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Peak to average power ratio reduction in spectrally efficient FDM using repeated clipping and filtering

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ABSTRACT

Multi-carrier transmission may be considered one of the important developments in wireless communications. Spectrally efficient frequency division multiplexing (SEFDM) is a promising multi-carrier modulation which can significantly improve utilization of spectral. The SEFDM has high peak to average power ratio (PAPR) like any multicarrier system. High PAPR reduces the random forest (RF) transmitter power amplifier efficiency, which minimize the use of this technique in limited power supply transmitters. In this work, a repeated clipping and filtering method is introduced to reduce the PAPR in SEFDM with minimum or no out of band radiation. The results of the simulated approach show that the PAPR of the SEFDM was reduced from 16.264 dB to 7.9146 dB with marginal degradation in system performance when the clipping ratio varied from 4 to 2.

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1. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) is the latest technique that is used in the physical layer of multi-carrier wireless systems to solve overlapping using orthogonal sub-carriers. For the future communication networks, due to the scarcity of frequency spectrum, introducing techniques that reduce spectral use, while guaranteeing overall performance of the system would be preferable. To increase efficiency of the spectral, non-orthogonal multicarrier techniques are enjoying increasing attention in recent years [1].

In the next generation of wireless communication networks, non-orthogonal communication systems are considered as prospective candidates for the physical layer interface. Spectrally efficient frequency division multiplexing (SEFDM) technique, which was introduced in 2003, is an early application of non-orthogonal multi-carrier communication system [2]. SEFDM technique reduces the transmission bandwidth significantly but slightly increases the transmission power [3]. The spectrum in SEFDM can be saved by breaking the principle of orthogonality, the results is non-orthogonal overlapping of sub-carriers, allowing bandwidth saving more than that in OFDM.

The variation range in the transmitted signal power is represented by peak to average power ratio (PAPR). This PAPR is used to measure the ratio of the highest transmitted power peak to the mean transmitted power in multi-carrier communication systems. All multi-carrier communication systems suffer from high PAPR, the power of the generated sub-carrier signals can be added constructively casing very high peak compared to the mean transmitted power. This uncontrolled PAPR will generate non-linear distortions in the transmitter RF power amplifier that will cause spectral spreading and increase bit error rate (BER) [4]. Many literatures proposed different approaches to reduce PAPR, all the proposed approaches came with system performance trade-offs. Increasing system computational complexity, higher BER, lower data rates, and increase the transmission power are some examples of these trade-offs [5].

The methods that have been used to decrease the PAPR of an OFDM signal can be divided in four categories: i) signal distortion, ii) coding methods, iii) probabilistic (scrambling) techniques and iv) pre-distortion methods [6]. The most straight forward method is the distortion-based techniques. These techniques decrease the PAPR, by non-linearly distorting the OFDM signal in frequency domain. The distorted spectrum or spectral re-growth is corrected to an acceptable value using filtering operation. These methods include clipping and filtering, peak windowing, and non-linear companding. All the methods mentioned above must be applied after OFDM signal generation (after the includes a fast Fourier transform (IFFT)) [7].

Armstrong [8] introduces PAPR reduction technique, called the "clipping and frequency domain filtering". In this technique, the baseband signal is interpolated and clipped and then filtered with a new filtering form. The filter used includes a IFFT in forward and inverse forms. It is used to remove the out-of-band (OOB) noise, and the in-band discrete signal was undistorted. This technique achieves a significant PAPR reduction without increasing the OOB power. The in-band distortion appears in some cases, with a very small effect on the overall BER in most systems.

The sliding widow algorithm (SLW) was proposed in [4], the authors reduced the PAPR by extending the SEFDM symbol period and sliding a time window across it. This algorithm has high computational complexity and was simulated using 16 subcarriers only. A less complex tone reservation PAPR reduction method for multicarrier signals with non-orthogonal frequency spacing (SEFDM) was proposed in [9]. The reduction in PAPR using this method reflects negatively on signal bandwidth (which has been increased). This method was proposed for systems that used a large number of subcarriers.

Jia *et al*. [10] proposed a joint algorithm to reduce the PAPR for OFDM and SEFDM systems for the SEFDM transmitter proposed in [3]. The modification of tone reservation method has been used to reduce (PAPR) of SEFDM was introduced in [11]. In this method, the PAPR was reduced by introducing additional subcarriers to the system bandwidth and the resulted spectral efficiency was degraded more than that of OFDM. In this work, a new PAPR reduction method for SEFDM systems is suggested. The proposed method has low complexity and has a negligible effect on the system bandwidth.

The optimized iterative clipping and filtering method is investigated in [12], which is used in mixed-numerology systems. Xing *et al*. [13] derived a new piecewise nonlinear companding scheme for PAPR reduction in OFDM systems. This method improves the power spectral density performance.

The paper layout was divided into five sections, this section which is the introduction, and the other sections are as follows; section 2 gives an overview of SEFDM system. In section 3 an explanation for PAPR and the suggested PAPR technique with SEFM system will be presented. In section 4 the results of simulation for the used technique will be presented and discussed. Finally, the conclusions for the technique used were shown in section 5.

2. SPECTRALLY EFFICIENT FDM (SEFDM)

The SEFDM system is a multicarrier modulation (MCM) scheme that utilize the transmission bandwidth better than the conventional OFDM system [2]. SEFDM uses the spectrum efficiently by reducing the spacing between subcarriers and/or transmission time. Thus, the rule of orthogonality is violated [1]. The SEFDM signal includes a stream of SEFDM symbols, which is carrying a block of N complex input data symbols, transmitted within T seconds. If there are N non-orthogonal and overlapping subcarriers in an SEFDM signal, each of them is modulated by a complex symbol input, then the SEFDM signal $x(t)$ is given by:

$$x(t) = \frac{1}{\sqrt{T}} \sum_{l=-\infty}^{\infty} \sum_{n=0}^{N-1} S_{l,n} e^{\left(\frac{j2\pi\alpha(t-lT)}{T}\right)} \quad (1)$$

α represents the bandwidth compression factor (BCF), l is the counter of the data symbols, T is the symbol period of SEFDM, N is the number of sub-carriers and $s_{l,n}$ is the complex symbol transmitted on the n^{th} sub-carrier in the l^{th} SEFDM symbol. BCF and α, represents bandwidth compressions (the bandwidth saving). The bandwidth saving equals to $(1-\alpha) \times 100\%$. For OFDM the value of α equals to one ($\alpha = 1$), but α is less than unity ($\alpha < 1$) for SEFDM [3], also the frequency spacing between successive sub-carriers is given by $\Delta f = \alpha / T$.

The SEFDM signal, in convention, is generated using modulator sets operating at the frequencies of the subcarriers, as shown in Figure 1. Each input data symbols, $S_0, S_1 \ldots\ldots S_{N-1}$, is modulated by non-orthogonal subcarriers, these subcarriers are generated by a set of independent oscillators. The complexity of this generation method limits the system applicability [3].

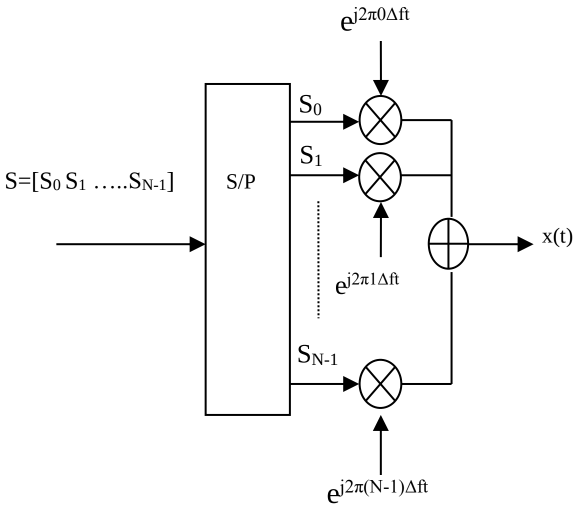


Figure 1. The block diagram for the SEFDM transmitter

To reduce the complexity of SEFDM system implementation, Kanaras *et al*. [14] implemented the SEFDM system using inverse discrete Fourier transform (IDFT). This proposed system is as shown in Figure 2. The SEFDM generation technique (that was introduced in [14], [15]) showed that there was a possibility to generate the SEFDM signal using an IDFT. This was done with a simple manipulation in the vectors of the input symbol. The manipulation has been done by insertion of zeros at each vector end, like zero padding manner.

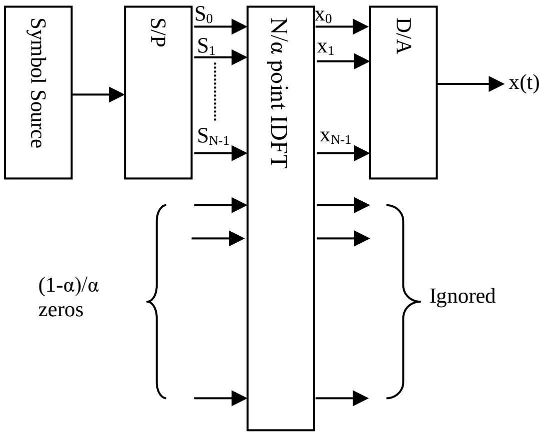


Figure 2. SEFDM transmitter block diagram using IDFT

On the other hand, the SEFDM receiver includes two stages. Stage one; is the demodulator, which consists of a set of N correlators that used to extract N statistics R[0] R[1]……..R[N-1] from the received signal $y(t)$, the extracted statistics will be used in the second stage to estimate the transmitted symbols. Stage two of the SEFDM receiver is the detector, which estimates the original transmitted symbols, $\hat{S}_0$, $\hat{S}_1$……$\hat{S}_{N-1}$, based on the statistics which collected from the demodulation stage as shown in Figure 3 [14].

The design of SEFDM system in [14] explains how the correlation between the carriers with their conjugates is implemented using standard DFT blocks. These correlation statistics which were generated by the DFT block are then entered into the detector that uses detection algorithms to fine estimate of the transmitted symbols [14].

The sepher detector (SD) is used in stage two of the SEFDM receiver. The SD detector achieves the maximum likelihood (ML) search with low complexity. This can be done by converting the search space to a sphere with multi-dimension and then looks for an acceptable solution which found within a given radius from the statistics point [16]-[18].

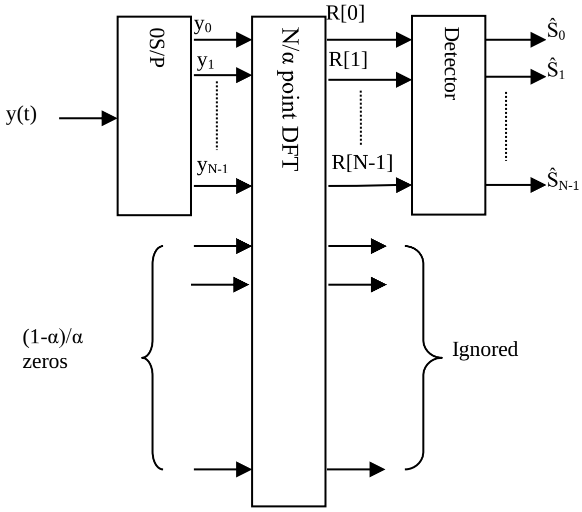


Figure 3. SEFDM Receiver block diagram using IDFT

3. PEAK TO AVERAGE POWER RATIO

The PAPR of a signal can be defined as the ratio of the maximum instantaneous power (peak) of the multicarrier transmitted signal to its mean power value. Let $x(t)$ represents a baseband OFDM signal transmitted, the PAPR is given by,

$$PAPR[x(t)] = \frac{\underset{0\le t\le T_s}{MAX}|x(t)|^2}{P_{av}} \tag{2}$$

P_{av} is the mean power of $x(t)$ which can be calculated in frequency domain, since IFFT is an orthogonal transform. T_s is the OFDM symbol duration [6].

3.1. PAPR in SEFDM

The instantaneous power $P_i(t)$ of a signal is a random variable depends on the input symbols vector **S**. $P_i(t)$ for the l^{th} SEFDM symbol is given by [9]:

$$P_i(t) = |x(t)|^2 \tag{3}$$

$$= \frac{1}{T}\sum_{n=0}^{N-1}\sum_{m=0}^{N-1} s_{l,n}s_{l,m}^{*} \exp\left(\frac{j2\pi\alpha t(n-m)}{T}\right) \tag{4}$$

As seen from (3), the instantaneous power of the SEFDM signals dependents on α. The peak signal power P_{peak} is the maximum value of $P_i(t)$:

$$Ppeak = max(Pi\ (t)) \tag{5}$$

and the average power P_{av} can be found from (3) as shown (6).

$$P_{av} = E\left[\sum_{n=0}^{N-1}\sum_{m=0}^{N-1} s_{l,n}s_{l,m}^{*} \exp\left(\frac{j2\pi\alpha t(n-m)}{T}\right) dt\right] \tag{6}$$

The transmitted symbols and the subcarriers are independent; this independency allows simplifying P_{av} by distributing the expectation operator between the symbol's element and the sub-carrier's element of (6) as shown in (7):

$$P_{av} = \sum_{n=0}^{N-1} E\left[\left|s_{l,n}\right|^2\right] + \sum_{n=0}^{N-1}\sum_{m=0,n\neq m}^{N-1} E\left[s_{l,n}s_{l,m}^{*}\right] sinc\big(\pi\alpha(n-m)\big)e^{\left(\frac{j\pi\alpha t(n-m)}{T}\right)} \tag{7}$$

3.2. Proposed clipping and filtering technique

In our proposed method, the amplitude of the IFFT output stage for the SEFDM modulator is applied to a hard limiter. This limiter will limit the amplitudes within a certain range [19], [20]. The filtering operation after clipping (applying the hard limit) is designed to reduce or cancel OOB distortion [6]. The output time domain SEFDM signal from the IFFT, will be clipped. The clipping operation will be done as:

$$C = f(x) = \begin{cases} \sqrt{c_R * E[|x|^2]} * \frac{x}{|x|}, |x|^2 > c_m \\ x, |x|^2 \leq c_m \end{cases} \tag{8}$$

where C is the time domain output signal, and

$$\mathrm{c_m} = \mathrm{c_R} * \mathrm{E}[|\mathrm{x}|^2] \tag{9}$$

- c_m is the threshold clipping limit, $|x|^2$ is the signal power and $E[|x|^2]$ is the expected (average) value of the signal power.
- c_R is the clipping ratio and it is defined as the division of the clipping limit by the average power of the original baseband signal.

In general, clipping is done at the transmitter side, however, the receiver needs to predict the clipping which was done and then to process the received SEFDM symbol. In most cases one clipping is done per SEFDM symbol, hence two parameters must be estimated by the receiver size and clip location. However, the estimation of these parameters is difficult, therefore, the clipping method causes both in band distortion and out of band radiation for the SEFDM signals. The system performance in this case is degraded because the bit error rate is increased, and the spectral efficiency is reduced. The out of band radiation can be reduced using filtering operation, which appears after clipping. On the other hand, peak re-growth may be caused by filtering, as a result, the signal may exceed the clipping threshold at certain points after clipping and filtering operation [21], [22].

The overall peak re-growth can be reduced by a repeated clipping and filtering (RCF) mechanism, which is used to get an acceptable PAPR value. Figure 4 shows the block diagram of the RCF PAPR reduction technique [9]. As shown from Figure 4 the input vector $A_0, \ldots, A_{N-1}$, which are in frequency domain is transformed to time domain using an IFFT with oversize in the first stage. The oversampling process is done by adding $N(l-1)$ zeros in the middle of the vector, where N is the number of subcarriers in SEFDM symbol [21].

This procedure gives the trigonometric interpolation of the signal in the time domain, which will achieve optimum interpolation if the input signal has frequencies integrated over the window of the FFT (the SEFDM has this property) [23]. The amplitude of the complex time domain signal that is above the clipping limit will be cut to the clipping threshold value while maintaining the complex signal phase [24].

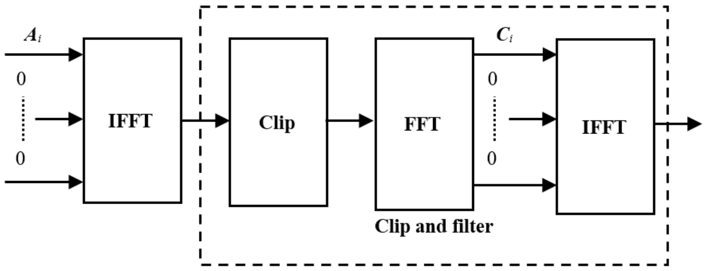


Figure 4. Repeated clipping and filtering mechanism to reduce the PAPR for SEFDM

The clipping signal is filtered in frequency domain in the next stage to decrease OOB power that appears because of clipping. The frequency domain filter includes two FFT stages [8]. In the last stage, the clipped signal c, which is in the time domain, is transformed to frequency domain again using FFT. The clipped signal has in-band and OOB frequency components. The in-band elements are passed unchanged to the inputs of the second stage IFFT, while the OOB elements are set to zero [20]. This procedure is repeated, for several iterations, which are chosen between one and four.

4. RESULTS AND DISCUSSION

This section will discuss the results of the proposed system simulation. The proposed PAPR reduction method with SEFDM system block diagram is shown in Figure 4. The system is tested under frequency-selective fading channel modeled by ITU for Pedestrian-A (Ped-A) channel which has 4 taps [25] given in Table 1.

Table 1. Ped-A channel parameters

Parameter	Value			
Path Number	1	2	3	4
Path delay in sec	0	$110e^{-9}$	$190e^{-9}$	$410e^{-9}$
Average Path Gain in dB	0	-9.7	-19.2	-22.8

The simulations parameters used here are listed in Table 2. The PAPR was computed statistically using the complementary cumulative distribution function (CCDF). The CCDF is defined as the probability of the PAPR of a signal greater than a threshold value, γ, which is Pr $\{PAPR > \gamma\}$.

Table 2. Simulation parameters

Parameter	Value
Number of subcarriers	90
Bandwidth compression factor α	0.8
Frequency spacing	12 kHz
Guard interval	5 μsec
Bandwidth	1.4 MHz
Channel type	ITU Pedestrian A
Clipping ratio CR	4,3,2,1.5
Simulation length	100 sub-frame
Channel estimation	Perfect
Receiver	Sphere detector

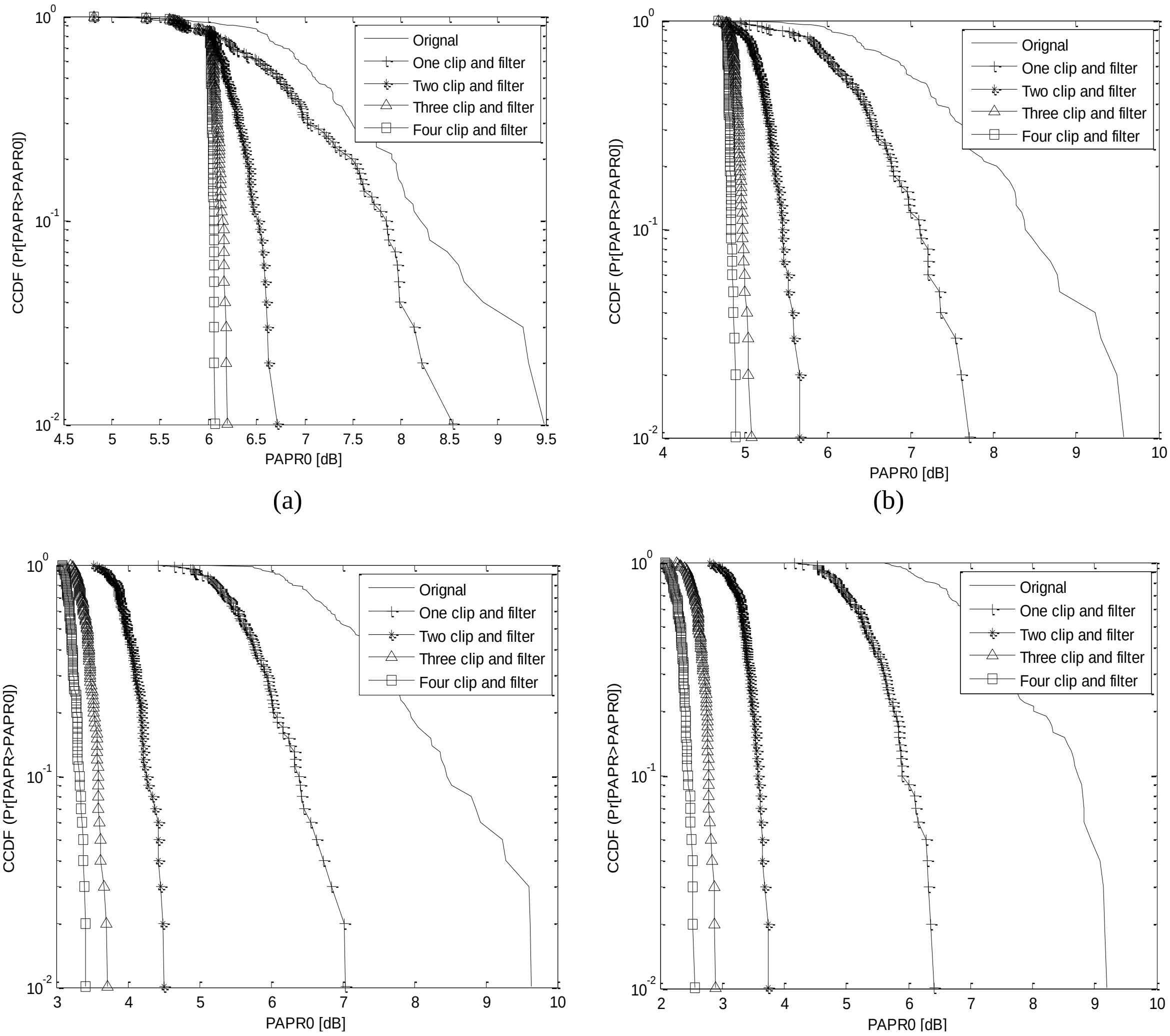
Figure 5 illustrates the repetition clipping (CR) and filtering effect on PAPR for different CR. Figure 5(a), (b), (c) and (d) shows the PAPR for different values of CR 4, 3, 2 and 1.5 respectively. As shown from this Figure, the PAPR reduction was done using four clipping and filtering steps for each CR value.

As mentioned in section 3.2, after each clipping a filtering operation is needed to reduce the out of band radiation and this will cause a peak re-growth (some peaks in the clipped filtered signal will exceed the clipping threshold), to overcome this problem the clipping and filtering operation must be done in multiple steps. As shown in Figure 5(a), after each clipping and filtering step the PAPR will be reduced, the PAPR was around 8.4 dB after the first step, while after the fourth step it becomes around 6.1 dB, which is a 2 dB reduction. This reduction (between step 1 and step 4) will increase as the CR increases, in Figure 5(d) the total PAPR reduction between step 1 and step 4 of clipping and filtering operation was about 4 dB.

The original PAPR without any peak limitation was 16.2648 dB, this ratio decreased to 13.6924 dB when the clipping ratio CR was 4 (see Figure 5(a)) and to 5.9996 dB when CR decreased to 1.5 (Figure 5(d)), also the BER for each case was measured. Four steps of clipping and filtering were chosen because these steps provide good performance enhancement with acceptable additional complexity, more enhancement can be done to the PAPR reduction but this will increase system complexity.

Figure 6 shows the BER vs. SNR for SEFDM system with different CR. As shown from the figure, the BER increases with the decrease of clipping ratio, this occurs because the clipping process cuts the peaks of the original signal to the pre-sited limit that cause a distortion in the signal, which will reduce the overall system performance. Each time the CR decreases (cutting more percentage from the signal), the original signal will lose more of its information causing an increment in the transmission error. As a result, the overall system signal to noise ratio will be reduced.

This sacrifice in system performance is required to reduce the power losses in the transmitter RF power amplifier and increase its efficiency (narrowing its linear operation region). This enhancement is important specially for limited power supply transmission devices (like mobile phones) because they have limited battery supply and reducing the power loss of its transmitter RF power amplifier (one of the main power consumption blocks of any transmitter) will increase its battery life.



(a) (b)

(c) (d)

Figure 5. CCDF of PAPR for SEFDM system with (a) CR = 4, (b) CR=3, (c) CR=2, and (d) CR=1.5

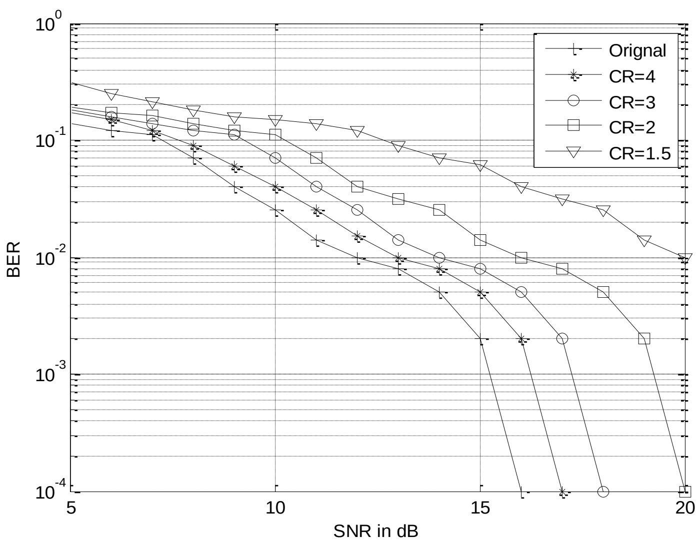


Figure 6. Performance of SEFDM with different clipping ratio (CR)

As presented in Table 3, The best PAPR reduction is when CR equals to 1.5, but this value will generate the highest BER (high percentage of the original signal information will be removed) and the lowest reduction in PAPR is when CR equals to 4 (in this case the BER will be slightly affected because smallest percentage of the original signal information removal). From Table 3, we can observe that the best tradeoff between PAPR value and BER is when CR=3, in this case the PAPR reduction is more than half the original value and the performance decreases by 2 dB only.

Table 3. Signal-to-noise (SNR) for different clipping ratio

Clipping ratio	PAPR IN dB	SNR FOR BER=10^{-4}
non	16.2648	16
4	13.6924	17.32
3	11.2687	17.87
2	7.9146	19.87
1.5	5.9996	35

5. CONCLUSION

This paper presented a clipping and filtering PAPR reduction method in SEFDM. This low complexity proposed system has higher performance compared to other available PAPR reduction methods that are more complex than this proposed one, in addition, this system does not change the total transmission bandwidth. A simulation model for the proposed PAPR reduction method was developed, and the simulation results show that when CR reduced, the PAPR is improved but the BER increased. The CR gives a direct proportion with the PAPR and a reverse fit with BER. To overcome the out of band radiation during the PAPR reduction, the clipping and filtering operation was done in four steps. The best BER for the proposed system is when CR=4, however, it has the worst PAPR. When CR=1.5 the system shows the best reduction in PAPR but gives the worst value of BER compared with the other values of CR. The optimum value for CR was chosen to be 3, at this value the BER was decreased by only 2 dB, while the PAPR reduction was more than half compared to the SEFDM system without any PAPR reduction. The PAPR can be reduced further by increasing the number of clipping and filtering steps, this will increase system complexity by producing more mathematical operations. Four steps of clipping and filtering was selected because it provides good PAPR reduction without adding too much complexity to the proposed system.

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