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A novel energy-efficient ICI cancellation technique for bandwidth improvements through cyclic prefix reuse in an OFDM system

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Abstract: Orthogonal frequency division multiplexing (OFDM), a very promising technique that is leading the evolution in wireless mobile communication to sideline the bandwidth scarcity issue in spectrum allocation, is severely affected by the undesirable effects of the frequency offset error, which generates inter carrier interference (ICI) due to the Doppler shift and local oscillator frequency synchronization errors. There are many ICI cancellation techniques available in the literature, such as self-cancellation (SC), maximum likelihood estimation (MLE), and windowing, but they present a tradeoff between bandwidth redundancy and system complexity. In this study, a new energy-efficient, bandwidth-effective technique is proposed to mitigate ICI through cyclic prefix (CP) reuse at the receiver end. Unlike SC and MLE where the whole OFDM symbol data is transmitted in duplicate to create redundancy at the transmitter end, the proposed technique uses the CP data (which is only 20% of the total symbol bandwidth) to estimate the channel, and it produces similar results with a huge bandwidth saving. The simulation results show that the proposed technique has a significant improvement in error performance, and a comparative analysis demonstrates the substantial improvement in energy efficiency with high bandwidth gain. Therefore, it outperforms the legacy ICI cancellation schemes under consideration.

Key words: Orthogonal frequency division multiplexing (OFDM); Fast Fourier transform (FFT); Cyclic prefix (CP); Inter symbol interference (ISI); Inter carrier interference (ICI); Maximum likelihood estimation (MLE)
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1 Introduction

Orthogonal frequency division multiplexing (OFDM) has become the most appropriate and preferred technique for accessing wideband communication to deploy a high-speed data access environment because of its inherent tendency to deliver high spectral efficiency. OFDM is immune to frequency selective fading and it offers a much higher data rate (Hwang *et al.*, 2009). OFDM data is transmitted through different subcarriers in a parallel fashion, where the whole bandwidth is divided into a number of orthogonal subcarriers and each subcarrier is modulated with a low data rate information-bearing signal. The OFDM system efficiently distributes the available frequency spectrum while maintaining orthogonality among the subcarriers and adequate channel spacing to avoid interference. However, orthogonality can be maintained if N subcarriers are spaced by $1/(NT_u)$ over the time interval T_u (Morelli *et al.*, 2007). Apparently, the whole information data stream is fragmented into a number of subsets, separately modulated with orthogonal carriers. These processed signals are then transformed into a time domain using inverse fast Fourier transform (IFFT).

OFDM has been widely used in Wi-Fi, Wi-Max, broadcasting, and various other networks where high spectrum efficiency, strong channel robustness, immunity to impulse interference, flexibility, and easy equalization are key requirements. To generate an OFDM signal, data is first encoded and interleaved to create a bursty data transmission. Data is distributed

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ORCID: Sandeep SAROWA, http://orcid.org/0000-0002-7236-1556 in N parallel streams using serial to parallel converters. Each of the N data streams is modulated using the appropriate digital modulation scheme to generate the modulated signal $X(m)$. However, in this study quadrature amplitude modulation (QAM) (Zhang *et al.*, 2011; Savitha and Kulkarni, 2012) is used to yield better results. Each of the N streams is then multiplexed with orthogonal frequency carriers through N times IFFT (NIFFT):

$$x(n)=\frac{1}{N}\sum_{m=0}^{N-1}X(m)\exp(\mathrm{j}2\pi mn/N). \quad (1)$$

$x(n)$ is the signal sequence after IFFT. In the channel, data is influenced by additive white Gaussian noise (AWGN), where a Doppler shift error is added. Thus, the received signal $y(n)$ can be presented as

$$y(n)=x(n)\exp(\mathrm{j}2\pi n\epsilon/N)+w(n), \quad (2)$$

where $w(n)$ is AWGN, ϵ is the frequency offset, and the exponential term is due to the Doppler effect.

On the receiver side, the whole process is reversed to recover the original data. The N times FFT (NFFT) is computed as

$$Y(m)=\sum_{n=0}^{N-1}y(n)\exp(-\mathrm{j}2\pi mn/N)+W(m), \quad (3)$$

where $W(m)$ is the FFT of $w(n)$.

There are two major issues observed in OFDM during the implementation. The first is the high peak to average power ratio (PAPR), which is caused by the large number of subcarriers (Himaza and Kumar, 2015) and the second is ICI, which is caused by the Doppler shift and local oscillator frequency synchronization error at the receiver (Chouhan and Sharma, 2014; Himaza and Kumar, 2015; Kumar *et al.*, 2015). The local oscillator issue can be dealt with with the help of offset estimation but the Doppler shift error is hard to estimate because of its random nature.

2 Maximum likelihood estimation technique

The MLE technique is a statistical approach for estimating the value of the frequency offset. In this technique, the offset is estimated and then its effect is cancelled out by multiplying the received signal with the complex conjugate of the estimated offset (Zhang *et al.*, 2011; Hou *et al.*, 2012; Savitha and Kulkarni, 2012). For the estimation, a replica of data needs to be transmitted at the receiver side, which is further processed by the MLE estimator followed by FFT operation.

For a modulated data $X(m)$ at the transmitter, the NIFFT operation would produce $x(n)$ as Eq. (1). The replication of data is performed as follows:

$$r(k)=x(n),\ k=0,\ 1,\ ...,\ N-1, \quad (4)$$

$$r(k+N)=x(n),\ k=0,\ 1,\ ...,\ N-1. \quad (5)$$

n is an independent random number from {0, 1, ..., N–1}. After data replication, the data frame is as shown in Fig. 1.

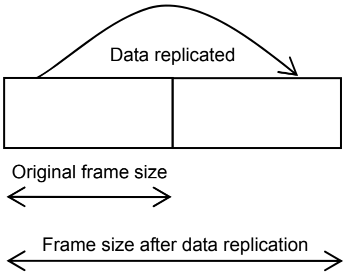

Fig. 1 The data frame after data replication

If $r(n)$ is the data transmitted through the channel with no noise, $t(n)$ is the transmitted signal which is exposed to the Doppler error (ϵ), then $t(n)$ can be calculated as

$$t(n)=r(n)\exp(\mathrm{j}2\pi n\epsilon/N). \quad (6)$$

First N symbols are demodulated by NFFT, which gives the demodulated signal $T_1(m)$, and the next N symbols are demodulated by another NFFT, which gives the demodulated signal $T_2(m)$. According to MLE, $T_1(m)$ and T_2(m) are related to each other:

$$T_2(m)=T_1(m)\exp(\mathrm{j}2\pi\epsilon). \quad (7)$$

When noise is considered in the channel, the received signal $y(n)$ is expressed as

$$y(n)=r(n)\exp(\mathrm{j}2\pi n\epsilon/N)+w(n). \quad (8)$$

After performing two different NFFT, the processed signals $Y_1(m)$ and $Y_2(m)$ can be expressed as

$$Y_1(m)=T_1(m)+W_1(m), \tag{9}$$

$$Y_2(m)=T_1(m)\exp(\mathrm{j}2\pi\epsilon)+W_2(m). \tag{10}$$

The MLE of the frequency offset (Savitha and Kulkarni, 2012) is given as

$$\epsilon'=\frac{1}{2\pi}\arctan\left(\frac{\sum\limits_{m=0}^{N-1}\mathrm{Im}(Y_2(m)Y_1^*(m))}{\sum\limits_{m=0}^{N-1}\mathrm{Re}(Y_2(m)Y_1^*(m))}\right). \tag{11}$$

$Y_1{}^*(m)$ is the conjugate of $Y_1(m)$. Then the complex conjugate of the estimated frequency offset is multiplied by the received signal.

$$y'(n)=r(n)\exp(-\mathrm{j}2\pi n\epsilon'/N)+w(n). \tag{12}$$

$y'(n)$ is the finally recovered signal after processed by the estimator. It is further processed by FFT to produce demodulated signal at the receiver output. The overall complexity of the system is now increased a bit, but the ICI cancellation is much improved; however, the bandwidth efficiency remains the same as that of the SC technique. There is a loss of bandwidth efficiency almost 50% and energy associated with signal (loss of 3 dB) as the symbol width is now doubled.

3 Cyclic prefix analysis for bandwidth and energy loss

Many techniques have been proposed by researchers to improve the performance of the OFDM system, like data manipulation techniques (SC), estimation techniques (MLE and Kalman filter), but most of them accept a tradeoff between bandwidth utilization and bit error rate (BER) (Chouhan and Sharma, 2014; Himaza and Kumar, 2015; Kumar *et al.*, 2015). This study leans toward energy saving and bandwidth enhancement without compromising on BER degradation to make the system more generous and practical for realization (Li *et al.*, 2011; Dai *et al.*, 2013). A conventional OFDM system is designed to have CP to create a guard period at the beginning of each OFDM symbol in order to remove inter symbol interference (ISI) introduced by multipath propagation (Muquet *et al.*, 2002; Li *et al.*, 2012).

CP is the process where some of bits, from the last part of the symbol frame, are copied to the front of the symbol frame to avoid data interference among OFDM symbols (Fig. 2).

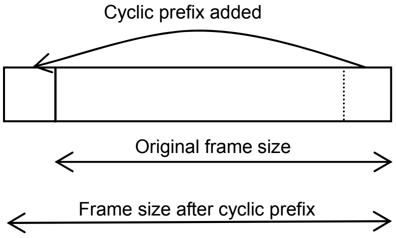

Fig. 2 Cyclic prefixing in a frame

Generally, the CP size is kept at 20% of the data frame size (N). Apparently, the net frame size becomes $N/5+N$ and the symbol time becomes $T_\mathrm{s}+T_\mathrm{c}$, where T_s and T_c are the time duration of symbol and time taken by CP binaries, respectively. The information regarding the start of the next symbol is also added up through CP, which is quite helpful for synchronization on the receiver side. CP is easily removed from the receiver side during the recovery of the original data.

Although bandwidth efficiency is decreased a bit by engaging CP, the transmission becomes more reliable. Bandwidth efficiency β is calculated by the ratio of the effective symbol time to the net symbol time (Muquet *et al.*, 2002; Li *et al.*, 2012):

$$\beta=\frac{T_\mathrm{s}}{T_\mathrm{s}+T_\mathrm{c}}. \tag{13}$$

The energy loss E can be calculated by

$$E=-10\lg\left(1-\frac{T_\mathrm{c}}{T_\mathrm{s}+T_\mathrm{c}}\right). \tag{14}$$

For example, at a 20% CP addition, the bandwidth efficiency is β=0.83, and the corresponding energy loss is E=0.79 dB.

Fig. 3 demonstrates the graphical relationship between bandwidth efficiency β and CP percentage. Fig. 4 demonstrates the graphical relationship between energy loss E and CP percentage. Energy contained in the symbol has a linear relation with CP. As the percentage of CP increases, energy loss associated with it increases proportionately, whereas the bandwidth efficiency is inversely proportional to it.

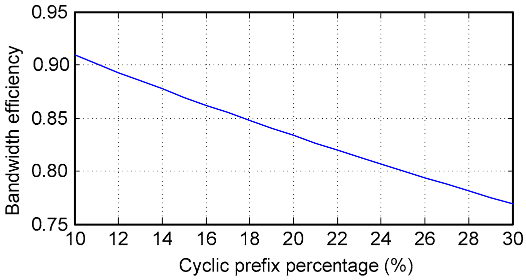

Fig. 3 Bandwidth efficiency vs. cyclic prefix percentage

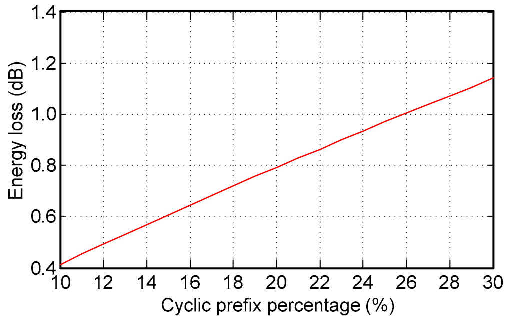

Fig. 4 Energy loss vs. cyclic prefix percentage

In Table 1, a comparative analysis of MLE, SC, and the proposed CP-based technique is presented in terms of bandwidth efficiency and energy loss. The performances of the proposed CP-based technique, which will be explained in the next section, are observed for four different values of CP (10%, 15%, 20%, and 25%). For all four values, energy saving associated with the transmitted signal and improvements in the spectrum efficiency are considerably high. The bandwidth efficiency and energy loss behavior analyzed here are intended to demonstrate the significant waste of resourceful spectrum and associated energy, which are apparently compensated for achieving high BER performance.

4 Proposed CP-based technique

The proposed CP-based offset estimation technique is somewhat similar to the MLE proposed in the literature. The block diagram of the proposed CP-based offset estimation technique for ICI cancellation is shown in Fig. 5. The received signal $y(n)$ is processed through estimation to generate the approximated frequency offset error ϵ' to compensate for the Doppler effect in the channel.

Table 1 Bandwidth efficiency and energy loss of ICI cancellation techniques

Technique	Cyclic prefix percentage	Bandwidth efficiency	Energy loss (dB)
MLE	0	0.50	3.00
SC	0	0.50	3.00
Proposed CP-based technique	25%	0.80	0.96
	20%	0.83	0.79
	15%	0.86	0.60
	10%	0.90	0.41

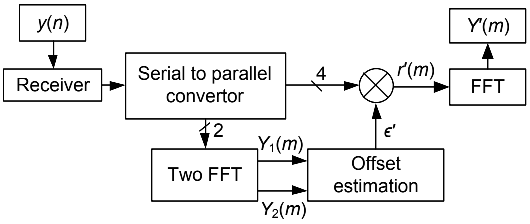

Fig. 5 Block diagram of the proposed CP-based offset estimation technique

ICI compensation is achieved by using CP (which is actually added to nullify the effect of ISI) instead of a dedicated replica of data. This is why the symbol time and width are not doubled, unlike in the case of MLE. Hence, the bandwidth efficiency is increased and energy loss is reduced.

The proposed CP-based technique works in a very similar way to MLE, where the offset is estimated and then its effect is canceled by multiplying the received signal with the complex conjugate of the estimated offset.

Let $X(l)$ be the signal data at the transmitter. NIFFT operation would produce $x(m)$ as

$$x(m)=\frac{1}{N}\sum_{l=0}^{N-1}X(l)\exp(\mathrm{j}2\pi ml/N). \tag{15}$$

CP $c(k)$ can be expressed as

$$\begin{aligned} c(k)=x(m),\ k&=0,\ 1,\ \dots,\ \frac{N}{5}-1,\\ m&=\frac{4N}{5},\frac{4N}{5}+1,\ \dots,\ N-1. \end{aligned} \tag{16}$$

$r(n)$ is the signal represented after adding CP, which is further calculated using Eqs. (17) and (18), where the frame size now becomes $6N/5$.

$$r(n)=c(k),\ n,\ k=0,\ 1,\ \ldots,\ \frac{N}{5}, \tag{17}$$

$$\begin{gathered} r(n)=x(m),\ n=\frac{N}{5},\frac{N}{5}+1,\ \ldots,\frac{6N}{5}-1, \\ m=0,\ 1,\ \ldots,N-1. \end{gathered} \tag{18}$$

Signal $r(n)$ is transmitted through a noise-free channel, and becomes $t(n)$ when exposed to the Doppler error.

$$t(n)=r(n)\exp(\mathrm{j}2\pi n\epsilon/M), \tag{19}$$

where $M=6N/5$ is the frame size. Since symbols are separated by N space, $t_2(n)$ and $t_1(n)$ can be calculated as

$$\begin{gathered} t_2(n)=r(m)\exp\left[\frac{\mathrm{j}2\pi(n+N)\epsilon}{6N/5}\right], \\ m=\frac{4N}{5},\frac{4N}{5}+1,\ \ldots,N-1, \end{gathered} \tag{20}$$

$$\begin{gathered} t_1(n)=r(m)\exp\left[\frac{\mathrm{j}2\pi n\epsilon}{6N/5}\right], \\ m=\frac{4N}{5},\frac{4N}{5}+1,\ \ldots,N-1. \end{gathered} \tag{21}$$

If the required symbols demodulated by NFFT generate $T_1(m)$, and 20% CP (symbols from frame size $N/5$ to $N-1$) demodulated by another NFFT generates $T_2(m)$, there will be a relationship between $T_1(m)$ and $T_2(m)$, which can be described as

$$\begin{gathered} T_2(m)=T_1(m)\exp(\mathrm{j}\pi\epsilon 5/3), \\ m=\frac{4N}{5},\frac{4N}{5}+1,\ \ldots,N-1. \end{gathered} \tag{22}$$

When noise $w(n)$ is considered in the channel, the received signal $y(n)$ can be represented as

$$y(n)=r(n)\exp(\mathrm{j}2\pi n\epsilon/M)+w(n),\ M=6N/5. \tag{23}$$

After operating with two different NFFT, we have

$$Y_1(m)=T_1(m)+W_1(m), \tag{24}$$

$$\begin{gathered} Y_2(m)=T_1(m)\exp(\mathrm{j}\pi\epsilon 5/3)+W_2(m), \\ m=\frac{4N}{5},\frac{4N}{5}+1,N-1. \end{gathered} \tag{25}$$

The estimation of the frequency offset is now

$$\epsilon'=\frac{3}{5\pi}\arctan\left(\frac{\sum\limits_{m=4N/5}^{N-1}\mathrm{Im}(Y_2(m)Y_1^*(m))}{\sum\limits_{m=4N/5}^{N-1}\mathrm{Re}(Y_2(m)Y_1^*(m))}\right). \tag{26}$$

Then the complex conjugate of the estimated frequency offset is multiplied to the received signal:

$$r'(n)=r(n)\exp(-\mathrm{j}2\pi n\epsilon'/N)+w(n). \tag{27}$$

For the required signal $Y'(m)$, $r'(n)$ is operated with FFT to derive the following expression:

$$Y'(m)=\sum_{n=0}^{N-1}(r'(n)\exp(-\mathrm{j}2\pi mn/N))+W(m). \tag{28}$$

5 Results and analysis

High bandwidth efficiency is required for most applications where bandwidth scarcity becomes a major bottleneck. When we implement SC and the maximum likelihood technique to compensate for the effect of ICI, bandwidth waste becomes a major issue (due to insertion of redundant data). Spectrum efficiency is deeply compensated for ICI reduction in various hybrid techniques (Singh *et al.*, 2015). CP used in the conventional OFDM system (more than 20% bandwidth loss to compensate for the effect of ISI) can be reused for offset estimation to reduce ICI effects.

Simulations are done with MATLAB software for the proposed CP-based technique, self-cancellation, MLE, and conventional OFDM. All techniques are compared based on BER at different offset error values, i.e., 0.01, 0.02, and 0.05 for 64 FFT and 16 FFT configurations with 16 QAM. CP values for the standard OFDM and the proposed CP-based offset estimation technique are 10%, 15%, 20%, and 25% (Figs. 6–12).

Simulation results (Figs. 6 and 7) give a clear indication of achievement of an optimum BER (similar to MLE) without compromise on bandwidth. Here, CP is 25% of the data frame, which means bandwidth efficiency and energy loss of the proposed CP-based technique are 80% and 0.96 dB (Table 1), respectively, unlike in the case of using the MLE and SC techniques, where they are 50% and 3 dB, respectively. Moreover, with this configuration, the proposed CP-based technique still produces much better BER results than the standard OFDM and SC technique.

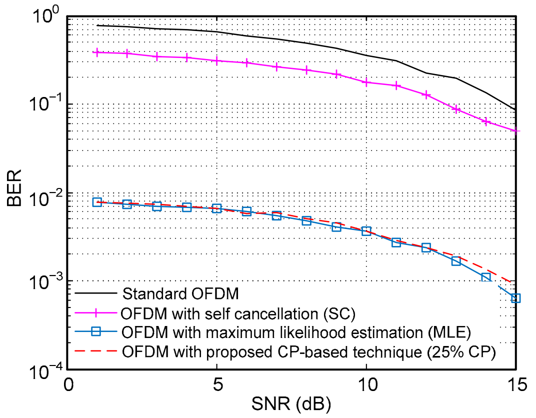

Fig. 6 BER vs. SNR for ICI cancellation techniques with 16 FFT at a 0.02 offset (25% CP)
BER: bit error rate; SNR: signal-to-noise ratio

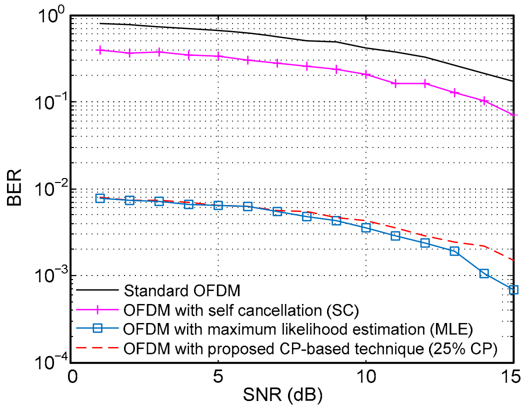

Fig. 7 BER vs. SNR for ICI cancellation techniques with 16 FFT at a 0.05 offset (25% CP)
BER: bit error rate; SNR: signal-to-noise ratio

As observed in Figs. 6 and 7, with 16 FFT operation, the BER performances of MLE and the proposed CP-based technique come out to be very close to each other. For both techniques, at 0.02 offset configuration, the BER is better than at 0.05 offset configuration. Moreover, the proposed CP-based technique outperforms the standard OFDM and SC schemes with a huge margin. With respect to bandwidth efficiency and energy loss, the proposed CP-based technique out performs all three considered techniques (SC, MLE, and standard OFDM) with huge gain (Table 1).

As demonstrated in Fig. 8, the BER performance of the proposed CP-based technique coincides with that of MLE and delivers a quite similar ICI cancellation effect with an outstanding spectrum efficiency (80%).

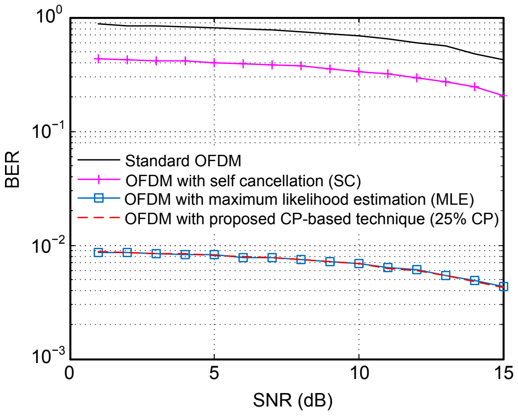

Fig. 8 BER vs. SNR for ICI cancellation techniques with 64 FFT at a 0.01 offset (25% CP)
BER: bit error rate; SNR: signal-to-noise ratio

Table 2 gives a statistical data analysis of the observed BER values for different signal-to-noise ratios (SNRs) at 5, 10, and 15 dB. Simulation is done for 4096 data bits, 64 subcarriers with the 16 QAM technique at 20 Hz frequency offset.

Table 2 BER analysis of ICI cancellation techniques at different SNRs

Technique	BER		
	5 dB	10 dB	15 dB
SC	0.406 860	0.339 355	0.229 248
MLE	0.008 027	0.006 797	0.004 290
Proposed CP-based technique			
20% CP	0.008 113	0.006 912	0.004 607
15% CP	0.009 461	0.008 095	0.005 433
10% CP	0.011 570	0.009 783	0.006 646

A comparative analysis is done for SC, MLE, and the proposed CP-based technique with CP values of 20%, 15%, and 10%. Data analysis shown in Table

2 demonstrates good BER results (similar to MLE) for the proposed CP-based technique at 20% CP with significant saving in the resourceful spectrum (almost 83% bandwidth efficiency) at very low energy loss (nearly 0.79 dB) as compared to other techniques. With a slight compromise on the BER value, the proposed CP-based technique (at 10% CP) can deliver a bandwidth efficiency of up to 90% with extremely low energy loss (nearly 0.41 dB as compared to 3 dB loss in MLE and SC).

Simulation results shown in Fig. 9 depict different CP configurations and corresponding BER degradation.

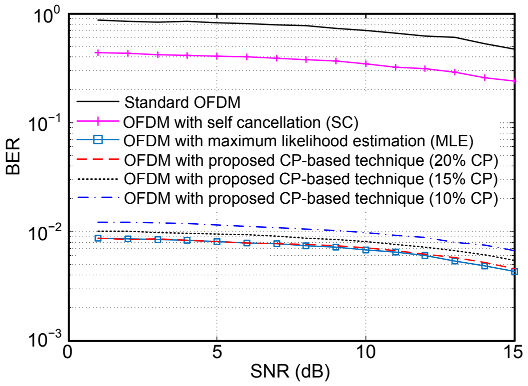

Fig. 9 BER vs. SNR for ICI cancellation techniques with 64 FFT at a 0.05 offset (20%, 15%, and 10% CP)
BER: bit error rate; SNR: signal-to-noise ratio

The BER analysis of the proposed CP-based technique with 20% CP (one of the most suitable and practical configuration) is shown in Figs. 10–12 for different offset values, i.e., 0.05, 0.02, and 0.01.

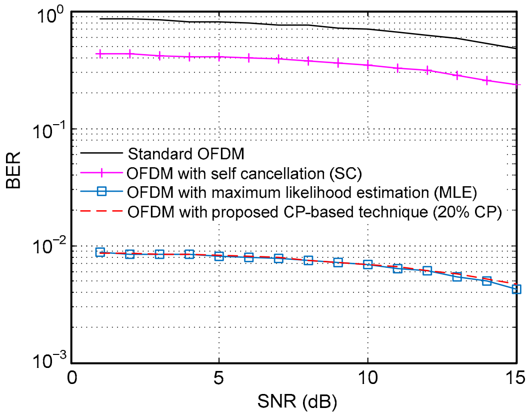

Fig. 10 BER vs. SNR for ICI cancellation techniques with 64 FFT at a 0.05 offset (20% CP)
BER: bit error rate; SNR: signal-to-noise ratio

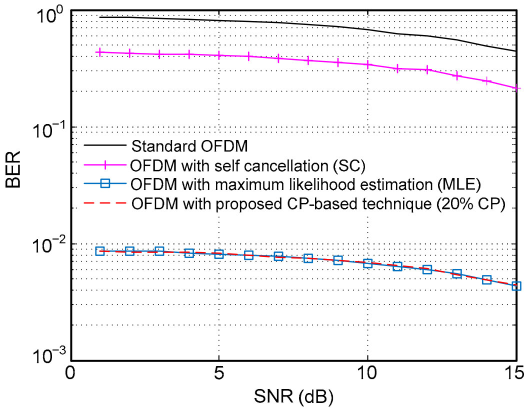

Fig. 11 BER vs. SNR for ICI cancellation techniques with 64 FFT at a 0.02 offset (20% CP)
BER: bit error rate; SNR: signal-to-noise ratio

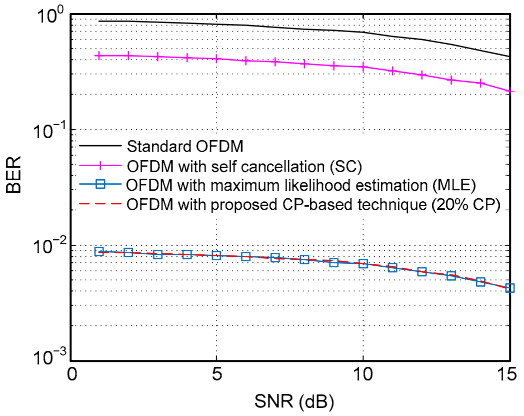

Fig. 12 BER analysis for the proposed CP-based technique at a 0.01 offset (20% CP)
BER: bit error rate; SNR: signal-to-noise ratio

As observed in Figs. 10–12, with the increase of the offset value, the BER performance deteriorates insignificantly. The huge amount of energy saving and spectrum gain apparently overshadows the effect of slight degradation of BER performance at higher offset values. Therefore, the proposed CP-based technique is more robust and much more practical for ICI cancellation in the OFDM system.

Simulation results in Fig. 12 clearly justify the high performance of the proposed CP-based technique at a low offset value (0.01) with a 20% CP configuration.

6 Conclusions

Simulation results and statistical analysis of tabulated data advocate for the proposed CP-based estimation technique as it produces BER performance results similar to those of the MLE technique but with no compromise on the bandwidth efficiency. The proposed CP-based technique delivers much better BER results than SC and standard OFDM along with a 80% bandwidth efficiency (alternatively, we can say, less than 0.96 dB energy loss at 25% CP). The performance improvement is well justified by observing the data collected in Tables 1 and 2. Therefore, by applying the proposed CP-based technique, the bandwidth efficiency can be improved much better than using the MLE technique, with an insignificant degradation of BER performance.

The bandwidth efficiency and energy loss of SC and MLE are 0.5 and 3 dB, respectively (no CP required here). In case of the proposed CP-based technique, the bandwidth efficiency is far better than those obtained using other techniques. The proposed CP-based technique also restricts energy loss to a great extent, i.e., 0.96 dB (25% CP), 0.79 dB (20% CP), 0.60 dB (15% CP), and 0.41 dB (10% CP) as compared to 3 dB loss in the SC or MLE technique. However, bandwidth efficiency decreases with the increase in percentage of CP. The most suitable configuration for the proposed CP-based technique, which gives the best possible BER (very near to MLE), is 20% CP configuration (Table 2) and at this configuration, a bandwidth efficiency of 83% is achievable with a low energy loss (0.79 dB). Although the BER value increases gradually with the decrease of CP percentage (Table 2), it leads to huge bandwidth and energy saving (Table 1).

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