Australian Journal of Basic and Applied Sciences, 4(11): 5621-5629, 2010
ISSN 1991-8178

ICI Self – Cancellation for FFT-OFDM System

Haitham J. Taha, Student Member, IEEE and M.F.M. Salleh, Member, IEEE

School of Electrical & Electronic Engineering, Universiti Sains Malaysia,
Seri Ampangan,14300 Nibong Tebal, Pulau Pinang, Malaysia

Abstract: Orthogonal frequency division multiplexing (OFDM) is the projected modulation of choice for fourth-generation broadband multimedia wireless systems. OFDM based wireless systems are spectrally efficient but they are vulnerable to Inter carrier interference (ICI). The rapid variation of the channel can induce ICI. ICI will significantly increase the difficulty of OFDM channel estimation. ICI due to carrier frequency offset can be mitigated by accurate frequency synchronization but ICI due to fast fading channel is more difficult to handle. ICI can be easily reduced by increasing the subcarrier spacing. However, a special problem in OFDM is its vulnerability to frequency offset errors due to which the orthogonality is destroyed that result in ICI. ICI causes power leakage among subcarriers thus degrading the system performance it suffers from ICI in the absence of precise frequency synchronization. In this paper, the OFDM system is modeled and simulated under AWGN channel. The interesting with combating the effects of ICI induced by carrier frequency offsets (CFO), where presented the ICI Self- Cancellation Scheme algorithm to combat ICI effect.

Key words: OFDM, carrier frequency offsets (CFO), Inter Carrier Interference (ICI), self-cancellation (SC)

INTRODUCTION

OFDM is emerging as the preferred modulation scheme in modern high data rate wireless communication systems. OFDM has been adopted in the European digital audio and video broadcast radio system and is being investigated for broadband indoor wireless communications. Standards such as HIPERLAN2 (High Performance Local Area Network) and IEEE 802.11a and IEEE 802.11g have emerged to support IP-based services (Evans and Baughan, 2000).

OFDM is a special case of multi-carrier modulation. Multi-carrier modulation is the concept of splitting a signal into a number of signals, modulating each of these new signals to several frequency channels, and combining the data received on the multiple channels at the receiver (White Paper: 2001). The OFDM system is very vulnerable when the channel changes within one OFDM symbol. In such case, the orthogonality between subcarriers is easily broken down result the ICI so that system performance may be considerably degraded (Hijazi and Ros, 2009).

However, a major problem in OFDM is its vulnerability to frequency offset errors between the transmitted and received signals, which may be caused by Doppler shift in the channel or by the difference between the transmitter and receiver local oscillator frequencies (Russell and Stuber 1995) In such situations, the orthogonality of the carriers is no longer maintained, which results in ICI. ICI results from the other sub-channels in the same data block of the same user. ICI problem would become more complicated when the multipath fading is present (X.Cai and Giannakis, 2003). If ICI is not properly compensated it results in power leakage among the subcarriers, thus degrading the system performance.

In (Armstrong: 1999), ICI self-cancellation of the data-conversion method was proposed to cancel the ICI caused by frequency offset in the OFDM system. In (Y. Fu, S.G. Kang, and C.C. KO, 2002), ICI self-cancellation of the data-conjugate method was proposed to minimize the ICI caused by frequency offset and it could reduce the peak average to power ratio (PAPR) than the data-conversion method. In (Zhao and S. Häggman, 2001), self ICI cancellation method which maps the data to be transmitted onto adjacent pairs of subcarriers has been described. But this method is less bandwidth efficient. In (van de Beek, Sandell, and Borjesson, 1997), the joint Maximum Likelihood symbol-time and CFO estimator in OFDM systems has been developed. And the CFO only is estimated and is cancelled at the receiver.

Corresponding Author: Haitham J. Taha, School of Electrical & Electronic Engineering, Universiti Sains Malaysia, Seri Ampangan,14300 Nibong Tebal, Pulau Pinang, Malaysia
E-mail: haithm1969@yahoo.com

In addition, statistical approaches have also been explored to estimate and cancel ICI (Tiejun , Proakis, and Zeidler, 2005).

In this paper the OFDM system is modeled and simulated under AWGN channel. We are concerned with combating the effects of ICI induced by CFO, presented the ICI Self- Cancellation Scheme algorithm to combat ICI effect.

The rest the paper is organized as follows; section 2 gives the OFDM system model, section 3 present the Inter Carrier Interference (ICI), section 4 present the ICI Self- Cancellation Scheme, section 5 present the Channel Estimation of OFDM Systems and section 6,7 presents the simulation results and Conclusions respectively.

2. Ofdm System:

The OFDM system under consideration is shown in Figure 1. Suppose that the symbol duration after serial-to-parallel (S/P) conversion is T_u. The entire signal bandwidth is covered by N subcarriers, and the space between two neighboring subcarriers is $1/T_u$. Denoting the sampling time by $T_s = T_u/N$, and assuming that the length of the cyclic prefix is $T_g = N_g T_s$ with Ng being an integer.

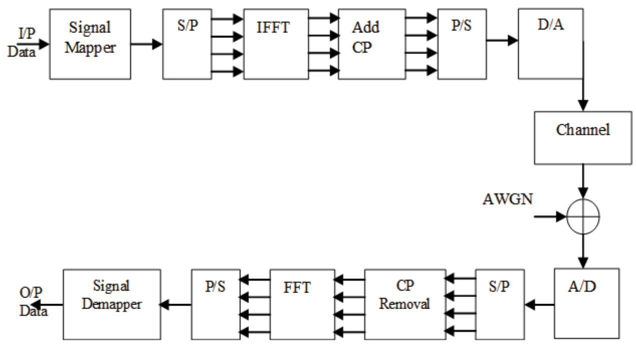

Fig. 1: OFDM system model

The duration of an OFDM symbol is $T = (N + N_g)T_s$. In an OFDM system, the transmitter usually applies an N-point IFFT to data block normalized QAM-symbols $\{X_{(n)}[k]\}$ $\left(i.e., E\left[X_{(n)}[k]X_{(n)}[k]*\right]=1\right)$, where *n* and *k* represent respectively the OFDM symbol index and the subcarrier index, and adds the cyclic prefix (CP), witch is a copy of the last samples of the IFFT output, to avoid inter-symbol interference (ISI) caused by multipath fading channels. In order to limit the periodic spectrum of the discrete time signal at the output of the IFFT, we use an appropriate analog transmission filter $G_t(f)$. As a result, the output baseband signal of the transmitter can be represented as (Yang, Letaief, Cheng and Cao, 2001: Hijazi and Ros, 2007).

$$x(t) = \sum_{n=-\infty}^{\infty} \sum_{d=-N_g}^{N-1} x_{(n)}[d]_{gt}\left(t - dT_s - nT\right) \tag{1}$$

Where $g_t(t)$ is the impulse response of the transmission analog filter and $x_{(n)}[d]$, with $d \in \left[-N_g, N-1\right]$ are the $(N + N_g)$ samples of the IFFT output and the cyclic prefix of the nth OFDM symbol given by:

$$x_{(n)}[d] = \frac{1}{N} \sum_{m=-\frac{N}{2}}^{\frac{N}{2}-1} X_{(n)}[m] e^{j2\pi\frac{md}{N}} \tag{2}$$

It is assumed that the signal is transmitted over a multipath Rayleigh fading channel characterized by:

$$h(t,\tau) = \sum_{l=1}^{L} \alpha_l(t)\, \delta(\tau - \tau_l T_s) \tag{3}$$

Where L is the total number of propagation paths, α_l is the *l*th complex gains of variance $\sigma^2_{\alpha_l}$ and τ_l is the

l th delay normalized by the sampling time (τ_l is not necessarily an integer). $\{\alpha_l(t)\}$ are wide-sense stationary (WSS) narrow-band complex Gaussian processes with the so-called Jakes' power spectrum of maximum Doppler frequency f_d (Jakes, 1983) and uncorrelated with respect to each other. The average energy of the channel is normalized to one $\left(i.e., \sum_{l=1}^{L} \sigma_{\alpha_l}^2 = 1\right)$. At the receiver side, after passing to discrete time through low pass filtering and A/D conversion, the CP is removed assuming that its length is no less than the maximum delay. Afterwards, a N-point FFT is applied to transform the sequence into frequency domain. The *kth* subcarrier output of FFT during the *n*th OFDM symbol is given by:

$$Y_{(n)}[k] = \sum_{m=-\frac{N}{2}}^{\frac{N}{2}-1} X_{(n)}[m] G_t[m] G_r[m] H_{(n)}[k,m] + W_{(n)}[k] \tag{4}$$

where $W_{(n)}[k]$ is white complex Gaussian noise with variance σ^2, $G_t[m]$ and $G_r[m]$ are the transmitter and receiver filter frequency response values at the *mth* transmitted subcarrier frequency, and $H_{(n)}[k,m]$ are the coefficients of the channel matrix from the *mth* transmitted subcarrier frequency to the kth received subcarrier frequency, and given by (Hijazi and Ros, 2007, Hijazi *et al.*, 2007):

$$H_{(n)}[k,m] = \frac{1}{N} \sum_{l=1}^{L} \left[e^{-j2\pi \frac{m}{N} \tau_l} \sum_{q=0}^{N-1} \alpha_l^{(n)}(qT_s) e^{j2\pi \frac{m-k}{N} q} \right] \tag{5}$$

Where

$k, m \in \left[-\frac{N}{2}, \frac{N}{2} - 1\right]$ and $\{\alpha_l^{(n)}(qT_s)\}$ is the T_s spaced sampling of the l^{th} complex gain during the n^{th} OFDM Symbol:

If we assume N transmission subcarriers within the flat region of the frequency response of each of the transmitter and receiver filters, then, by using the matrix notation and omitting the index time n, (4) can be rewritten as (Hijazi and Ros, 2007: Hijazi, Ros and Jourdain, 2007):

$$\underline{Y} = \underline{\underline{H}}\,\underline{X} + \underline{W} \tag{6}$$

3. Inter-carrier interference (ICI):

The inter-carrier interference (ICI) is the main disadvantage of OFDM, however, is its susceptibility to small differences in frequency at the transmitter and receiver, normally referred to as frequency offset. This frequency offset can be caused by Doppler shift due to relative motion between the transmitter and receiver, or by differences between the frequencies of the local oscillators at the transmitter and receiver. The frequency offset is modeled as a multiplicative factor introduced in the channel, as shown in Figure 2.

The received signal is given by,

$$y_n = x_n e^{\frac{j2\pi n\varepsilon}{N}} + w_n \tag{7}$$

where ε is the normalized frequency offset, and is given by $\Delta f N T_s$. Δf is the frequency difference between the transmitted and received carrier frequencies and Ts is the subcarrier symbol period. *w(n)* is the AWGN introduced in the channel.

The effect of this frequency offset on the received symbol stream can be understood by considering the received symbol *Y(k)* on the k^{th} sub-carrier (Amasa, 2009).

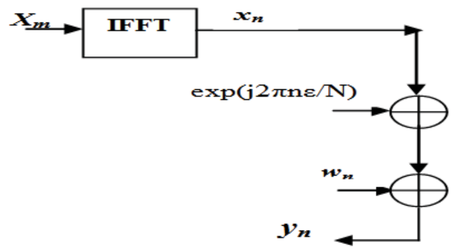

Fig. 2: Frequency offset model

$$Y(k) = X(k)S(0) + \sum_{l=0, l\neq k}^{N-1} X(l)S(l-k) + n_k \quad k=0,1,\ldots,N-1. \tag{8}$$

Where N is the total number of subcarriers, $X(k)$ is the transmitted symbol for the k^{th} subcarrier, n_k is the FFT of $w(n)$, and $S(l-k)$ are the complex coefficients for the ICI components in the received signal (Amasa, 2009).

The ICI components are the interfering signals transmitted on sub-carriers other than the k^{th} sub-carrier. The complex coefficients are given by:

$$S(l-k) = \frac{\sin(\pi(l+\varepsilon-k))}{N\sin(\pi(l+\varepsilon-k)/N)} \exp\left(j\pi\left(1-\frac{1}{N}\right)(l+\varepsilon-k)\right) \tag{9}$$

The carrier-to-interference ratio (CIR) is the ratio of the signal power to the power in the interference components. It serves as a good indication of signal quality. It has been derived from (8) in (Zhao and Häggman, 2001) and is given below. The derivation assumes that the standard transmitted data has zero mean and the symbols transmitted on the different sub-carriers are statistically independent. . In deriving the Theoretical CIR expression, the additive noise is omitted (Amasa, 2009). The desired received signal power on the k^{Th} sub carrier can be represented as

$$E\left[\left|C(k)\right|^2\right] = E\left[\left|X(k)S(0)\right|^2\right] \tag{10}$$

The ICI power is represented as:

$$E\left[\left|I(k)\right|^2\right] = E\left[\left|\sum_{l=0, l\neq k}^{N-1} X(l)S(l-k)\right|^2\right] \tag{11}$$

CIR is given by below equation (Amasa, 2009).

$$CIR = \frac{\left|S(k)\right|^2}{\sum_{l=0, l\neq k}^{N-1}\left|S(l-k)\right|^2} = \frac{\left|S(0)\right|^2}{\sum_{l=0}^{N-1}\left|S(l)\right|^2} \tag{12}$$

4. ICI Self- Cancellation Scheme:

ICI self cancellation is a scheme that was introduced by Zhao and Sven-Gustav in 2001in (Zhao and Häggman, 2001), to combat and suppress ICI in OFDM. Succinctly, the main idea is to modulate the input data symbol onto a group of subcarriers with predefined coefficients such that the generated ICI signals within that group cancel each other, hence the name self- cancellation. It is seen that the difference between the ICI co-efficient of two consecutive sub-carriers are very small. This makes the basis of ICI self cancellation (Amasa, 2009).

Here one data symbol is not modulated in to one sub-carrier, rather at least in to two consecutive sub-carriers. If the data symbol 'a'is modulated in to the 1st sub-carrier then '-a' is modulated in to the 2nd sub-carrier. Hence the ICI generated between the two sub-carriers almost mutually cancels each other. This method is suitable for multipath fading channels as here no channel estimation is required. This method is also suitable for flat channels. The method is simple, less complex & effective. The major drawback of this method is the reduction in band width efficiency as same symbol occupies two sub-carrier (Amasa, 2009).

In this scheme, data is mapped onto group of subcarriers with predefined coefficients. This results in cancellation of the component of ICI within that group due to the linear variation in weighting coefficients, hence the name self- cancellation.

4.1. ICI Canceling Modulation:

In an OFDM communication system, assuming the channel frequency offset normalized by the subcarrier separation is ε and the ICI self-cancellation scheme requires that the transmitted signals be constrained such that

$X(1) = -X(0), X(3) = -X(2), ..., X(N-1) = -X(N-2)$ (Anandpara *et al*., 2003), then the received signal on subcarrier *k* can be written as in (8).

The first term in the right-hand side of (8) represents the desired signal. The second term is the ICI component. The sequence *S(l-k)* is defined as the ICI coefficient between *l*th and *k*th subcarriers, which can be expressed as (9)

Using (9), this assignment of transmitted symbols allows the received signal on subcarriers k and k + 1 to be written as (Anandpara *et al*., 2003)::

$$Y'(k) = \sum_{\substack{l=0 \\ l=even}}^{N-2} X(l)\left[S(l-k) - S(l+1-k)\right] + n_k \tag{13}$$

$$Y'(k+1) = \sum_{\substack{l=0 \\ l=even}}^{N-2} X(l)\left[S(l-k-1) - S(l-k)\right] + n_{k+1} \tag{14}$$

Where n_k and n_{k+1} is the noise added to it.
And the ICI coefficient S'(l-k) is denoted as (Zhao and Häggman, 2001),

$$S'(l-k) = S(l-k) - S(l+1-k) \tag{15}$$

4.2. ICI Canceling Demodulation:

ICI modulation introduces redundancy in the received signal since each pair of subcarriers transmit only one data symbol. This redundancy can be exploited to improve the system power performance, while it surely decreases the bandwidth efficiency. To take advantage of this redundancy, the received signal at the $(k + 1)^{th}$ subcarrier, where k is even, is subtracted from the k^{th} subcarrier. This is expressed mathematically as (Anandpara *et al*., 2003)::

$$\begin{aligned} Y''(k) &= Y'(k) - Y'(k+1) \\ &= \sum_{\substack{l=0 \\ l=even}}^{N-2} X(l)\left[-S(l-k-1) + 2S(l-k) - s(l-k+1)\right] + n_k - n_{k+1} \end{aligned} \tag{16}$$

Subsequently, the ICI coefficients for this received signal becomes (Anandpara *et al*., 2003):

$$S''(l-k) = -S(l-k-1) + 2S(l-k) - S(l-k+1) \tag{17}$$

When compared to the two previous ICI coefficients |S (*l*-k)| for the standard OFDM system and |S'(*l*-k)| for the ICI canceling modulation, |S''(*l*-k)| has the smallest ICI coefficients, for the majority of l-k values, followed by |S' (*l*-k)| and |S (*l*-k)| (Anandpara *et al*., 2003):. This is shown in Figure 6 for N = 32 and ε = 0.2. The combined modulation and demodulation method is called the ICI self-cancellation scheme. The reduction of the ICI signal levels in the ICI self-cancellation scheme leads to a higher CIR. The theoretical CIR is given by (Anandpara *et al*., 2003):

$$CIR = \frac{\left|-S(-1) + 2S(0) - S1(1)\right|^2}{\sum_{\substack{l=0 \\ l=even}}^{N-1} \left|-S(l-1) + 2S(l) - S(l+1)\right|^2} \tag{18}$$

5. Simulation Results:

To analyze the effect of ICI on the received signal, we consider a system with *N=32*carriers. The frequency offset values used are 0.4 and 0.6, and *l* is taken as 0, that is, we are analyzing the signal received at the sub-carrier with index 0.

The complex ICI coefficients *S(l-k)* are plotted for all sub-carrier indices in Figure 3, 4 and 5.
The figure.4 shows that for a larger *ε*, the weight of the desired signal component, *S(0)*, decreases, while the weights of the ICI components increase. The authors also notice that the adjacent carrier has the maximum contribution to the ICI. This fact is used in the ICI self-cancellation technique described in below section.

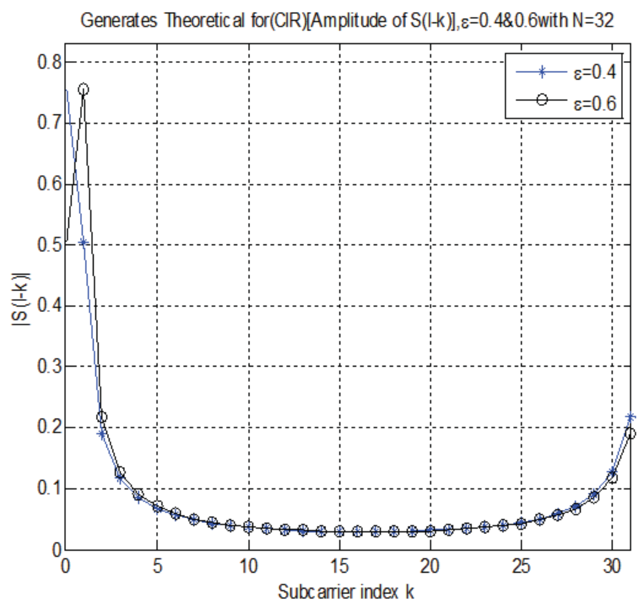

Fig. 3: ICI Coefficients (Amplitude) for N=32 carriers

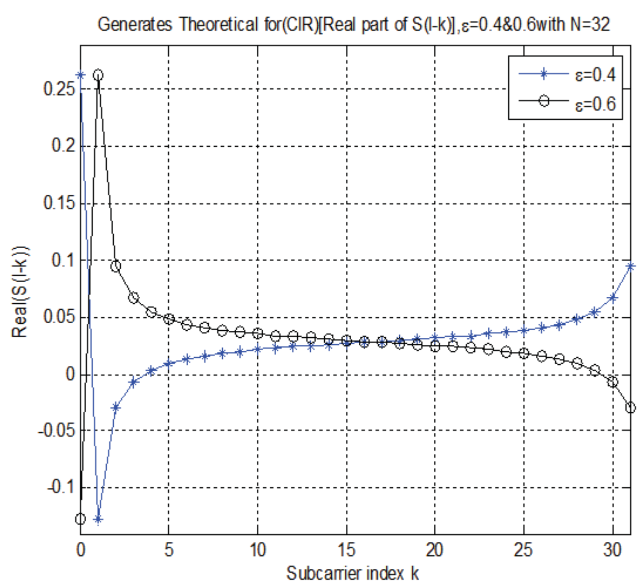

Fig. 4: ICI Coefficients (Real part) for N=32 carriers

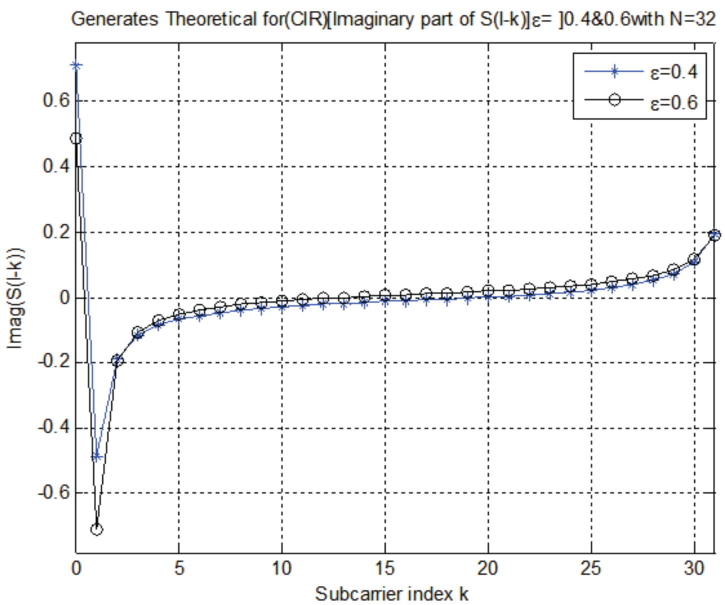

Fig. 5: ICI Coefficients (Imaginary part) for N=32 Carriers

Figure 6 shows the amplitude comparison of $|S(l-k)|, |S'(l-k)| \, and \, |S''(l-k)|$ for N = 32 and $\varepsilon = 0.2$, on a logarithmic scale. It is seen that |S'(l-k)| << |S(l-k)| for most of the l-k values. Hence, the ICI components are much smaller in (15) than they are in (9). Also, the total number of interference signals is halved in (15) as opposed to (9) since only the even subcarriers are involved in the summation.

For the majority of (*l-k*) values, $|S'(l-k)|$ is much smaller than $|S(l-k)|$ and the $|S''(l-k)|$ is even smaller than $|S'(l-k)|$.

Thus, the ICI signals become smaller when applying ICI cancelling modulation. On the other hand, the ICI cancelling demodulation can further reduce the residual ICI in the received signals. This combined ICI cancelling modulation and demodulation method is called the ICI self-cancellation scheme. Until now, three types of ICI coefficients are obtained: 1) *S(l-k)* the standard OFDM system 2) *S'(l-k)* for ICI cancelling modulation and 3) *S"(l-k)* for combined ICI cancelling modulation and demodulation.

On the other hand, the ICI cancelling demodulation can further reduce the residual ICI in the received signals. This combined ICI cancelling modulation and demodulation method is called the ICI self-cancellation scheme.

It is worth mentioning that the proposed ICI cancelling demodulation also improves the system signal-to-noise ratio. The signal level increases by a factor of 2, due to coherent addition, whereas the noise level is proportional to $\sqrt{2}$ because of non coherent addition of the noise on different sub-carriers.

Figure 7, below shows the comparison of the theoretical CIR curve of the ICI self-cancellation scheme, calculated by (17), and the CIR of a standard OFDM system calculated by (14). As expected, the CIR is greatly improved using the ICI self-cancellation scheme. The improvement can be greater than 16 dB for 0 < ε < 0.5, especially for small to medium frequency offsets in the range, the CIR improvement can reach 18 dB.

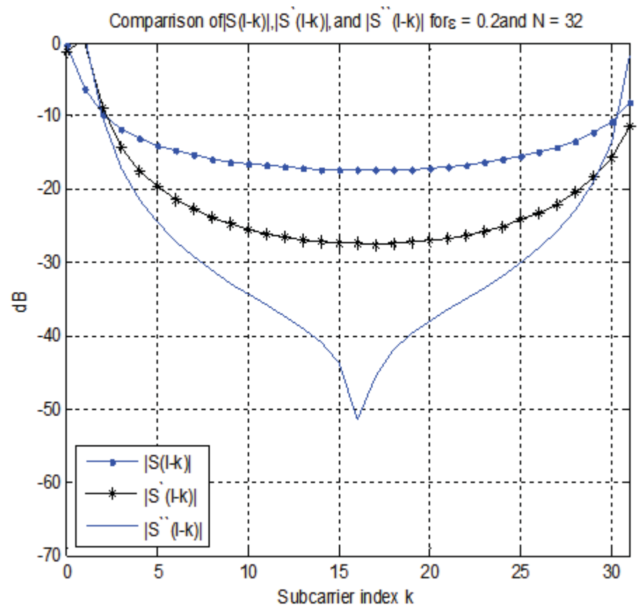

Fig. 6: Comparison of |S(l-k)|, |S`(l-k)|, and |S``(l-k)| for N = 32 and $\varepsilon = 0.2$

Due to the repetition coding, the bandwidth efficiency of the ICI self-cancellation scheme is reduced by half. To fulfill the demanded bandwidth efficiency, it is natural to use a larger signal alphabet size. When the channel frequency offset is small, the use of a larger signal alphabet size might increase the system bit-error rate (BER) compared to a smaller alphabet size. However, for medium to large channel frequency offsets significant BER improvement is obtained by using ICI self cancellation scheme.

where using the theoretical results for the improvement of the CIR should increase the power efficiency in the system and gives better results for the BER. Hence, there is a tradeoff between bandwidth and power tradeoff in the ICI self-cancellation scheme.

6. Conclusion:

In this paper, the ICI Self- Cancellation Scheme algorithm to combat ICI effect. Where the carrier frequency deviation led to the occurrence of ICI.

The performance of OFDM systems in the presence of frequency offset between the transmitter and the receiver has been analyzing in terms of the CIR and the bit error rate (BER) performance. ICI which results from the frequency offset degrades the performance of the OFDM system. Here in this paper we use method of the ICI self-cancellation (SC). The self cancellation does not require very complex hardware or software for implementation. In self cancellation method does reduce bandwidth efficiency because the frequency offset can be estimated from the preamble of the data sequence in each OFDM frame, and the Self cancellation does not require very complex hardware or software for implementation. However, it is not bandwidth efficient. The simulations were performed in an AWGN channel. This model can be easily adapted to a flat-fading channel with perfect channel estimation.

Further work can be done by performing simulations to investigate the performance of these ICI cancellation schemes in multipath fading channels without perfect channel information at the receiver.

ACKNOWLEDGMENTS

This work is funded in USM fellowship, USM-RU-PRGS, and the thanks and grateful to Dr. Salih M. Salih (University of Anbar, Iraq) for his big help.

REFERENCES

Armstrong, J., 1999. Analysis of new and existing methods of reducing intercarrier interference due to carrier frequency offset in OFDM, IEEE Transactions on Communications, 47(3): 365-369.

Amasa, R., 2009. Inter carrier Interference Cancellation in OFDM System. MS.c. Thesis, National Institute of Technology.

Anandpara, M., E. Erwa, J. Golab, R. Samanta and H. Wang, 2003. Inter carrier Interference Cancellation for OFDM Systems. In: COMMUNICATIONS, E. K.W. (ed.). USA.

Cai, X. and G.B. Giannakis, 2003. Bounding performance and suppressing intercarrier interference in wireless mobile OFDM. IEEE Transaction on communications, 51(12): 2047-2056.

Evans, B.G. and K. Baughan, 2000. Vision of 4G," Electronics & Communication Engineering Journal, 12(6): 293-303.

Fu, Y., S.G. Kang and C.C. KO, 2002. A new scheme for PAPR reduction in OFDM systems with ICI self cancellation," in Proc. VTC 2002- Fall, IEEE 56th Vehicular Technology Conf., 3: 1418-1421.

Hijazi, H. and L. Ros, 2009. Rayleigh Time-varying Channel Complex Gains Estimation and ICI Cancellation in OFDM Systems", European Transactions on Telecommunications, pp: 1-15.

Hijazi, H. and L. Ros, 2007. Time-varying Channel Complex Gains Estimation and ICI Suppression in OFDM Systems" in IEEE Global Communications Conference, Washington, USA.

Hijazi, H.L. Ros and G. Jourdain, 2007. OFDM Channel Parameters Estimation used for ICI Reduction in time-varying Multipath channels" in European wireless conference, Paris, France.

Jakes, W.C., 1983. Microwave Mobile Communications. Piscataway, NJ: IEEE Press.

Russell, M., G.L. Stuber, 1995. Interchannel interference analysis of OFDM in a mobile environment", Vehicular Technology Conference, IEEE 45th, 2: 820-824.

Tiejun (Ronald) Wang, John G. Proakis, and James R. Zeidler, 2005.Techniques for suppression of intercarrier interference in OFDM systems. Wireless Communications and Networking Conference, IEEE Volume 1, Issue, 13-17(1): 39-44.

van J.-J. de Beek, M. Sandell and P.O. Borjesson, 1997. ML estimation of time and frequency offset in OFDM systems," IEEE Trans. Signal Process., 45: 1800-1805.

White Paper 2001. High-speed wireless OFDM communication systems, Wi-LAN Inc.

X.Cai, G.B. Giannakis, 2003. Bounding performance and suppressing intercarrier interference in wireless mobile OFDM", IEEE Transaction on communications, 51(12): 2047-2056.

Yang, B., K.B. Letaief, R.S. Cheng and Z. Cao, 2001. Channel estimation for OFDM transmission in mutipath fading channels based on parametric channel modeling" in IEEE Transaction. Communication, vol. 49, no. 3: 467-479.

Zhao, Y. and S. Häggman, 2001. Intercarrier interference self cancellation scheme for OFDM mobile communication systems," IEEE Transactions on Communications, 49(7): 1185-1191.