Int. J. Electron. Commun. (AEÜ) 69 (2015) 573–578

Contents lists available at ScienceDirect

International Journal of Electronics and Communications (AEÜ)

journal homepage: www.elsevier.com/locate/aeue

PAPR reduction in OFDM systems using peak insertion

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ARTICLE INFO

Article history:
Received 1 September 2013
Accepted 16 November 2014

Keywords:
PAPR reduction
OFDM
Peak insertion

ABSTRACT

A technique for Peak-to-Average Power Ratio (PAPR) reduction of Orthogonal Frequency Division Multiplexing (OFDM) signals by Peak Insertion (PI) is proposed in this paper. PI depends on the duality property of the DFT and PAPR duality of an impulse. A relatively high peak is inserted to the OFDM symbol in the frequency domain such that the PAPR of the transmitted time domain signal is reduced. PAPR reduction up to about 11 dB at PAPR CCDF of 10^{-4} is achievable by PI, but at the expense of increased signal power, which can be reduced by scaling to the desired level without affecting its PAPR. Computer simulation tests show that a tradeoff can easily be made between BER and the PAPR of the transmitted signal to achieve a desired system performance. The PI technique does not require any sort of side information transmission, searching, optimization, and iterative or parallel application of IDFT. PI is faster, simpler, and capable of achieving greater PAPR reduction as compared with other similar techniques which result in transmitted power increase, and therefore, it seems to be suitable to be used for OFDM signal PAPR reduction.

1. Introduction

Due to its high spectral efficiency, immunity to frequency selective fading, and high data rate, Orthogonal Frequency Division Multiplexing (OFDM) became a popular modulation technique in digital communication systems [1–7]. OFDM is the modulation standard for the IEEE802.11a/g wireless LANs, World wide Interoperability for Microwave Access (WIMAX), Digital Audio Broadcasting (DAB), Digital Video Broadcasting (DVB), Asymmetric Digital Subscriber Line (ADSL), etc. [2–5,7–9].

OFDM systems suffer mainly from the sensitivity to frequency offset and high Peak-to-Average Power Ratio (PAPR) of the transmit signal [1,2,4,5,7–10]. The latter is the major drawback of OFDM systems. The PAPR of a signal $x(n)$ is defined as a ratio by

$$\mathrm{PAPR} = \frac{\max \left|x(n)\right|^2}{E[\left|x(n)\right|^2]} \tag{1}$$

where $|x(n)|$ is the magnitude of $x(n)$, and $E[\cdot]$ denotes the expectation operation.

High PAPR occurs due to the summation of many subcarrier-modulated signals and the manner in which their phases can align in the frequency domain. A high PAPR requires a wide dynamic range high power amplifier (HPA) at the transmitter [11]. That is, the power amplifier needs to be backed-off to accommodate high peaks. This results in significant reduction in transmission power which leads to a very low power efficiency.

There are many techniques for PAPR reduction in OFDM systems. The basic techniques include amplitude clipping, clipping and filtering, coding, tone reservation (TR), tone injection (TI), active constellation extension (ACE), partial transmit sequence (PTS), selective mapping (SLM), and interleaving [6,7,9,12]. In the literature, many approaches have been proposed to reduce PAPR depending on modifications and optimizations to these basic techniques.

Amplitude clipping is the simplest technique for PAPR reduction. It causes both in-band and out-of-band distortion. The former results in degradation in error performance [13] and it cannot be reduced by filtering. While out-of-band radiation reduces spectral efficiency, it can be reduced by filtering, but at the expense of a risk of some peak regrowth [12]. Repeated clipping and filtering operation can be used to reduce the overall peak regrowth [12,14]. The deleterious effects of amplitude clipping may be reduced when it is used together with other techniques. However, any gained advantages are at the expense of increased system complexity [15,16].

Coding can also be used to reduce PAPR. The idea is to select the code words that minimize the PAPR for transmission [9,12]. This approach suffers from data rate loss and from the need to perform an exhaustive search to find the best codes and store large lookup tables for encoding and decoding, especially for large number of subcarriers.

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http://dx.doi.org/10.1016/j.aeue.2014.11.009
1434-8411/

Similarly, TR based approaches that reserve a number of tones, called Peak Reduction Carriers (PRC), need to perform an exhaustive search to find the optimum PRC amplitudes and phases that minimize the PAPR [12]. Usually, PRCs increase the required bandwidth and the transmit signal power, which is a common problem with ACE and TI based techniques [12]. Modifications to the latter techniques are presented in [17,18] with added system complexity. However, PAPR reduction techniques based on interleaving, PTS, and SLM also have the problem of the need to search to find the best permutation or phase factor combination, for every OFDM symbol before it can be transmitted. The search complexity increases exponentially with the number of subcarriers [3,4,10,12]. Various techniques have been suggested to reduce the search complexity [3,4,6,10,19–25]. These methods achieve significant reduction in search complexity with marginal PAPR reduction.

In this paper, a PAPR reduction technique using peak insertion (PI) is proposed and examined. The proposed technique depends on the duality property of the DFT and the conclusion that the PAPR of a signal in one domain (time or frequency) is reversely proportional to the PAPR of the same signal in the other domain. In the proposed technique, a single relatively high peak is simply inserted into the OFDM symbol in the frequency domain to increase its PAPR and reduce its PAPR in the time domain. Effectively, this is similar to what is done by the TI and ACE techniques, but the proposed technique does it using a single tone rather than many PRCs, and the value of the inserted peak is determined without any PAPR optimization iterations. Therefore, the proposed technique is simpler, faster and the effects of the inserted peak on PAPR and other system parameters are much easily controllable.

The remainder of the paper is organized as follows: Section 2 shows how the duality property of the DFT leads to the reverse proportionality between the PAPR values in time and frequency. Section 3 presents in details the effect of inserting a peak into an OFDM symbol on the PAPR of the transmitted signal. Then, the model of the proposed system is presented in Section 4 and its BER performance is evaluated in Section 5. Finally, conclusions are given in Section 6.

2. PAPR duality

The symmetry in the DFT equations leads to the symmetry or duality property. That is, if $g(n)$ is an N-point discrete time domain signal and $G(k)$ is its DFT,

$$g(n)\overset{\text{DFT}}{\leftrightarrow}G(k)$$

then,

$$G(n)\overset{\text{DFT}}{\leftrightarrow}g(k)$$

where the DFT equations are defined by:

$$G(k)=\frac{1}{\sqrt{N}}\sum_{n=0}^{N-1}g(n)e^{\frac{-j2\pi nk}{N}}\quad \text{for}\quad k=0,1,\ldots,N-1 \tag{2a}$$

and

$$g(n)=\frac{1}{\sqrt{N}}\sum_{k=0}^{N-1}g(k)e^{\frac{j2\pi nk}{N}}\quad \text{for}\quad n=0,1,\ldots,N-1 \tag{2b}$$

A simple and useful example for the present analysis is the impulse function. Let

$$g(n)=\delta(n)\quad \text{for}\quad 0\le n\le N-1 \tag{3}$$

Then,

$$G(k)=\frac{1}{\sqrt{N}}\quad \text{for}\quad 0\le k\le N-1 \tag{4}$$

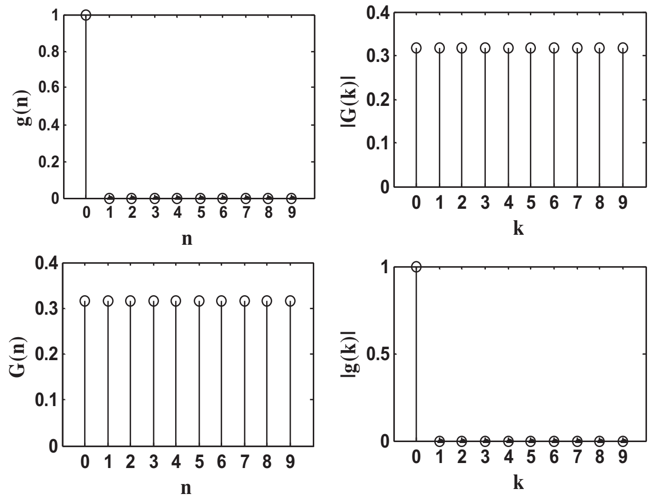

Fig. 1. DFT duality.

However, if we have the constant dc signal in the time domain, $G(n)=1/\sqrt{N}$, then its DFT is the impulse function $\delta(k)$ which is $g(k)$, as shown in Fig. 1, for $N=10$.

It is interesting to note that due to the nature of the DFT, the PAPR of the function $g(\cdot)$ is high with respect to the PAPR of $G(\cdot)$. Then, it seems that the duality property applies to the PAPR. Recalling the linearity property of the DFT, the effect of superimposing an impulse to a signal in one domain is raising the function sample magnitude values in the other domain by a $1/\sqrt{N}$ dc level. That is, for the DFT pair $g(n)$ and $G(k)$, when a relatively high valued impulse is inserted into the samples of $g(n)$, it becomes

$$g_\alpha(n)=g(n)+\alpha\delta(n-n_0) \tag{5}$$

where α is the strength of the inserted impulse and $\alpha>>\left|\max\{g(n)\}\right|$, inserted in the (n_0+1)th sample. Then,

$$\text{PAPR}\{g_\alpha(n)\}>\text{PAPR}\{g(n)\} \tag{6}$$

The DFT of $g_\alpha(n)$ is given by

$$G_\alpha(k)=G(k)+\frac{\alpha}{\sqrt{N}}e^{\frac{-j2\pi kn_0}{N}} \tag{7}$$

For α being much greater than the maximum sample value of $g(n)$, it will also be the dominant component of every sample of $G_\alpha(k)$, and hence its maximum and mean square value (msv), making them closer to each other in value as compared to their values for $G(k)$. The result is

$$\text{PAPR}\{G_\alpha(k)\}<\text{PAPR}\{G(k)\} \tag{8}$$

Therefore, it is concluded that the PAPR of a signal in one domain can easily be controlled (decreased) just by inserting a relatively high impulse (peak) to its image in the other domain, however, with an increase in the power of the signal. This idea can easily be applied to OFDM signal PAPR reduction.

3. Effect of PI on OFDM signal PAPR

In this section, a detailed analysis for the effect of PI on the PAPR of OFDM signals, is presented. The proposed PI technique is implemented by adding an impulse to the original OFDM symbol in the frequency domain. The resulting signal $Y(k)$ is given by

$$Y(k)=X(k)+\alpha\delta(k-k_0)\quad \text{for}\quad 0\le k\le N-1 \tag{9}$$

where $X(k)$ is the original OFDM symbol