disturbs the orthogonality of the carriers. The CFO also induces inter carrier interference (ICI) and degrades the OFDM system performance (Ufuk et al., 2000). To achieve a better performance of OFDM system with reduced ICI, the CFOs should be estimated and compensated in efficient manner.

Several estimation and compensation algorithms are developed to improve the efficiency of OFDM system. Based on the need of pilots, the CFO estimation algorithms are grouped into training based and blind algorithms. A survey is carried out on those estimation and compensation algorithms. The paper provides the definition and effects of CFO in section 2. The various estimation algorithms used for estimating CFOs are summarized in section 3. Section 4 discusses the compensation algorithms for mitigating the ICI caused by CFO and section 5 concludes.

CARRIER FREQUENCY OFFSETS IN OFDM SYSTEM

OFDM has magnified to be the most popular communication system for the high data rate environment. Generally the orthogonality of the subcarriers relies on the condition that transmitter and receiver operate with exactly the same frequency (Jean, 1999; Taewon, et al., 2009). When the sub-carriers are orthogonal to each other, the spectrum of each carrier has a null at centre frequency. This results no interference between the carriers. When there is a frequency mismatch between the oscillators of transmitter and receiver, CFO occurs which causes ICI. The CFO also leads to loss of orthogonality between the carriers and reduces the amplitude of useful signal.

Causes of frequency offsets

When the receiver signal is shifted in the frequency domain, CFO occurs (Thomas & Hanzo, 2000). The frequency offsets can be caused by Doppler shift due to relative motion between the transmitter and receiver or by difference between the frequencies of local oscillators at transmitter and receiver (shafiee, 2003; Patrick, 1999). The Doppler effect is given as,

$$f_d = \frac{v.f_c}{c} \tag{1}$$

where v, f_d and c are the velocity of the moving receiver, Doppler frequency and the speed of light respectively (Saeed and Matin, 2012). If the frequency error is an integer multiple I of the subcarrier spacing Δf, then the received frequency domain signals are shifted by $I*\Delta f$. Beside affecting the orthogonality between the subcarriers, the frequency errors also causes ICI (Thierry, 1995). The CFO also induces the loss of subcarriers orthogonality. Figure 1 shows the loss of orthogonality between the carriers due to frequency offset. The ICI is caused when the frequency reference of the receiver is offset with respect to that of the transmitter by a frequency error.

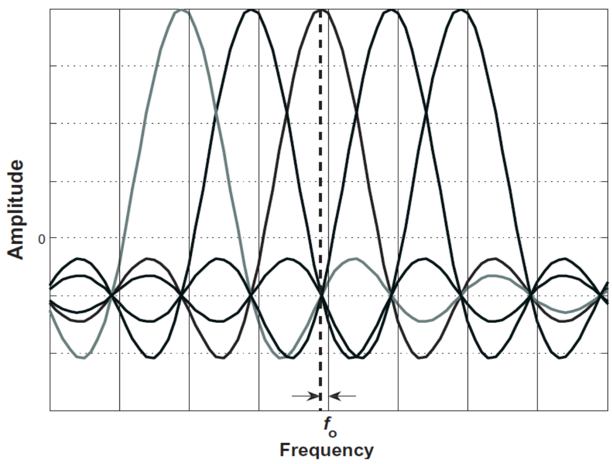


Figure 1: Carrier frequency offset [3]

Let us consider f_c as carrier frequency of transmitter and f_c' to that of receiver, then the frequency offset is given as,

$$f_{offset} = f_c - f_c' \tag{2}$$

The normalized CFO (ε) is defined as,

$$\varepsilon = \frac{f_{offset}}{\Delta f} \tag{3}$$

where Δf is the sub carrier spacing and ε has two parts namely integer (ε_i) and fractional (ε_f). Fractional offset is the one that causes the ICI in OFDM system (Aziz et al., 2012). The CFO not only introduces ICI, it also reduces the useful signal amplitude at frequency domain. In order to obtain an OFDM system with good performance, it is necessary to estimate and compensate the CFO.

CFO ESTIMATION TECHNIQUES

ICI caused due to CFO degrades the performance of OFDM system and hence it is essential for estimation of CFO. Some of the CFO estimation algorithms are discussed in this section. Generally, the estimation algorithms are grouped into training symbol based algorithms and blind algorithms.

Training symbol based algorithms:

The training based algorithms make use of the pilot symbols for the estimation of CFO. Since the receiver has the knowledge of transmitted input, the computation complexity is low in these algorithms. The major problem with these algorithms is the spectral efficiency is less due to the pilot symbols.

Blind algorithms:

In contrast to the training based algorithms, blind algorithms will not use any pilot symbols. Since the pilots are not used, the blind algorithms improve the bandwidth efficiency (Zhang et al., 2010). As the receiver does not have any knowledge about the transmitted input, the computational complexity of blind algorithms is high.

The CFO was initially estimated by using maximum likelihood (ML) estimation. The author initially shows the effect of frequency offsets on signal to noise ratio (SNR) and a lower bound for SNR has been derived. Later, an algorithm for ML estimate of frequency offset is presented. It estimates and removes the offsets based on the repeated data symbol. This estimate is quite accurate and conditionally unbiased for small offsets (Paul 1994). The ML estimate of offset is given as

$$\hat{\varepsilon} = \frac{1}{2\pi}\tan^{-1}\left\{\frac{\left(\sum_{k=-K}^{K}\mathrm{Im}\left[Y_{2k}Y_{1k}^{*}\right]\right)}{\left(\sum_{k=-K}^{K}\mathrm{Re}\left[Y_{2k}Y_{1k}^{*}\right]\right)}\right\} \tag{4}$$

The frequency synchronization is done in frequency domain after taking FFT (Fast Fourier transform). A joint ML estimation of the time and carrier-frequency offset is presented and evaluated (Van de Beek, 1997). The redundant information contained in the cyclic prefix is used for the process of estimation and reduces the need of pilots. Morelli (1999) proposed a new estimator which is an extension of Schmidl and Cox algorithm (SCA) developed by Schmidl and Cox. This algorithm employs only one symbol with identical parts and the simulation results show that the estimation accuracy is slightly superior to SCA. The only disadvantage with the proposed algorithm is its computation complexity is high as compared to SCA. Similarly Yun Hee et al., (2001) uses only one training symbol for both frame/ symbol timing and frequency synchronization without any performance degradation. Also a new training symbol is not required for timing synchronization which is not the case in extended SCA algorithm.

Li and Zhang (2003) developed a new CFO estimation scheme that uses scattered pilots (SP) to estimate both integer and fractional CFO. It can increase the spectral efficiency of the system as compared to continual pilots (CP). Also the SP-based algorithm is predominant to CP-based algorithm in static channels for the estimation of fractional CFO. A novel technique for the estimation of frequency offset even with the large values of gain and phase imbalances in the receiver mixer is proposed by Shafiee, 2003. Based on the common phase shift among subcarriers, a blind estimation algorithm via over-sampling is described by Chen & Wang (2004). This algorithm requires only one training symbol and hence it is data efficient. A reliable estimation of CFO is achieved even in the absence of virtual carriers.

Zhu and Lee (2006) developed two estimation algorithms for estimating CFO in which each of them utilizes only one OFDM block with null subcarriers and pilots. The integer and fractional CFO can be estimated based on these two algorithms. An improved accuracy and reduced complexity are obtained by these algorithms. In contrast to Zhu and Lee method, the author suggested an estimation algorithm that deals with estimation of integer CFO without the aid of pilot symbols (Eu-Suk et al., 2007). It provides accurate estimation of CFO but there exists a trade off between the performance and estimation range, based on the cyclic prefix.

Zhang, Xiaofei, et al. proposed a novel blind trilinear decomposition based CFO estimation algorithm for multiple antennas (Zhang et al., 2010). The concept of trilinear alternating least square (TALS) for data detection is adopted for trilinear model. This method shows better performance than ESPRIT but the computational complexity is large. By deriving the system model with multi-invariance property, a multi-invariance MUSIC (multiple signal classification) algorithm for CFO estimation is proposed by Zhang et al., (2012). It accurately estimates both integer and fractional CFO and results in better performance than ESPRIT and trilinear decomposition algorithm. The disadvantage of this algorithm is its higher complexity due large search array.

A virtual carrier based algorithm is developed for estimating CFO where the rooting is performed directly for the cost function (Ufuk et al., 1997). It has large estimation range and low estimation accuracy. Weile & Yin (2013) performed a slight modification of Hui's method for improving the performance. In this, the first order derivative of the cost function is considered for rooting.

Table 1: List of various methods for estimation of CFO from literature

REFERENCE	CATEGORY	METHOD	PARAMETER ESTIMATED
Paul (1994), Van de Beek (1997)	Blind algorithms	Maximum likelihood estimation of time and carrier frequency offsets	Frequency and time offset
shafiee (2003)			CFO with IQ imbalance
Zhang et al., (2010)	Blind algorithm	blind trilinear decomposition algorihtm	CFO
Morelli (1999)	Training symbol based algorithm	Extended schmidl and cox algorithm	Frequency offset
Li and Zhang (2003)	Training symbol based algorithm	Li and Zhang algorithm	Integer and fractional CFO
Chen & Wang (2004)	Blind algorithm	Based on Over-sampling	CFO via over-sampling
Zhu and Lee (2006)	Training symbol based algorithm		CFO
Eu-Suk et al., (2007)	Blind algorithm		Integer CFO
Zhang et al., (2012)	Blind algorithm	MUSIC algorithm	Integer and fractional CFO
Ufuk et al., (1997)	Blind algorithm	Virtual carrier based algorithm	CFO
Weile & Yin (2013)	Blind algorithm	Rooting algorithm	CFO
Wang & Lai (2014)	Semi blind algorithm	Subspace based algorithm	CFO in frequency domain
Yang & Wang (2014)		Polynomial rooting algorithm	CFO estimation in time dispersive OFDM
Weiyang et al., (2015)	Blind algorithm		CFO and IQ imbalance
Besseghier & Bouzidi(2015)	Semi blind algorithm		Channel and CFO
Lin & Phoong (2016)	Blind algorithm	Cyclic prefix based algorithm	CFO
Jayaprakash & Reddy (2017)	Blind algorithm	covariance power fitting criterion and phase information algorithm	CFO

This is also an ML estimator of CFO estimation. It is more accurate than MUSIC-like algorithm and other search free methods but remains computational intensive. Wang & Lai (2014) proposed a frequency domain approach of CFO estimation based on MUSIC algorithm. It is subspace-based algorithm that used eigen structure of the received signal for the estimation of CFO. As compared to ML algorithm, it has significantly larger CFO estimation range.

An efficient CFO estimation for time-dispersive OFDM system using polynomial rooting algorithms is proposed by Yang & Wang (2014). Initially the snapshot vectors are obtained based on the time shift invariance feature of the received signal. The author studies the root-MUSIC algorithm, which is applied to the equalized snapshot vectors for the estimation of CFO in time domain. Similar to MUSIC algorithm, the root-MUSIC algorithm also uses the eigen space of the covariance matrix derived from snapshot vectors.

It is more computationally efficient than its spectral searching counterpart. In order to mitigate the noise enhancement in the equalization process, prior to the root-MUSIC algorithm, the author develops a time sample selection scheme.

Weiyang et al., (2015) proposed a blind CFO estimation based on null subcarriers, which jointly estimates the CFO and I/Q imbalance in OFDM system. Initially the CFO is estimated based on which I/Q imbalance estimation is performed. The accuracy of the CFO estimator increases by minimising its cost function. A joint semi-blind estimation of channel and CFO is performed based on the new design of pilot pattern and virtual subcarriers are used in this algorithm (Besseghier & Bouzidi, 2015). Newton-Raphson algorithm with large step size is used for the estimation of CFO that has faster convergence and lower complexity. This algorithm is described as follows, where y is the receiver signal, $\hat{\omega}^n$ is the CFO estimate at n[th] iteration and D = diag(1, . . ., $N-1$).

$$\hat{\omega}^{m+1} = \hat{\omega}^m - \left[\frac{\partial^2 J(\omega)}{\partial^2 \omega}\right]^{-1} \frac{\partial J(\omega)}{\partial \omega}\bigg|_{\omega=\hat{\omega}^m} \quad (5)$$

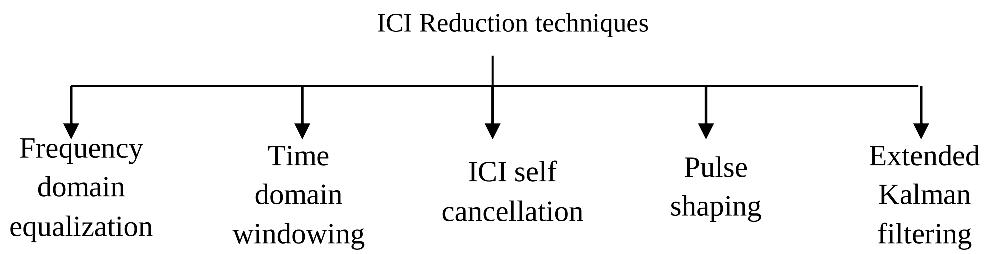
where $$\frac{\partial J(\omega)}{\partial \omega} = 2tr\left(\Re\left\{jy^H D D_\omega \psi D_\omega^H y\right\}\right)$$

$$\frac{\partial^2 J(\omega)}{\partial \omega^2} = 2tr\left(\Re\left\{y^H D\left(D_\omega \psi D_\omega^H D - D D_\omega \psi D_\omega^H\right) y\right\}\right)$$

Thus the parameters that are considered for developing an efficient CFO estimation algorithm are estimation range, estimation accuracy and computational complexity. Though several conventional approaches are available for CFO estimation, the issues of limited CFO estimation range or high computational complexity occurs. Therefore the development of an efficient CFO estimation algorithm with a large frequency acquisition region and low computational complexity is a critical issue to explore.

ICI REDUCTION TECHNIQUES:

The offsets between the frequency reference of the transmitter and receiver gives rise to ICI which in turn degrades the performance of OFDM system. To reduce these ICI, various researchers developed different techniques to mitigate the frequency offsets as follows:



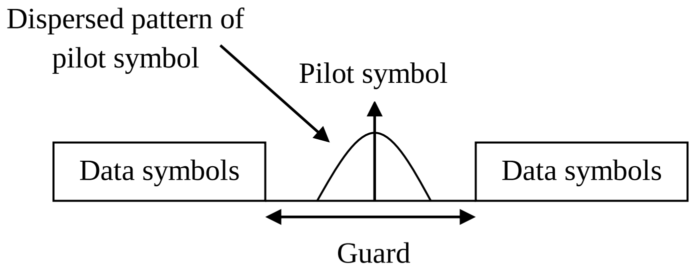


Figure 3: Dispersed pattern of pilot symbol

Frequency domain equalization

The effects of distortion are removed by frequency domain equalization techniques. In 1993, Ahn and Lee applied this technique to OFDM over a frequency non-selective fading channel. Generally, the pattern of ICI varies from frame to frame and remains invariant over all the symbols in a demodulated frame. The ICI is estimated through the insertion of frequency domain pilot symbols in each frame and the equalizer coefficients are derived. By means of linear or decision-feedback equalizers, compensation for fading distortions is achieved (Ahn & Lee, 1993). Fig. 3 shows the dispersed pattern of pilot symbol within the data symbols.

However, it reduces only ICI due to fading distortion but the major source of ICI is frequency offset and Doppler shift. Also it is suitable only for flat fading channel but in mobile communication the channels are frequency selective fading. These are the two facts that limit the usage of this technique for ICI reduction.

Time domain windowing

Time domain windowing technique is used to reduce the sensitiveness to distortions and frequency offsets. In OFDM system, the frequency response of the DFT filter extends over the whole frequency range and represents high side lobes. Due to this the OFDM signal is highly sensitive to frequency distortions and phase noise. Hence, a time limited window called Nyquist window is applied in front of DFT (Muschallik , 1996). This reduces the side lobes and maintains the orthogonality of the carriers. Initially the author uses the square windowing of $2T_u$, where T_u is the guard interval. Under normal conditions, this window is unrealizable due to its long guard interval. Then an adaptive Nyquist window with raised cosine function is developed which uses the guard interval of T_u. This windowing is adaptive and intersymbol interference (ISI) free for reduction of ICI. The improvisation of C/N (carrier to noise) ratio upto 1.3 dB in Guassian channel due to the reduction of side lobes is presented. Later Muller & Stefan (2001), proposed an optimum Nyquist window, which shows a superior behaviour with nonzero normalized frequency offsets (NFO). This window exhibits significantly reduced side lobes.

Song & Leung (2005) proposed a second order polynomial Nyquist window function to enhance the signal to interference (SIR) ratio. This is referred to as second order continuity window (SOCW) and unity roll of factor is considered. It results in better performance than raised cosine window and acts as anti frequency offset for the system with small frequency offsets. Based on the bit error rate (BER) and SIR measure, the effects of various Nyquist windows like raised cosine window, BTRC, SOCW, Frank's window and double jump window are examined by Tan (2005); Beaulieu & Tan (2007).The author initially presents the ICI analysis for receiver windowing OFDM system in a Rayleigh slowly fading channel with the presence of CFO. The ICI power values for the Nyquist windows are tabulated in Table 1.

Table 2: ICI power values of different windows

WINDOWS	ICI POWER VALUE (NFO=0.1) (dB)
Raised cosine	2.60
BTRC	1.42
SOCW	0.85
Frank's window	< above values

It is shown that BTRC, SOCW and Frank's window provides better performance than raised cosine window. At small and moderate CFO, Frank's window gives smaller ICI power value. However, at large CFO and roll of factors, BTRC outperforms the remaining three windows. In terms of BER, Frank and SOCW windows yields better performance when roll of factor approaches one.

ICI self cancellation

Zhao and Haggman (1996) describes a method called ICI self cancellation for reducing the ICI influences. The main idea is to modulate one data symbol onto a group of subcarriers and 10dB increase of CIR value is achieved. The analysis of this method with linear and cubic variations in weighting coefficients over a group of three adjacent coefficients is performed by Armstrong, 1999. As a result, the ICI signal generated within a group can be self cancelled with each other. The ICI self cancellation schemes with different ICI cancelling modulation and demodulation methods are developed to mitigate the ICI caused by CFO.

The above mentioned ICI self cancellation methods perform based on the mapping of the data symbol onto the subcarriers. Let us consider the data symbol before ICI cancelling modulation be a_k, and X_k (K=0…, N–1) be the data symbol after modulation. The Table 2 shows the mapping scheme of the different methods (Sathananthan, 2000; Zhao, 2001; Sathananthan, 2004; Ryu, 2005).

They are classified as follows,

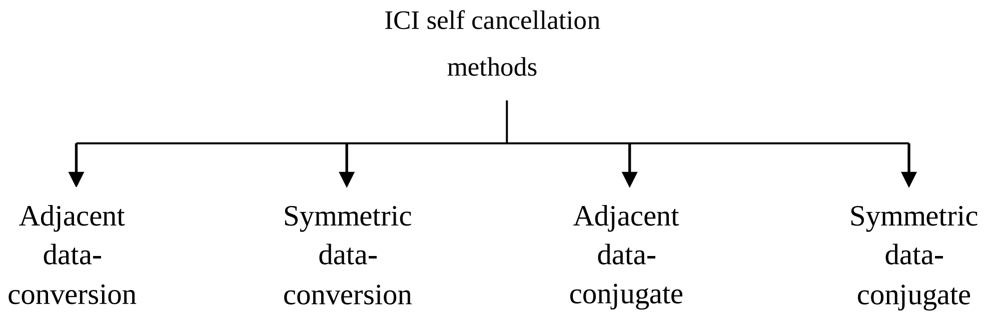


Table 3: Mapping scheme of different cancellation methods

ICI CANCELLATION METHODS	MAPPING SCHEME
Adjacent data conversion	$X_{2k} = a_k \quad X_{2k+1} = -a_k$
Symmetric data conversion	$X_k = a_k \quad X_{k+1} = -a_k$
Adjacent data conjugate	$X_{2k} = a_k \quad X_{2k+1} = -a_k^*$
Symmetric data conjugate	$X_k = a_k \quad X_{k+1} = -a_k^*$

Though the ICI self cancellation provides better ICI reduction, the major drawback of this technique is reduced spectral efficiency. The bandwidth efficiency problem of this scheme can be minimized by increasing the number of subcarriers or using larger signal alphabet size (Pen et al., (2007)). Also based on the design of symbol mapping, the ICI can be mitigated efficiently. Yang et al., (2007) proposed a vector based coding scheme at transmitter and corresponding subcarrier combiner at receiver respectively to mitigate the effects of ICI. Similarly Ma (2017) proposed a differential grouping weighted symmetry data-conjugate mapping scheme to suppress the effect of ICI in fast time-varying channel. This mapping scheme improves the bandwidth efficiency and shows better performance on carrier to interference ratio.

Pulse shaping

Due to CFO, the orthogonality is lost between the carriers and some power of side lobes exist at the centre of individual carriers which is called ICI power. As the CFO increases the ICI power also increases. The purpose of pulse shaping is to reduce the amplitude of side lobes and reduces the ICI power. Let f_c be the carrier frequency, D_k as complex data symbol, $p(t)$ as pulse shaping function and f_k as k^{th} subcarrier frequency.

Tan & Beaulieu (2004) given the expression of complex envelope of the transmitted OFDM symbol with pulse shaping as follows

$$x(t) = e^{j2\pi f_c t} \sum_{k=0}^{N-1} D_k \sqrt{p(t)} e^{j\pi f_k t} \quad (6)$$

where k=0,…,N–1. A number of pulse shaping functions are proposed in order to reduce the side lobes. An optimized “better than” raised cosine (BTRC) pulse is proposed (Assimonis et al., (2010)). It employs an additional free parameter (FP) whose optimal value is in quadratic relationship with the filter’s roll of factor. It is shown that higher values for roll of factor lead to stronger ICI suppression. For low and moderate NFOs, this pulse shows enhanced performance by means of ICI power reduction and SIR.

Mourad proposed a sinc power (SP) pulse shape for reduction of ICI in OFDM system. The highest amplitude in main lobe and lower amplitude in side lobes is found in SP pulse shape than BTRC. It is proved that the drop in average ICI power and increase in SIR for the OFDM system is achieved by SP pulse shaping (Mourad, 2007). Later a modification of SP pulse is performed and derived a new pulse shape as improved sinc power (ISP) pulse shape (Kumbasar & Oguz , 2007). ISP is defined by modifying SP with $\exp\{-a(fT)^2\}$ and it has lowest amplitude at all frequencies. This pulse results in better SIR and BER performance than other pulse shapes. The Fourier transform functions of significant pulse shapes are listed in table 3. A comparative study of different pulse shaping functions is performed (Mohanty & Susmita Das, 2008). The choice of parameters for the comparison is: i). α - (0≤α≤1), the roll of factor and β=πα/ln2, ii) a - the design parameter to adjust the amplitude and iii) n - the degree of the sinc function. The ICI power value of those pulse shapes are provided for α=1, n=2, a=1 and normalized frequency offset of 0.05.

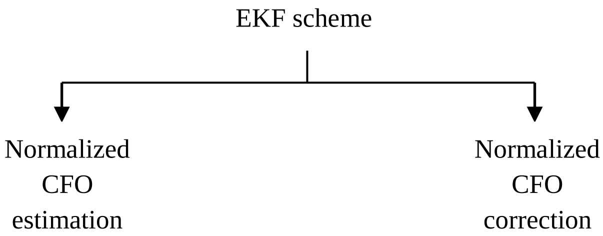
From the table, it is inferred that among the significant pulse shapes, the average ICI power value is minimum for ISP pulse shape. That is the side lobe is maximum for rectangular pulse and minimum for ISP pulse. Thus ISP reflects better performance in terms of ICI reduction than that of the other pulse shape. Also the major drawback of ICI self cancellation is overcome by pulse shaping i.e. no loss of spectral efficiency.

Table 4: Transform functions and ICI power values of different pulse shapes

PULSE SHAPES	FUNCTIONS	ICI POWER VALUE (DB)
Rectangular pulse (REC)	$P_{REC} = \text{sinc}(fT)$	-22
Raised cosine pulse (RC)	$P_{RC} = \text{sinc}(fT)\dfrac{\cos(\pi\alpha fT)}{1-(2\alpha fT)^2}$	-33
Better than raised cosine pulse (BTRC)	$P_{BTRC} = \text{sinc}(fT)\dfrac{[2\beta fT\sin(\pi\alpha fT)+2\cos(\pi\alpha fT)-1]}{1+(\beta fT)^2}$	-40
Sinc power pulse (SP)	$P_{SP} = \text{sinc}^n(fT)$	-49
Improved sinc power pulse (ISP)	$P_{ISP} = \exp\{-a(fT)^2\}\sin c^n(fT)$	-58

Extended Kalman filtering

The Kalman filtering is a powerful recursive estimation algorithm that has found various applications in communications. Senevirathna et al., (2008) performed the CFO estimation of OFDM communication system using Extended Kalman filtering (EKF). The Kalman filter that linearizes about the current mean and covariance is called ad EKF. Later, a planar extended Kalman filtering (PEKF) is proposed to reduce the ICI effects (shi, 2010). In this, the received signal is divided into real and imaginary part. Based on the relationship between the real and imaginary part, the PEKF is used to estimate the frequency offsets. The estimated CFO is compensated without the knowledge of original phase error information. Diliyanzah et al., (2014) employed the EKF to estimate CFO and to correct those estimated CFO. The author describes two phases in EKF scheme such as,



In the initial phase, the CFO is estimated based on recursive iteration procedure. The simulation results prove that the EKF estimation technique offers faster convergence. In the correction phase, the estimated CFO is mitigated by multiplying the received signal with the complex conjugate of the estimated CFO and applying FFT. Let $y(n)$ be the received signal and the normalized CFO correction phase is given as,

$$X(n) = FFT\left\{ y(n) e^{-j\frac{2\pi n\hat{\varepsilon}(n)}{N}} \right\} \tag{7}$$

where $\hat{\varepsilon}(n)$ is the normalized CFO, N is the total number of subcarriers. The ICI self cancellation method is not efficient for higher frequency offsets which overcomes by EKF method.

FUTURE DIRECTIONS

The rapid increase in the technology and mobile data services in the near future leads to the problem of global bandwidth shortage. This increases awareness towards the enormous underutilized millimeter wave (mm-wave) bands. These bands are potentially viable solution for increasing the capacity and data rate of the future cellular system (Pi & Khan, 2011). However, the communication system in these bands has significant signal attenuation. As moving towards higher frequency bands (E-Band), the oscillators are not accurate. Thus the CFO has more impact on the bandwidth efficiency and performance of the system (Mehrpouyan et al., 2014). Hence, new algorithms are needed to estimate and compensate the CFO for the future cellular systems such as 5G.

CONCLUSION

A general perspective of the techniques in estimating and compensating CFO for OFDM system from very basics to up-to-date advances is provided. Significant efforts are underway in this research area to promote develop new schemes with improved efficiency and affordable complexity. ICI self cancellation is effective technique for multiple Doppler frequency offsets and it allows the ICI signals in a group to self-cancel each other. Hence, among the compensation techniques reviewed, it is of simple, effective and low cost for ICI reduction. The problem of bandwidth efficiency is overcome by pulse shaping. Novel ideas must be found to meet the challenges in the field of CFO and to satisfy the user demands.

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