International Journal of Engineering Applied Sciences and Technology, 2016
Vol. 1, Issue 5, ISSN No. 2455-2143, Pages 69-74
Published Online March – April 2016 in IJEAST (http://www.ijeast.com)

REDUCTION OF PEAK TO AVERAGE POWER IN OFDM SYSTEMS: A SURVEY

Kuldeep Singh Chauhan
ME Scholar
IET DAVV, Indore, M.P

Mrs. Pratibha Singh
Assistant Professor
IET DAVV, Indore, M.P

Abstract—**Orthogonal Frequency Division Multiplexing (OFDM) has emerged as one of the main factors for the attainment of high data rates in various wireless technologies used globally. Due to high amplitude fluctuations, conventional OFDM signals suffer from a high value of Peak to Average Power Ratio (PAPR) which in the worst case can be proportional to the square of the number of sub-carriers used. This causes non-linear distortion in high power amplifiers used in wireless communication systems. Therefore employing techniques to circumvent the PAPR problem has been an active area of research. This paper compares various PAPR reduction techniques such as clipping, selective mapping, partially transmitting sequences etc., their complexities pertaining to computation and their practical applicability in terms of implementation on hardware. As data rates and mobility supported by OFDM systems increase, the number of subcarriers needed also increases, thereby leading to high PAPR values. As future applications would demand higher data rates and higher mobility, techniques to reduce PAPR values would become inevitable and occupy high importance. This paper brings out a clear picture of a basic OFDM system, the PAPR problem, existing techniques for reduction of PAPR, their implementation complexity and practical applicability.**

Keywords:- **OFDM, PAPR-, High Power Amplifier, Clipping, Filtering SLM, PTS, Commanding, Interleaving**

I. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) is one of the most powerful modulation techniques being used today rendering high data rates and spectral efficiency. Another major advantage of this technique is simple digital implementation with the advent of VLSI technology. The drawback lies in the fact that the amplitude variations of OFDM signals is large, which requires large back-off in the high power amplifiers used. To reduce distortions caused by a HPA without setting it to large back-offs, several techniques have been introduced that limit the peak of the envelope of the signal (**clipping)**[1],[5], a problem that is often referred to as peak-to-average power ratio (PAPR) reduction. The PAPR reduction techniques have varying PAPR-reduction capabilities and complexity of implementation. PAPR is a very well-known measure of the envelope fluctuations of a multicarrier (MC) signal and plays a crucial role in the selection of any particular technique. The challenge of reducing the envelope fluctuations in the time domain OFDM signal with the aim to increase the system performance (reduce both BER and the out-of-band radiation) has culminated into reducing PAPR. In this paper we introduce the basic concepts regarding OFDM, the significance of PAPR and various techniques developed to reduce PAPR in OFDM systems[1],[5]. Computational complexity of various PAPR reduction techniques have also been mentioned and explained. Also their practical applicability considering hardware complexity has been explained.

II. OFDM THEORY

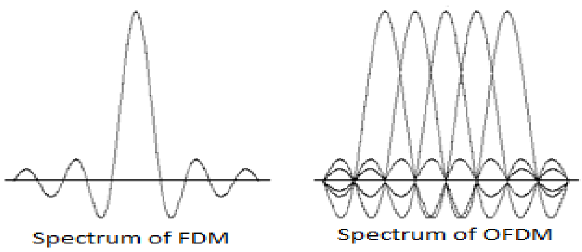

Fig-1:- Spectrum of frequency division multiplexing(FDM) and Orthogonal frequency division multiplexing(OFDM) [21],[28]

Orthogonal Frequency Division Multiplexing is a form of multicarrier modulation which is well suited for data transmission over dispersive channels. Here the different sub-carriers are orthogonal to each other leading to mutual independence. It's achieved by placing each carrier exactly at the nulls in the modulation spectra of the rest of the carriers.

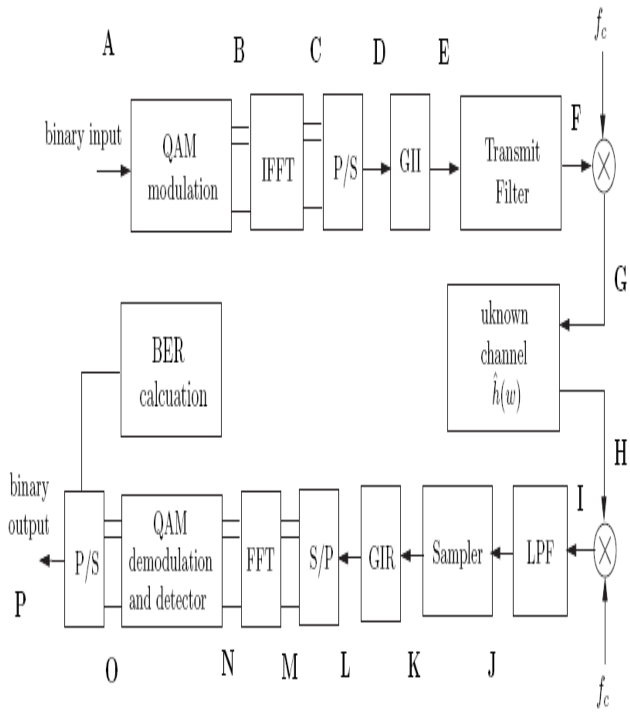

Fig-2:- OFDM Transceiver Structure [21]

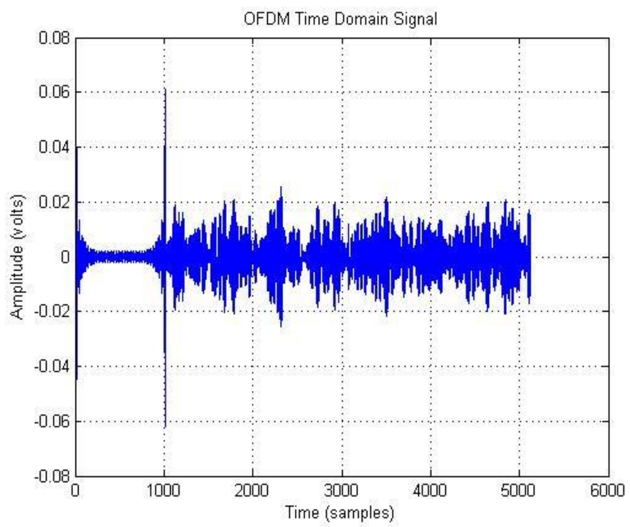

Fig-3: OFDM Time Domain Signal

The above simulation waveform shows te time domain OFDM signal. It can be seen that the signal attains high peaks above the average value of the OFDM signal.

A. PEAK-TO-AVERAGE POWER RATIO (PAPR)

The peak to average power ratio depends on the ratio of the maximum power of the complex pass-band signal and the mean power of it. The value of PAPR can be calculated using following equation:

$$PAPR = \max\{x^2(t)\} / mean\{x^2(t)\}$$

Where $x(t)$ represents the time domain OFDM signal. To calculate the probability of having PAPR greater than the threshold value for the OFDM signal, its customary to use the Complementary Cumulative Distribution Function (CCDF). By simulating the OFDM system and plotting the CCDF, we compare the PAPR reduction capability of various PAPR reduction techniques.

To clearly understand the necessity of PAPR reduction, we need to consider the transfer characteristics of a high power amplifier, which is shown below. [2],[21],[28]

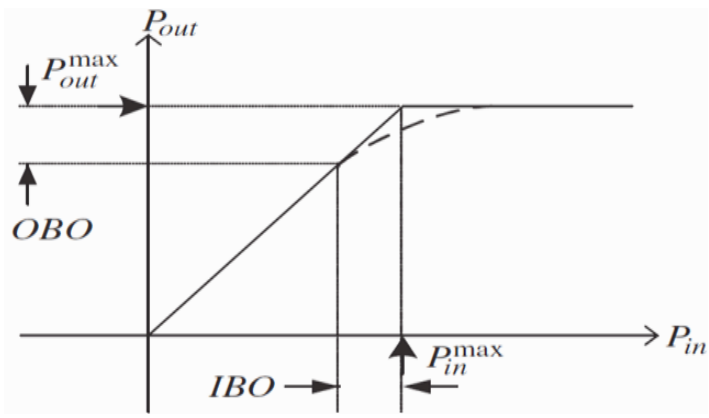

Fig-4:- Graph showing the transfer characteristics of a high power amplifier.

In the above diagram, the input power is denoted by Pin whereas the outputs power is represented by $Pout$. To operate the amplifier in the linear region, the maximum output and input powers are limited to $Pout_{max}$ and $(P)in_{max}$ respectively. Both input and output powers are backed off to insure a linear operation and the area of the backing off is termed by Input Back-Off (IBO) and Output Back-Off (OBO) [5],[9]

Due to the limitation imposed on the maximum peak of the OFDM signal due to the use of HPAs, it becomes mandatory to attain low values of PAPR. The undesirable increase in the power of the side lobes of the OFDM signal is referred to as spectral spreading or spectral re-growth. As demonstrated in the figure, when the nonlinearity of the HPA is higher, IBO is smaller, resulting in higher spectral spreading. This leads to higher interference between the sub-bands of the OFDM signal, unless the frequency separation between adjacent subcarriers is also increased to maintain orthogonally among sub carriers. However, this would reduce spectral efficiency which is a major factor for using OFDM.

B. DIFFERENT TECHNIQUES FOR PAPR REDUCTION AND THEIR COMPARISON:

Different PAPR reduction techniques can be broadly classified as:
Signal Distortion Techniques: These can be further sub-divided into four categories:[1],[5],[7]

a) Clipping and Filtering: It is one of the simplest signal distortion methods in which the high peaks of the OFDM signal are clipped prior to passing it through the HPA. This method employs a clipper that limits the OFDM signal amplitude to a predetermined clipping level. If the signal exceeds the pre-determined level; the amplitude is clipped. Mathematically, it can be written as:

$T(x[n]) = x[n]$ if $|x[n]| \leq CL$

$CL\ ej\angle x[n]$ if $|x[n]| > CL$,

b) Peak Windowing: This technique limits such high peaks by multiplying them by a weighting function called a window function. Many window functions can be used in this process as long as they exhibit good spectral properties. Satisfactory spectral properties are shown by window functions include Hamming, Hanning, Kaiser Windows etc. To reduce PAPR, a window function is aligned with the signal samples in such a way that its valley is multiplied by the signal peaks while its higher amplitudes are multiplied by lower amplitude signal samples thus resulting in reduced distortion compared to the clipping and filtering technique

c) Companding [2]: Since OFDM and speech signals behave similarly in the sense that high peaks occur infrequently, same companding transforms can be used to reduce PAPR. Companding has lesser complexity and also doesn't depend on the number of sub-carriers, but does degrade the BER performance of the system

d) Peak Cancellation: In the peak cancellation technique, a peak cancellation waveform is generated, scaled, shifted and subtracted from those sections of the OFDM signal which have high amplitude peaks.

Multiple Signaling and Probabilistic Techniques: They can be further classified into 6 categories.

1) Selective Mapping (SLM) [4],[9] : The concept behind this approach is to generate a set of sufficient different OFDM symbols *x(m)*, $0 \leq m \leq M-1$, each of length N, all representing the same information as the original OFDM signal, and then transmitting the OFDM signal x having the smallest value of PAPR which is achieved by comparing the various PAPR values.
2) Partial Transmit Sequences (PTS)[3],[9]: In this technique, an input data block of length N is partitioned into a number of independent or disjoint sub-blocks. The IDFT for each of these sub-blocks is computed separately and then weighted by a phase factor which adds a particular phase. The phase factors are selected in such a it minimizes the PAPR of the combined signal of all the sub-blocks added up.
3) Interleaved OFDM: This technique generates multiple OFDM signals using interleavers, which is somewhat similar to the SLM technique but here interleavers are used in place of phase additions.
4) Tone injection & tone reservation [8], [12]: In this technique, a subset of tones is reserved for reduction of PAPR of the OFDM signal while the others are used for data transmission. Due to low values of SNR, they carry no information but reduce PAPR by statistical redistribution.
5) Active Constellation Extension [11],[14]: In this technique, the modulation constellation over an active subcarriers in the OFD data block is modified or pre-distorted so that the PAPR is reduced to render higher degrees of freedom. The cost to pay here is degrading the BER.
6) Constrained Constellation Shaping [11],[12],[13]: In this technique, the modulation points over the data sub carriers in OFDM symbols are pre-modified within an allowed error to reduce the PAPR of the system. Again, BER degradation is the negative aspect.

Coding Techniques for reduction of PAPR [9]: Coding techniques is an efficient paradigm for PAPR reduction. Due to the inherent error detection and correction capabilities of different coding techniques viz. Linear Block Codes, Golay Complementary Sequences, BCH codes etc., coded OFDM is a popular choice for reduction of PAPR in OFDM systems. The coding pattern is modified in such a way that the codes used attain maximum PAPR reduction.

III. COMPARISON OF VARIOUS PAPR REDUCTION TECHNIQUES

Prior to employing a particular PAPR reduction technique, one should bear in mind that the power required is proportional to $\mathbf{N^2}$, where N is the number of sub-carriers used in the OFDM system. Earlier OFDM systems focused on the simplicity of the PAPR reduction method in implementing it on hardware. Hence, prior to comparing the various PAPR reduction techniques, it becomes mandatory to analyze the

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computational complexity of the most common PAPR reduction techniques when it comes to hardware implementation. The table below depicts the computational complexity of the commonly used PAPR reduction schemes:

TABLE 1: COMPUTATIONAL COMPLEXITY

Method	**Complexity**
Clipping and Filtering	$4NL + 2N$ multiplications, $4NL + 2N$ additions
SLM	$2MN(1 + \log2\ N) + M$ multiplications, $3MN(1 + \log2\ N) + M(N - 1) - 1$ additions
PTS	$2MN \log2(N) + 2N + 1$ multiplications $3MN \log2(N) + (M - 1)[2N(M + 1) - 1]$ additions

It can be seen that the least complex method as far as computational complexity is concerned, is the Clipping and filtering technique. But a close look at the technique reveals its inherent shortcomings. Let us consider the figure showing the time domain OFDM signal. Observing the time domain OFDM signal, it can be concluded that the OFDM signal undergoes abrupt amplitude fluctuations, a characteristic which can be attributed to the fact that the message modulates the numerous subcarriers which add up in time domain constructively. Now, if we wish to clip the signal in time domain maintaining a fixed threshold value, we would end up in clipping the signal peaks which may contain important information. Thus the peaks clipped could have contained crucial information which is lost. The consequence would be an increase in BER or BER degradation.[5],[9] Currently wireless systems like Wi-Max, Mobile-Wi-Max, LTE, DVB-T standards support up to 512, 2048 and 8192 sub-carriers. So clipping and filtering for one or more iterations may seem least demanding on the implementation front, however signal transmission and reception could become substantially erroneous. With the advent of very high integrated circuits with eventually furthermore increasing computational capabilities, the focus has now shifted on SLM and PTS techniques. PTS technique requires sending transmitting sub-blocks of the original data which some phase factor added. The main drawback is the overhead data needed to be sent which can be substantially large making PTS practically non-viable for large data sizes. The SLM requires generating replicas of the same signal but with different values of PAPR attributed to different phase shifts without sub-blocking. The sub blocking of data blocks adds the advantage of rendering higher degrees of freedom in the mapping of the symbol bits thereby facilitating PAPR reduction.

IV. COMPARATIVE RESULTS [1],[3],[5], [9]

Table 2: Comparative results

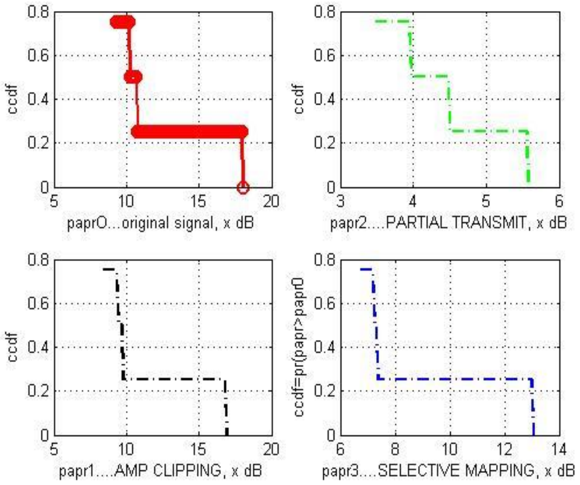
V. SIMULATION RESULTS

The various simulation results have been simulated using MATLAB 10. Simulation results have been carried out for:

1. Time Domain OFDM signal.
2. CCDF plots for different PAPR reduction techniques.
3. Combined CCDF plot for the different PAPR reduction schemes.

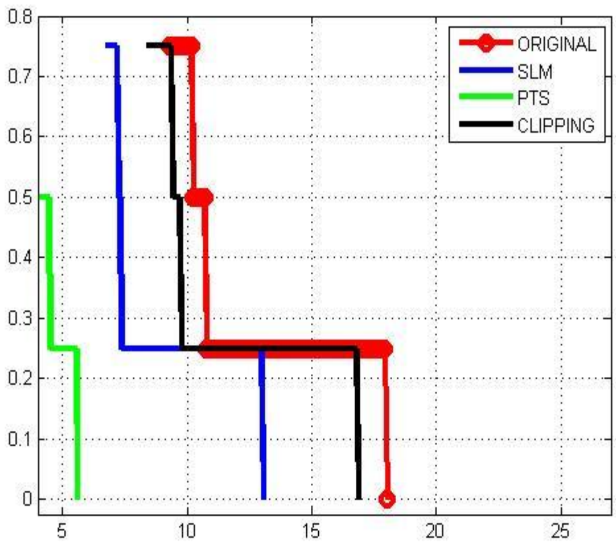
PAPR Reduction Technique	**BER Increase**	**Implementation Complexity**	**Power Increase**
Clipping and Filtering	yes	Low	No
Companding	yes	Low	No
SLM	no	High	No
PTS	no	High	No
Interleaving	no	High	No
Coding	no	High	Depends on the coding technique used

Fig 5:- Comparative study of PAPR reduction capabilities of PAPR reduction techniques



The above simulation results show the different PAPR reduction capabilities of the of the PAPR reduction techniques employed commonly. The y-axis shows the ccdf value whereas the x-axis shows the increasing values of PAPR. We expect the probalilty of higher values of PAPR to gradually reduce. The graph which has the maximum plummeting slope of the CCDF curve with the probability reaching a common point for the least PAPR value has the maximum PAPR reduction capability.

Fig 6:- CCDF plot for Different PAPR Reduction Techniques.



The above simulation result plots the CCDF for the different PAPR reduction techniques on a single graph for an easy visualization of the PAPR reduction capability. The graph clearly shows that the probabilty of PTS attaining a PAPR(X) is the least where X can be chosen as any value lying in the obtained PAPR range. The combined CCDF curve illusrates the above mentioned result. For example at a probability of 0.3, the PAPR obtained for PTS is around 5Db, whereas the PAPR values for SLM, Clipping & Filtering and normal OFDM signals are 7Db, 10dB and 12dB respectively. This augmants the fact that PTS has the highest capability of PAPR reduction among the analyzed techniques.

VI. CONCLUSION

It is clear from the above tabulation and previous discussions that there are certain trade off regarding every PAPR reduction technique used. The selection of particular techniques should be based on system requirements. It can be observed though, that the clipping and filtering method has been extensively used in previous OFDM implementations, especially repetitive or iterative clipping and filtering methods was the one to be used mostly in commercial and industrial applications due to its *'simplicity and low computational complexity'*. The price to pay is the high BER due to reparative clipping as makes high peaks in the OFDM signal occur with low probability. But this was acceptable thus far in most systems thus far as the computational complexity of other PAPR reduction techniques increases manifold as the number of sub-carriers (N) increases. But the need for higher data rates and mobility asks for higher number of sub-carriers. Examples of such systems are WiMAX, Mobile WiMAX, LTE and DVB-T systems which support 512, 2048, 2048 and 8192 sub-carriers respectively. The need would increase in the time to come. Thus researchers are now looking forward to PAPR reduction systems which could address the problem of non-linear increase in computational complexity with respect to the increase in the number of sub-carriers (N). Thus low complexity SLM, blind SLM and Partially Transmitted Sequences (PTS) techniques have been proposed recently to circumvent the challenge of escalating complexity. Also, it has been proved that at higher number of sub-carriers (N>256), iterative clipping and filtering is the least demanding but higher BER and in-band and out-of-band growth is the price to pay. Although out of band distortions can be filtered out, but nothing can be done about increase in in-band distortions. With the advance in hardware design (High Speed Integrated Circuits), and alternative computational methods, there has been a paradigm shift in PAPR reduction techniques. As is clear from the graph and the tabulations above, PTS achieves the maximum reduction in PAPR. Thus, despite additional side information, optimization and computational complexity, PTS will be one of the sought after PAPR reduction technique.

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