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Research Article

Performance on ICI Self-Cancellation in FFT-OFDM and DCT-OFDM System

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In orthogonal frequency division multiplexing (OFDM) system, the existence of frequency offset in AWGN channel affects the orthogonality among the subcarriers and consequently introduces the intercarrier interference (ICI). The paper investigates new ICI self-cancellation technique to mitigate the effect of ICI in FFT-OFDM and compares it to DCT based OFDM system in terms of bit error rate (BER) and carrier to interference ratio (CIR). The proposed method for group size three results in a significant 20 dB improved CIR in FFT-OFDM. In terms of BER, proposed ICI self-cancellation technique outperforms the other self-cancellation techniques in FFT-OFDM. Also, this paper investigates outperforming BER and CIR improvement by using DCT-OFDM without applying self-cancellation techniques, due to its energy compaction property.

1. Introduction

Orthogonal frequency division multiplexing (OFDM) is a special form multicarrier (MC) that dates back to 1960s. The concept of the multicarrier transmission was first clearly introduced by Chang in 1966 [1], and its detailed description can also be found in [2, 3]. In 1971, Weinstein and Ebert proposed an improved OFDM system [4] in which the discrete Fourier transform (DFT) was employed to generate orthogonal subcarriers in place of the bank of demodulators and oscillators. This scheme also reduces the system implementation complexity significantly, by using the inverse discrete Fourier transform (IDFT) and discrete Fourier transform (DFT). In this system model the baseband signal was modulated by IDFT at transmitter side and demodulated by DFT at the receiver side and by using IDFT modulation all the subcarriers were orthogonal to each other and in frequency domain they were overlapped.

Flexibility of the OFDM system provides opportunities to use advanced techniques, such as adaptive loading and transmitter and receiver diversities, to improve transmission efficiency. In 1948, Shannon suggested that in frequency selective channel the highest data rate can be achieved by using a multicarrier (MC) system with an intensive set of subchannels and adapting transmission powers and data rates according to the signal to noise ratio (SNR) at different subchannels. In 1980, Peled and Ruiz proposed OFDM system with cyclic prefix [5]. In this the cyclic prefix is used to maintain the orthogonality among the subcarriers and this results in the reduction of intersymbol interference (ISI) and intercarrier interference (ICI). Because in DFT circular convolution in (discrete) time domain corresponds to multiplication in (discrete) frequency domain, the circular convolution is needed and not the regular convolution, while the real channel requires only normal convolution.

So if cyclic prefix is used at the place of guard interval then regular convolution can be used to create circular convolution.

In 1980, Hirosaki proposed an equalization algorithm to reduce the intersymbol interference (ISI) and intercarrier interference (ICI) [6] for the ISI and ICI caused by a channel distortion, synchronization error, or phase error. In 1985, Cimini proposed pilot-based OFDM system [7] to reduce the effect of multipath propagation and cochannel interference on a narrow band digital mobile channel. In this, by using pilot signal the effect of flat Rayleigh fading can be reduced significantly. An improvement in signal to interference ratio of 6 dB can be obtained over the burst Rayleigh channel.

In 1990s, OFDM system has been exploited for high data rate communication mobile radio channel, but it has some drawbacks. One of them is high peak to average power ratio (PAPR) and the second is intercarrier interference (ICI). So in communication system a number of techniques are used to deal with high PAPR such as clipping, clipping and filtering, tone reservation, tone injection, selected mapping, and partial transmit sequence [8]. And to mitigate the effect of ICI in 1999, Jeon et al. proposed a frequency domain equalization ICI cancellation scheme [9]. This scheme is used when ICI is caused by fading distortion. In this method the pilot subcarriers are added in between the transmitted data symbols, so at the receiver side, by using the pattern of pilot subcarrier the equalization technique is applied. In 1999, Armstrong also proposed a time domain windowing ICI cancellation scheme [10] and it is only used when the ICI is caused by band limited channel. In this method a time domain window function is multiplied at the transmitter side and the same window function is multiplied at the receiver side to reduce the effect of ICI.

The above two ICI cancellation schemes are not effective because the major source of ICI is frequency offset due to frequency mismatch between the transmitter and receivers local oscillator and Doppler shift due to relative motion between the transmitter and receiver. After that new ICI cancellation schemes are proposed for pulse shaping and ICI self-cancellation. These schemes reduce the effect of ICI caused by frequency offset.

In 2001, Zhao and Häggman introduced an ICI self-cancellation technique [11]. In this technique one data symbol is mapped on two subcarriers at transmitter side and at receiver side these groups of subcarriers are combined so the effects of ICI on these subcarriers cancel each other. This scheme is easy to implement but the bandwidth efficiency is reduced. And after that different ICI self-cancellation techniques are described based on a data symbol mapped on each of the two subcarriers to mitigate the ICI [12–15]. In this when a data symbol is mapped on two subcarriers the carrier to interference ration (CIR) improved by 15 dB. And a data symbol is mapped on two subcarriers with a predefined weighting coefficient. So the ICI generated between the subcarriers is mutually cancelled.

Orthogonal frequency division multiplexing (OFDM) is the promising communication technique in the broadband wireless mobile communication system due to its high spectral efficiency and robustness to frequency selective fading. In OFDM, multicarrier modulation (MC) is used comprising multiple numbers of frequency channels, known as subcarriers, and these subcarriers are orthogonal to each other.

Currently, OFDM has been employed in many communication systems such as Wireless Local Area Network (WLAN) system, Worldwide Interoperability for Microwave Access (WiMAX) IEEE 802.16, Digital Audio Broadcasting (DAB) system, Digital Video Broadcasting (DVB) system and HIPERLAN2 (High Performance Local Area Network), LTE (Long-Term Evolution), and UWB (Ultra-Wide Band).

The major problem in OFDM is its carrier frequency offset error between the transmitted and received signal due to the frequency mismatch between the local oscillator of the transmitter and the receiver or Doppler shift due to relative motion between the transmitter and receiver. In this situation, the orthogonality among the subcarriers is no longer maintained that results in introduction of intercarrier interference (ICI) in OFDM, and the performance of the system is degraded.

Many ICI cancellation schemes have been proposed to improve the performance of the OFDM system. ICI cancellation schemes are used to reduce the fading distortion [9] frequency offset and IQ imbalance effect [16] and are also effective when the channel is band limited [10]. ICI self-cancellation scheme [11, 13, 17] is used when ICI is caused by frequency offset, where one data symbol is mapped onto group of subcarriers to reduce the effect of ICI but the bandwidth efficiency reduced by half when group size is two. In ICI self-cancellation selection of weighting coefficient [14] is carefully done to reduce the effect of ICI. A comparison of FFT-OFDM and DCT-OFDM is given in [18, 19] in terms of CIR and BER where DCT-OFDM system prevails due to energy compaction property [20]. Deepmala [21] and Mishra [22] have discussed approximations of signals (functions) using fixed point theorems (PD-operator) and summability operators as double digital filter. Acar et al. [23] and Husain et al. [24] also studied approximation properties of certain operators and generalized $H(\cdot,\cdot,\cdot)$-η-cocoercive operators and generalized set-valued variational-like inclusions and their applications in engineering fields. Deepmala [25] studied the existence theorems for solvability of a functional equation arising in dynamic programming. Gupta et al. [26] discussed analytical approach of nonconventional mapping scheme with discrete Hartley transform in OFDM system.

In this paper, an ICI self-cancellation scheme has been proposed, where one data symbol is mapped on three subcarriers which improves CIR and BER, while the bandwidth efficiency reduced by one third. The organization of paper is as follows. OFDM system model is described in Section 2. The next section analyzes ICI in FFT-OFDM system, while Section 4 will help to understand the ICI self-cancellation in FFT-OFDM followed by an important discussion of proposed scheme in Section 5. Analysis of ICI in DCT-OFDM system is covered in Section 6; the last two sections produce simulation results and conclusion as Sections 7 and 8, respectively.

2. System Model

A high data rate serial input bit stream is converted into a parallel lower data rate bit stream and passes through the signal mapper, where modulation (MPSK, QAM) is done and fed into IFFT/IDCT. Cyclic prefix is used to remove intersymbol interference (ISI) and converted from parallel to serial and fed into the channel. At the receiver side original

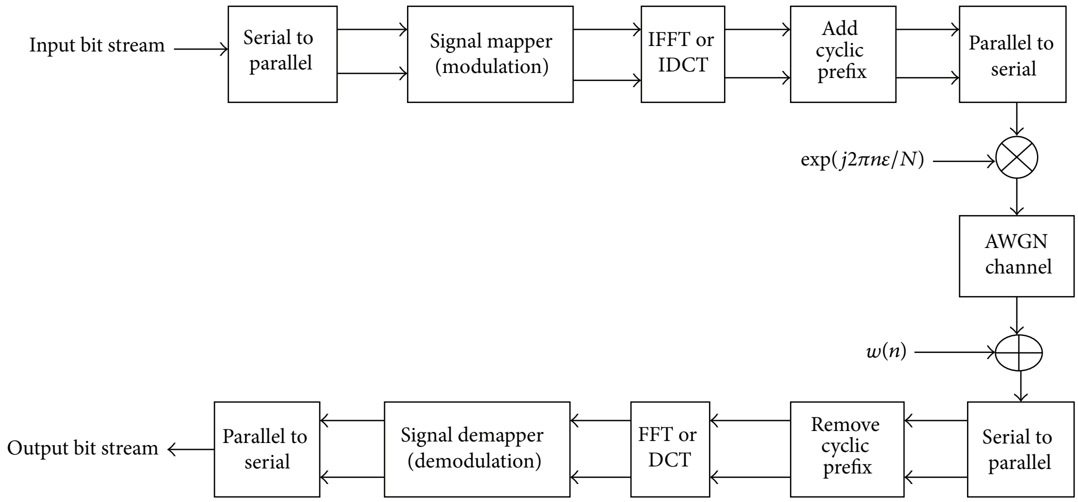

Figure 1: Block diagram of OFDM system model.

bit stream is retrieved by applying the reverse process of what was done at the transmitter. It has been shown in Figure 1.

3. ICI Analysis of FFT-OFDM System

In OFDM system, after IFFT the transmitted signal can be expressed as

$$x(n) = \frac{1}{N}\sum_{t=0}^{N-1} X(t)\, e^{j2\pi nt/N}, \quad (1)$$

where $x(n)$ represents the time domain nth sample of the OFDM transmitted signal, N is the total number of OFDM subcarriers, and $X(t)$ represents the modulated symbol in frequency domain for the tth subcarrier where $0 \le t \le N-1$.

The received signal after passing through the AWGN channel affected by frequency offset:

$$y(n) = x(n)\, e^{j2\pi n\varepsilon/N} + w(n), \quad (2)$$

where ε represents the normalized frequency offset and it is given by $\Delta f N T_s$, where Δf is the frequency difference of local oscillator between the transmitter and receiver and T_s is the symbol period. $w(n)$ is the AWGN noise added to the channel.

The received signal after taking FFT in frequency domain at the kth subcarrier can be expressed as

$$Y(k) = \sum_{n=0}^{N-1} y(n)\, e^{-j2\pi kn/N}. \quad (3)$$

The received signal on the kth subcarrier can be further expressed as

$$Y(k) = \underbrace{X(k)\,S(0)}_{\text{Desired signal}} + \underbrace{\sum_{t=0,t\neq k}^{N-1} X(t)\,S(t-k)}_{\text{ICI signal}} + W(k). \quad (4)$$

In this equation, right hand side first term of it represents the desired signal and second term represents ICI signal for kth subcarrier, $W(k)$ is the FFT of $w(n)$, and $S(t-k)$ is the complex ICI coefficient between the tth and kth subcarrier in the received signal. These coefficients are expressed as

$$S(t-k) = \frac{\sin[\pi(t+\varepsilon-k)]}{N\sin[\pi(t+\varepsilon-k)/N]} \cdot \exp\left[j\pi(t+\varepsilon-k)\left(1-\frac{1}{N}\right)\right]. \quad (5)$$

The carrier to interference ratio (CIR) is the ratio of the signal power to the power in the ICI component. It indicates the quality of the signal. If the received signal on the 0th subcarrier is considered, then the carrier to interference ratio (CIR) of OFDM system is given as

$$\mathrm{CIR} = \frac{E\left[|C(k)|^2\right]}{E\left[|\mathrm{ICI}(k)|^2\right]} = \frac{|S(k)|^2}{\sum_{t=0,t\neq k}^{N-1}|S(t-k)|^2} = \frac{|S(0)|^2}{\sum_{t=1}^{N-1}|S(t)|^2}. \quad (6)$$

And CIR (in dB) of OFDM system depends on normalized frequency offset (Figure 2).

4. ICI Self-Cancellation in FFT-OFDM System

In ICI self-cancellation, one data symbol is mapped on group of subcarriers with predefined weighting coefficient. The weighting coefficients are carefully selected so that at the receiver side the ICI signals within the group of subcarriers are cancelled by each other.

4.1. ICI Self-Cancellation Scheme. In this ICI self-cancellation one data symbol is mapped on two consecutive subcarriers to mitigate ICI. Then transmitted data symbols are $X(1) = -X(0), X(3) = -X(2), \ldots, X(N-1) = -X(N-2)$. Further the received signal $Y(k)$ is determined by the difference between two adjacent subcarriers. So the difference between

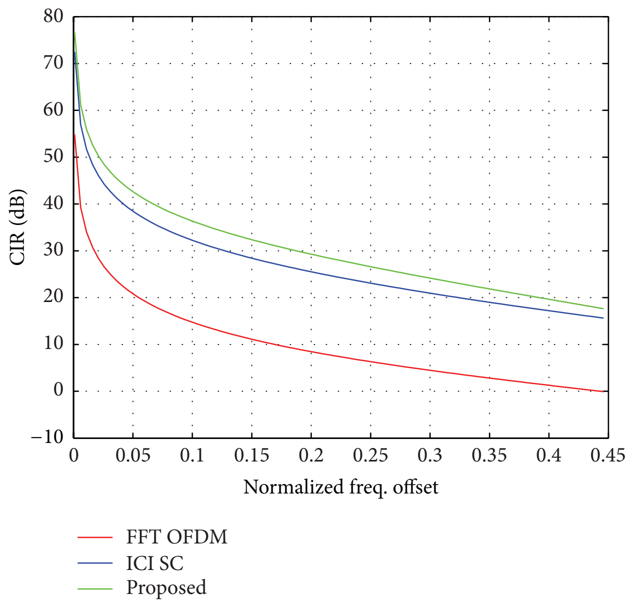

Figure 2: CIR versus normalized freq. offset.

adjacent ICI coefficients is very small $[S(t-k)-S(t+1-k)]$ and the generated ICI signal on tth subcarrier will be cancelled significantly by the generated ICI signal on $(t+1)$th subcarrier. The received signal on kth and $(k+1)$th subcarrier is

$$Y'(k)=\sum_{t=0,2,4}^{N-2}X(t)[S(t-k)-S(t+1-k)]+W'(k)$$
$$Y'(k+1)=\sum_{t=0,2,4}^{N-2}X(t)[S(t-k-1)-S(t-k)]+W'(k+1). \quad (7)$$

To further reduce the ICI received signal on $(k+1)$th subcarrier, it is subtracted from the kth subcarrier, where k is even number. Consider

$$\begin{aligned}Y''(k)&=\frac{1}{2}\left[Y'(k)-Y'(k+1)\right]\\&=\frac{1}{2}\left[X(k)\{2S(0)-S(1)-S(-1)\}\right.\\&\quad+\sum_{\substack{t=0,2,\ldots\\t\neq k}}^{N-2}X(t)\{2S(t-k)-S(t+1-k)\\&\quad\left.-S(t-k-1)\}\right]+W''(k).\end{aligned} \quad (8)$$

And the CIR of ICI self-cancellation is higher than standard OFDM expressed as

$$\mathrm{CIR}=\frac{|2S(0)-S(1)-S(-1)|^2}{\sum_{t=2,4,6}^{N-2}|2S(t)-S(t+1)-S(t-1)|^2}. \quad (9)$$

5. Proposed ICI Self-Cancellation Scheme

In this ICI self-cancellation one data symbol is mapped on three consecutive subcarriers to mitigate ICI. Then transmitted data symbols are $X(1)=-X(0), X(2)=-X(0),\ldots,X(N-2)=-X(N-3), X(N-1)=-X(N-3)$. Then the received signal $Y(k)$ is determined by the difference among three adjacent subcarriers. The received signal on kth subcarrier is written as

$$\begin{aligned}Y'(k)&\\&=\sum_{t=0,3,\ldots}^{N-3}X(t)[S(t-k)-S(t+1-k)-S(t+2-k)]\\&\quad+W'(k).\end{aligned} \quad (10)$$

Similarly, the received signal on $(k+1)$th subcarrier is written as

$$\begin{aligned}Y'(k+1)&\\&=\sum_{t=0,3,\ldots}^{N-3}X(t)[S(t-k-1)-S(t-k)-S(t+1-k)]\\&\quad+W'(k+1).\end{aligned} \quad (11)$$

And similarly, the received signal on $(k+2)$th subcarrier is written as

$$\begin{aligned}Y'(k+2)&\\&=\sum_{t=0,3,\ldots}^{N-3}X(t)[S(t-k-2)-S(t-k-1)-S(t-k)]\\&\quad+W'(k+2).\end{aligned} \quad (12)$$

To further reduce the ICI received signal on $(k+1)$th and $(k+2)$th subcarrier is subtracted from the kth subcarrier:

$$\begin{aligned}Y''(k)&=\frac{1}{3}\left[Y'(k)-Y'(k+1)-Y'(k+2)\right]\\&=\frac{1}{3}\left[X(k)\{3S(0)-S(2)-S(-2)\}t\right.\\&\quad+\sum_{\substack{t=0,3,\ldots\\t\neq k}}^{N-3}X(t)\{3S(t-k)-S(t+2-k)\\&\quad\left.-S(t-k-2)\}\right]+W''(k).\end{aligned} \quad (13)$$

CIR of this ICI self-cancellation is written as

$$\mathrm{CIR}=\frac{|3S(0)-S(2)-S(-2)|^2}{\sum_{t=3,6,\ldots}^{N-3}|3S(t)-S(t+2)-S(t-2)|^2}. \quad (14)$$

6. ICI Analysis in DCT-OFDM System

In DCT-OFDM system, after IDCT the transmitted signal can be expressed as

$$x_n = \sqrt{\frac{2}{N}} \sum_{t=0}^{N-1} \beta_t d_t \cos\left(\frac{\pi t (2n+1)}{2N}\right), \quad (15)$$

where x_n represents the nth sample of the OFDM transmitted signal. N is the total number of DCT-OFDM subcarriers and d_t represents the modulated symbol for the tth subcarrier where $0 \le t \le N-1$. And

$$\beta_t = \begin{cases} \frac{1}{\sqrt{2}} & t = 0 \\ 1 & t = 1, 2, \ldots, N-1. \end{cases} \quad (16)$$

The received signal after passing through the AWGN channel affected by the frequency offset is

$$y_n = x_n \cos\left(\frac{2\pi n \varepsilon}{N}\right) + w(n). \quad (17)$$

The received signal after taking DCT on the kth subcarrier can be expressed as

$$y_k = \sqrt{\frac{2}{N}} \beta_k \sum_{n=0}^{N-1} y_n \cos\left(\frac{\pi k (2n+1)}{2N}\right), \quad (18)$$

where

$$\beta_k = \begin{cases} \frac{1}{\sqrt{2}} & k = 0 \\ 1 & k = 1, 2, \ldots, N-1. \end{cases} \quad (19)$$

It can be further expressed as

$$y_k = d_k \beta_k S_{k,k} + \sum_{t=0, t\neq k}^{N-1} d_t \beta_t S_{t,k} + W(k), \quad (20)$$

where in the right side first part represents desired signal, second part represents ICI signal, and $W(k)$ is the DCT of $w(n)$. In second part $S_{t,k}$ is the ICI coefficient between the tth and kth subcarrier in the received signal and it can be expressed as

$$S_{t,k} = \frac{1}{2N} \beta_k \cdot \sum_{n=0}^{N-1} \left\{ \cos\left(\frac{\pi(ab+d)}{2N}\right) + \cos\left(\frac{\pi(ac+d)}{2N}\right) + \cos\left(\frac{\pi(ab-d)}{2N}\right) + \cos\left(\frac{\pi(ac-d)}{2N}\right) \right\} \quad (21)$$

$$a = 2n+1$$
$$b = t+k$$
$$c = t-k \quad (22)$$
$$d = 4n\varepsilon.$$

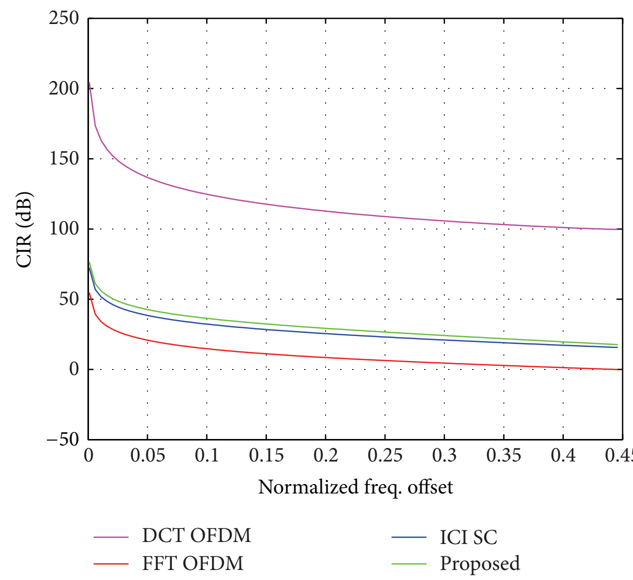

Figure 3: CIR versus normalized freq. offset (0th subcarrier index).

The received signal on kth subcarrier is considered; then CIR of DCT-OFDM is expressed as

$$\text{CIR}_{\text{DCT}} = \frac{E\left[|C(k)|^2\right]}{E\left[|\text{ICI}(k)|^2\right]} = \frac{|S_{k,k}|^2}{\sum_{t=0,t\neq k}^{N-1} |S_{t,k}|^2}. \quad (23)$$

7. Simulation Results

In this section the simulations have been shown for FFT-OFDM with and without ICI self-cancellation, proposed ICI self-cancellation, and DCT-OFDM. Figures 3 and 4 show the CIR versus normalized frequency offset ($0 \le \varepsilon \le 0.3$) for all FFT-OFDM and DCT-OFDM for total number of subcarriers $N = 64$ are used. It can be observed that the proposed ICI self-cancellation scheme has the higher value of CIR than existing self-cancellation method while it compares to DCT-OFDM at 0th subcarrier and then DCT-OFDM has the higher CIR for all offset values shown in Table 1.

Considering the scenario at 63rd subcarrier for DCT-OFDM, CIR is higher when offset value is less than or equal to 0.04 due to energy compaction property, and for higher offset value proposed method has high value of CIR (Table 2).

8. Conclusion

In this paper, a new ICI self-cancellation scheme is proposed to mitigate the effect of frequency offset. The proposed scheme performs better than the existing ICI self-cancellation in FFT-OFDM. Improvement in CIR is 3 dB to 4 dB. While it compares to DCT-OFDM, the DCT-OFDM gives good results without ICI self-cancellation in terms of CIR (at lower subcarrier index) and at higher value of subcarrier index (worst case) DCT-OFDM performance is poor compared to proposed ICI self-cancellation scheme. Some interesting applications of the FFT-OFDM and DCT-OFDM can be seen in [21, 22].

Table 1: CIR comparison among all FFT-OFDM and DCT-OFDM at the first (0th) subcarrier.

Normalized freq. offset	FFT-OFDM CIR (dB)	FFT-OFDM with SC GS2 CIR (dB)	FFT-OFDM with proposed SC CIR (dB)	DCT-OFDM CIR (dB)
0.1	15.1044	32.6236	36.7266	125.4124
0.2	8.6474	25.7274	29.5058	113.0451
0.3	4.6120	21.1125	24.3512	105.9674

Table 2: CIR comparison among all FFT-OFDM and DCT-OFDM at the last (63th) subcarrier.

Normalized freq. offset	FFT-OFDM CIR (dB)	FFT-OFDM with SC GS2 CIR (dB)	FFT-OFDM with proposed SC CIR (dB)	DCT-OFDM CIR (dB)
0.03	26.5240	44.1881	48.3871	52.5000
0.04	23.6921	41.3454	45.5374	46.8288
0.05	21.5560	39.1950	43.3778	42.5466
0.07	18.4010	36.0016	40.1591	36.2092
0.09	16.0756	33.6250	37.7484	31.5205
0.15	11.3572	28.6844	32.6523	21.8958
0.30	4.6120	21.1125	24.3512	7.0959

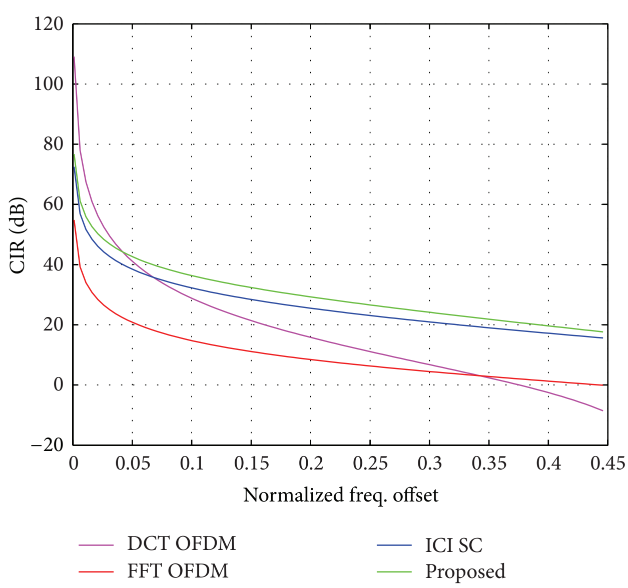

Figure 4: CIR versus normalized freq. offset (63th subcarrier index).

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Authors' Contribution

All the authors carried out the preparation of the present paper. Each author contributed equally in the development of the paper. Shilpi Gupta and Vishnu N. Mishra conceived the study and participated in its design and coordination. All the authors drafted the paper, participated in the sequence alignment, and read and approved the final version of the paper.

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