

Peak to Average Power Ratio(PAPR) Reduction Techniques in OFDM: An Overview

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ABSTRACT: With the advancement in wireless communication systems and the increase in demand for high data rates, Orthogonal Frequency Division Multiplexing (OFDM) has proved to be a key technology for the future 3G and 4G wireless communication system. OFDM offers a considerable high spectral efficiency, multipath delay tolerance, immunity to the frequency selective fading channels and power efficiency. However, one major disadvantage of OFDM system is the high PAPR (Peak to Average Power Ratio) of the transmitted signal. A number of techniques are employed to reduce PAPR ratio. In this paper, various techniques proposed for PAPR reduction techniques have been discussed along with the criteria of their selection. This paper provides an intuitive knowledge of the concept used with the comprehensive and comparative review of some PAPR reduction techniques.

KEYWORDS: OFDM, IFFT, PAPR, PAPR reduction techniques, signal scrambling, signal distortion

I. INTRODUCTION

With the growing mobile radio communication systems, Orthogonal Frequency Division Multiplexing(OFDM) has been considered as the essence of most 4G communication systems fixed Wi-Fi system, mobile Wi-Fi system fixed WiMAX system mobile WiMAX system and Long Term Evolution (LTE system)[1]. OFDM is a Multi-carrier Modulation (MCM) scheme in which a large number of closely spaced orthogonal sub-carrier signals are used to carry data on several parallel data streams or channels. Unlike Frequency Division Multiple Access (FDMA), OFDM uses the spectrum much more efficiently by spacing the channels closer together. OFDM is a promising technology of the future communication system.

Amongst all attractive advantages of OFDM, there are some disadvantages of OFDM like high PAPR (Peak to Average Power Ratio) and BER (Bit Error Rate). The peak to average power ratio (PAPR) of a transmitted signal is one of main challenges in wideband multi-carrier systems that use orthogonal frequency division multiplexing (OFDM) or multiple-input multiple-output (MIMO) OFDM.

In order to utilize the technical features of OFDM, it is necessary to analyze the characteristics of PAPR including its distribution and reduction in OFDM systems. The distribution of PAPR bears stochastic characteristics in OFDM system and can be expressed in terms of Complementary Cumulative Distribution Function (CCDF).

Various approaches have been proposed to reduce PAPR which are classified into different approaches: clipping technique, coding technique, probabilistic (scrambling) technique, adaptive predistortion technique, and DFT-spreading technique.

An effective PAPR reduction technique should give the best tradeoff between the capacity of PAPR reduction and transmission power, data rate loss, implementation complexity and Bit-Error-Ratio (BER) performance etc.

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II. DISTRIBUTION OF OFDM SIGNAL

Figure 2.1 represents the end-to-end block diagram of an OFDM system. Let a block of N data symbols $X = (X_k, k = 1, 2, \dots, N - 1)$, of vector X , be transmitted in parallel such that each symbol (X_k) modulates a subcarrier f_k ($k = 1, 2, \dots, N - 1$), where N is the number of subcarriers. The N subcarriers are chosen to be orthogonal, such that $f_k = k\Delta f$, where $f_k = \frac{1}{T}$ and T is the OFDM symbol period.

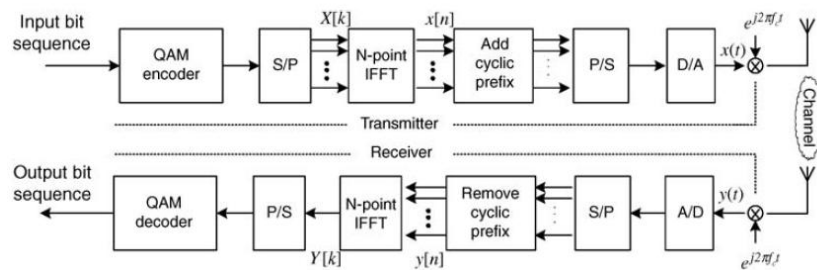


Figure 2.1: Block Diagram Of OFDM System

The complex envelope of the OFDM signal, $x[n]$, after IFFT at the transmitter can be expressed as

$$x[t] = \frac{1}{N} \sum_{k=0}^{N-1} X[k] e^{j2\pi f_k t}, \quad t \in [0, T]$$

With large N , OFDM signal approaches Gaussian distribution with mean zero and variance σ^2 with Probability Density Function

$$F\{x(t)\} = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{[x(t)]^2}{2\sigma^2}}$$

III. PAPR: AN OVERVIEW

In general, PAPR (Peak to Average Power Ratio) of OFDM signal $x(t)$ is defined as the ratio of peak power to average power. Mathematically, it can be expressed as

$$PAPR\{x(t)\} = \frac{\max_{0 \leq t \leq NT} [|x(t)|^2]}{P_{av}}$$

where P_{av} is the average power of $x(t)$.

The PAPR of discrete time baseband signal may vary from that of continuous time signal $x(t)$. However, the PAPR of discrete time signal can be made comparatively same if the continuous time signal $x(t)$ is L -times oversampled. L -times oversampled time-domain samples are LN -point IFFT of the data block with $(L-1)N$ zero-padding. Therefore, the oversampled IFFT output can be expressed as

$$x[n] \triangleq \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k e^{j2\pi \frac{k}{LN} n}$$

The PAPR for L -times oversampled time domain OFDM signal can be expressed as

$$PAPR\{x[n]\} = \frac{\max_{0 \leq n \leq NL-1} [|x[n]|^2]}{E[|x[n]|^2]}$$

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IV. PAPR REDUCTION TECHNIQUES

As a high PAPR degrades the performance of an OFDM system, it is necessary to reduce the PAPR. Several techniques have been proposed to reduce PAPR in OFDM systems. In this section, we discuss these techniques briefly.

The PAPR reduction techniques are divided into two categories: signal scrambling techniques and signal distortion techniques.

4.1 SIGNAL SCRAMBLING TECHNIQUES

Signal scrambling techniques scramble the codes to reduce PAPR. The different proposed signal scrambling techniques are Block Coding Techniques, Selected mapping (SLM), Partial Transmit Sequence (PTS), Interleaving Technique, Tone Reservation (TR) and Tone Injection (TI).

4.1.1 Block Coding Techniques

The Block Coding Technique was first proposed by Wilkinson and Jones in 1995[11]. The main idea behind this technique was to select codeword which does not contain excessive peak envelope powers. A suitable set of code words is selected for any number of carriers, any M-ary phase modulation scheme, and any coding rate. Different encoding/decoding techniques are implemented on these code words[2]. The codeword are selected such that they also offer error detection and correction.

The simplest approach to implement block coding technique is to sequentially search the Peak Envelope Power for all possible code words for a given length and a given number of carriers. This sequential searching is appropriate for short codes. For longer code words, many sophisticated searching techniques (like natural algorithms) can be employed. With the selected code words, the encoding and decoding techniques can be employed using a look-up table or combinatorial logic exploiting the mathematical structure of the codes.

4.1.2 Sub-Block Coding Techniques

The introduction of Sub-block coding (SBC)[5] was based on the observation that all $\frac{3}{4}$ rate systematically coded block codes with the last bit as an odd parity checking bit demonstrate lowest peak envelope power. This coding scheme is termed as systematic odd parity checking coding (SOPC).

In this technique, a 3-bit data word is mapped onto a 4-bit code word. Then, the set of permissible code words with the lowest PAPRs in the time domain is chosen. The code rate must be reduced to decrease the desired level of PAPR. It is found that more than 3 dB reduction in PAPR can be achieved by using sub-block coding technique.

4.1.3 Selected Mapping

In selected mapping technique[9], for PAPR reduction, the input data block $X = [X[0], X[1], \dots, X[N-1]]$ is multiplied with M different sequences $S^m = [S_0^m, S_1^m, \dots, S_{N-1}^m]^T$ where $S_v^m = e^{j\varphi_v^m}$ and $\varphi_v^m \in [0, 2\pi)$ for $v = 0, 1, \dots, N-1$ and $m = 1, 2, \dots, M$ which generate a modified data block $X^m = [X^m[0], X^m[1], \dots, X^m[N-1]]^T$. IFFT of M independent sequences $\{X^m[v]\}$ are taken to produce the sequence $x^m = [x^m[0], x^m[1], \dots, x^m[N-1]]^T$ amongst which the one with the lowest PAPR is selected for transmission[18]. The SKM technique can handle any number of carriers. The drawback of SLM technique is that the overhead of side information needs to be transmitted to the receiver.

4.1.4 Partial Transmit Sequence (PTS)[12]

In Partial Transmit Sequence (PTS) technique, the input data block of N symbols is partitioned into disjoint sub blocks of equal size which are consequently located[17]. Each partitioned sub block is multiplied by a corresponding phase factor, the corresponding time domain signal with lowest PAPR is selected and transmitted. The PAPR performance of the PTS technique is affected not only the number of sub blocks, and the number of the allowed phase factors, but also by the sub block partitioning.

4.1.5 Interleaving

In this technique, the high PAPR of highly correlated data can be reduced if long correlation patterns are broken down.

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An adaptive interleaving technique has also been proposed to reduce complexity of the scheme[3]. The key idea behind adaptive interleaving is to establish an early terminating threshold. Rather than searching all the interleaved sequences, the search is terminated as soon as the PAPR value reaches below the threshold.

The interleaving patterns for the Interleavers are obtained by OGA (Orthogonal Genetic Algorithm) optimization algorithm. The generated Interleavers are mapped with original OFDM frame to generate the permuted data block. The PAPR of permuted data block is computed using IDFT operations and the data block with the lowest PAPR is then chosen for the transmission.

This interleaving method of PAPR reduction is less complex than the PTS method but achieves comparable results. The scheme does not guarantee PAPR reduction and PAPR value of N , for the worst case. Therefore, higher order error correction method should be employed in addition to this technique.

4.1.6 Tone Reservation[13]

Tone Reservation (TR) is an efficient technique to reduce PAPR in OFDM signals by reserving a small set of tones.. In this technique, N subcarriers are partitioned into data tones and peak reduction tones (PRTs). The key idea in Tone Reservation technique is to determine the PAPR reduction vector c to be added to the original time domain signal x to reduce the PAPR. Let $c = \{c_n | n = 1, 2, \dots, N - 1\}$ denote the complex symbols to be used for tone reservation at the reserved tones. After tone reservation processing, the data vector changes to $x + c$ and the resultant OFDM signal is given as

$$\tilde{X} = IFFT(x + c) = X + C$$

where $C = IFFT(c)$.

In this technique, the amount of PAPR reduction depends on the numbers of reserved tones, their location within the frequency vector, and the amount of complexity. Tone Reservation is a less complex method with no special receiver operation, and there is no need for side information.

4.1.9 Tone Injection (TI)

Similar to TR, TI approach also uses additive correction approach to optimize C . The key idea of TI technique[13] is to increase the size of constellation so that each of the points in the original constellation can be mapped onto several equivalent points in the expanded constellation where the extra degrees of freedom can be subjugated for PAPR reduction. The Tone Injection technique does not utilize additional subcarriers for peak reduction tones (PRTs), therefore, it does not incur any loss of data rate. The demerits of TI technique includes the injected signal which occupies the frequency band as the information bearing signals and requires extra IFFT operation which makes the technique more complex.

4.2 SIGNAL DISTORTION TECHNIQUES

The signal distortion techniques reduce high peaks directly by distorting the signal former to amplification. Different proposed signal distortion techniques include Clipping and Filtering, Peak Windowing, Envelope Scaling, Peak Reduction Carrier, Random Phase Updating and Companding.

4.2.1 Clipping and Filtering

Clipping is the simplest PAPR reduction technique. In this technique the signal above a pre-specified level is clipped off[4]. In this approach, the amplitude peaks are corrected using a suitable correcting function in such a way that a given amplitude threshold of the signal does not exceed after correction. Usually, clipping is performed at the transmitter side. Therefore, the receiver needs to approximate the clipped portion and to compensate the received OFDM symbol accordingly.. However, it is difficult to obtain this information. Clipping causes in-band signal distortion, which results in BER performance degradation. Another demerit of clipping technique of PAPR reduction is out-of-band radiation, which imposes out-of-band interference signals to adjacent channels.

The out-of-band radiation can be reduced by Filtering but at the expense of peak regrowth. The propose scheme of Clipping and Filtering requires the signal to be oversampled by a factor of four and normalized so that the signal power is one[10].

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This scheme can be used for any number of sub carriers and does not require any redundancy.

4.2.2 Peak Windowing

Peak Windowing technique[14] is an improved clipping technique which attenuates peak signals by using narrowband windows such as Gaussian window, Cosine window, Kaiser window or Hamming window. This minimizes out-of-band radiation. The OFDM signal is multiplied with these windows; resulting in a spectrum which is a convolution of the original OFDM spectrum with the spectrum of the applied window. Ideally, the window should be as narrow band as possible. On the other hand, in the time domain, the window should not be too long because many signal samples is affected thus increasing the BER. Peak Windowing technique reduces PAPR down to about 4dB, independent of the number of sub carriers. The SNR loss caused by the signal distortion is limited to about 0.3dB.

4.2.3 Envelope Scaling

This technique, proposed by Foomooljareon and Fernando[15], can be implemented only in the case when envelopes of all sub carriers are equal, as in PSK modulation. In this technique of PAPR reduction, the input envelope of some sub carriers is scaled before implementing the IFFT operation. The output which gives the lowest PAPR is sent to the system. As the envelopes of all the sub carriers are equal, the receiver of the system doesn't need any side information for decoding the receiver sequence.

When the scheme used in QAM modulation, the scaling of carrier envelope will result in serious BER degradation.

4.2.4 Peak Reduction Carrier

The technique proposed by Tan and Wassell[16] involves the use of a higher order modulation scheme to represent a lower order modulation symbol. The amplitude and phase of the PRCs is allowed to lie within the constellation region representing the data symbol to be transmitted. The use of higher order modulation scheme for the representation of lower order symbol results in an increased probability of error, thus worsening the overall BER performance. So there exists a tradeoff between PAPR reduction and BER.

4.2.5 Random Phase Updating

In this technique proposed by Nikookar and Lidsheim[7], random phase is generated and assigned to each carrier. This phase is updated by a random increment till the peak value of the OFDM signal goes below a certain threshold level. After successful updating of phase shift, the PAPR is calculated and the iteration is continued till the minimum threshold level is achieved or the maximum number of iterations has been reached. The random phase increment can be considered uniform or Gaussian and these increments should be known to both transmitter and receiver. For this, a large amount of side information is required. The efficiency of the algorithm depends on the selected threshold level and consequently the number of iterations and not on the number of sub carriers.

4.2.6 Companding

Non-linear companding[8] can be considered as one of the efficient technique to reduce PAPR and increase the OFDM efficiency. The OFDM signal can be considered as Gaussian distributed and thus companding proves to be an appropriate method for PAPR reduction. One of the non-linear companding technique is μ -law companding which mainly focuses on enlarging signals with small amplitude and keeping peak signals unchanged, thus increasing the average power of the transmitted signals which results in exceeding the saturation region of HPA.

Non-linear companding may introduce companding noise which are the noises caused by the peak regrowth after DAC to generate in-band distortion and out-band noise. Another demerit of companding is the quantization error which is significantly large for large signals. This degrades the BER performance of the system. So, there is tradeoff between PAPR and BER performance of the system.

V. CRITERIA FOR SELECTION PAPR REDUCTION TECHNIQUE

Any PAPR reduction technique, with PAPR reduction, also affects other characteristics of the system. Thus, while selecting a specific PAPR reduction technique, many other factors need to be considered.

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- **Capability of PAPR reduction:** It is the most important factor need to be considered as some of the techniques like Clipping may have harmful effects like in-band distortion and out-of-band distortion.
- **Bandwidth consideration:** Bandwidth is an important factor need to be considered as it affects other factors of the system like bandwidth expansion which is caused due to side information carried (like phase factors in PTS). The expansion of bandwidth results in data code rate loss.
- **Implementation complexity:** Implementation and computational complexity are another factor which bare needed to be considered. While implementing reduction technique, both time and hardware requirement should be minimal.
- **Power consideration at the transmit signal:** Some techniques lead to power increase in the transmitted signal after PAPR reduction like Tone Reservation as some of the power is used for peak reduction carriers.
- **BER consideration:** Some PAPR reduction techniques like PTS, SLM leads to degradation in BER performance of the system. Thus, it is an important factor need to be looked at. If the side information is received in error at receiver, may also degrade the BER performance with erroneous data frame.
- **Data rate consideration:** Some techniques require reducing data rate. For example, in Block Coding Technique, a one out of four information symbol is required to control PAPR. In some techniques, like Interleaving, data rate is reduced due to side information.
- **Spectral spillage:** Any PAPR reduction technique should not disturb the attractive features of OFDM. Therefore, it is required to avoid the spectral spillage in the PAPR reduction.

V. COMPARISON OF DIFFERENT PAPR REDCTION TECHNIQUES

Figure 5.1 shows a graph relating Complementary Comprehensive Distribution Function (CCDF) with PAPR of different PAPR reduction techniques. From the graph, it can be observed that the performance of different PAPR reduction techniques is different.

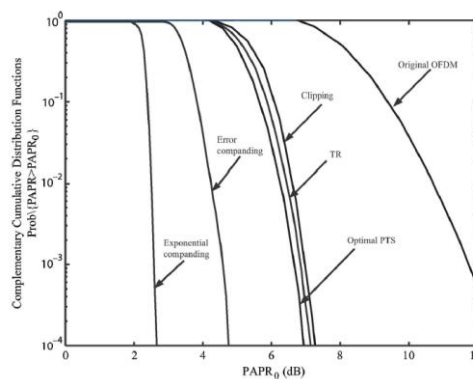


Figure 5.1 Comparisons Of CCDF for Different PAPR Reduction Techniques.

For example, when $CCDF=10^{-2}$, the PAPR for exponential companding, error companding, PS, TR, Clipping technique and Original OFDM is 2.6 dB, 4.5 dB, 6.5 dB, 6.8 dB, 6.9 dB and 10.9 dB respectively. An efficient PAPR reduction technique should give the lowest PAPR while keeping a minimal BER level.

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Type / Parameter	Distortion less	Power Increase	Data Rate loss
Clipping & Filtering	No	No	No
Coding	Yes	No	Yes
Partial Transmit Sequence(PTS)	Yes	No	Yes
Selected Mapping	Yes	No	Yes
Interleaving	Yes	No	Yes
Tone Reservation	Yes	Yes	Yes
Tone Injection	Yes	Yes	No

Table 5.1 Comparison of Different PAPR Reduction Techniques

Table 5.1 demonstrates the comparison between different PAPR reduction techniques based on the criteria of distortion loss, power increase and data rate loss.

VI. CONCLUSION

Orthogonal Frequency Division Multiplexing is a multicarrier modulation technique with many advantages such as high spectral efficiency, robustness to channel fading, immunity to impulse interference and less non-linear distortion. Despite of all the advantages, one of the serious drawbacks of OFDM is that it exhibits high PAPR. High PAPR leads to saturation in high power amplifiers and thus degrading the performance of the system. Thus, it is essential to reduce the PAPR. In this paper, we described different techniques proposed to reduce PAPR. With the reduction in PAPR, these techniques also affect other aspects of the system such as BER performance, data rate, computational complexity, etc. hence, the appropriate PAPR reduction should be chosen according to the requirements of the system.

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