

A Survey on Peak to Average Power Reduction Techniques for OFDM Systems

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Abstract—Orthogonal Frequency Division Multiplexing (OFDM) has become one of the key enablers of high data rate which is synonymous with high speed communication. One of the major challenges in OFDM systems is the high value of peak to average power ratio or which is commonly called PAPR. High values of PAPR results in non linear distortion in the High Power Amplifiers used in wireless communication systems. In this paper, we present a detailed analysis of OFDM systems, their advantages and limitations. Also the commonly employed PAPR reduction techniques are also analyzed under the light of PAPR reduction capability and complexity of implementation. Finally the effect of the various techniques on BER performance of the system has also been summarized.

Index Terms:-

OFDM, PAPR-, High Power Amplifier, Clipping, Filtering SLM, PTS, Companding, Interleaving.

I. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) is one of the key enablers of high data rate. In today's world, the requirement of high data rate is increasing very rapidly. The data transmission or exchange of information can be made by two modes i.e. wired and wireless medium and these services also require a dependable transmission of data in the harsh environment. As we know that, in real time system the transmission of data experiences much attenuation due to noise, multipath propagation, interference, nonlinearity etc. and also transmission system has power limitation and cost factor. So, multicarrier modulation technique gained lot of popularity due to its robustness in dealing with impairments. In multicarrier modulation, most ordinarily used technique is OFDM, which is very widely used in wireless communication. But OFDM has major drawback of high peak to average power (PAPR) ratio. When the peak deviation about average is significantly high, the signal level moves outside the

dynamic linear range of power amplifier which is used at transmitter side. Hence, high PAPR in OFDM results the amplifier in saturation thus leading to ICI, and having distortion due to in band and out of band radiation.

For reduction of PAPR, many algorithms/techniques has been developed and each technique has some advantage and disadvantages.[1], [13]

Clipping and filtering is one of the basic techniques, in which high peaks of the OFDM signal are clipped for reducing the peak power which undergoes high distortion. Tone Reservation technique allows the data rate loss with more probable of increasing power. Again the technique like Tone Injection (TI) and Active Constellation Extension (ACE) having a criteria of increasing power will be undesirable in case of power constraint environment. Partial Transmit Sequence (PTS) technique has more complexity than that of Selective Mapping (SLM) technique.

II. OFDM Theory:

Orthogonal Frequency Division Multiplexing is a special form of multicarrier modulation which is particularly fit for transmission over a dispersive channel. The different carriers are orthogonal to each other here, that is, they are totally independent of one another. This is accomplished by placing the carrier exactly at the nulls in the modulation spectra of each other.

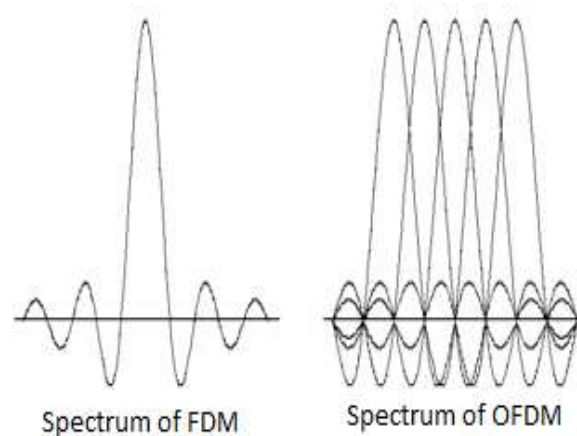


Fig-1:- Spectrum of frequency division multiplexing and Orthogonal frequency division multiplexing

The transceiver structure for the implementation of OFDM is shown in figure 2. At the outset, the Analog to digital converter (A/D) converts the analog signal to digital signal or in the form of data stream, then source encoding is used to compress the digital data up to an extent such that it can be received without any loss. Then, the information symbol is obtained from source encoder which is passed through a channel encoder which adds the redundant bits to the data sequence for reliable communication or to make the data transmission robust to disturbances which are present in the transmission channel. Now, the information sequence at the output of the channel encoder is passed through the digital modulator which outputs the signal waveform. The modulation may be binary or m-array. In Binary modulation, bit 1 and 0 uses distinct waveforms and the m-array modulation uses m number of distinct waveform and this modulated waveform is transmitted. In the channel, the modulated signal is affected by the addition of random noise which is probabilistic in nature. [14]

At the receiver side, the demodulator demodulates the received signal into binary sequence and matched filter is also used at receiver side to increase SNR. Now the output of the demodulator is passed through the channel decoder to recovers information sequence. This information sequence is fed to the source decoder to reconstruct the signal which was actually transmitted by source. Then that signal is converted to analog signal and received by the user. Throughout this process the channel introduces the attenuation in the signal which increases the probability of error /BER as decrease in SNR.

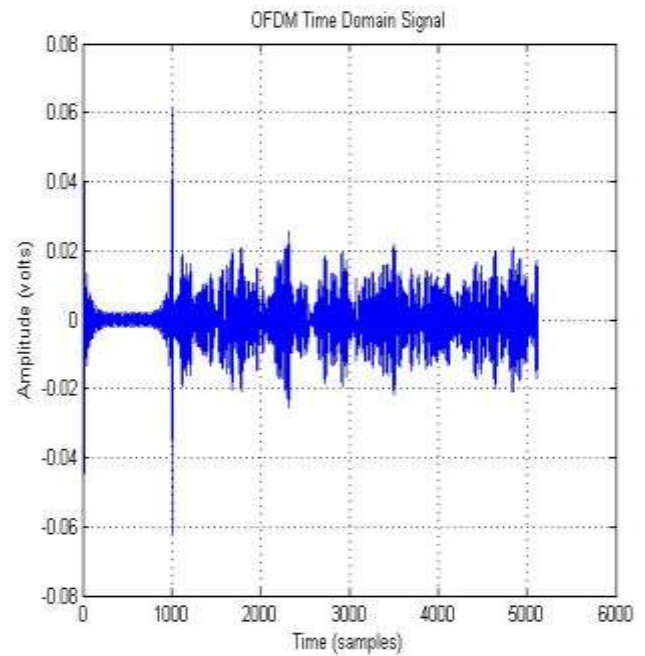


Fig-3: OFDM Time Domain Signal

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

PAPR depends upon the ratio between the maximum power of the complex pass-band signal and the mean power of the same, we can calculate the PAPR. The value of PAPR can be calculated using following equation:

$$PAPR = \max \{x^2(t)\} / \text{mean}\{x^2(t)\} \quad \dots(1)$$

Where $x(t)$ is present in the equation to denote the amplitude of the complex pass-band signal. To calculate the probability of having PAPR greater than the threshold value for the OFDM signal, we could use Complementary Cumulative Distribution Function (CCDF) which is mathematically calculated as:

$$\text{Probability (PAPR } \{x\} > Y) = 1 - (1 - e^{-Y})^N \quad \dots(2)$$

Where N is the number of sub-carriers.

By simulating the CCDF, we compare the theoretical values with the simulation results and see that the PAPR keeps increasing when the number of carriers increases. In the simulation part there is a figure showing the CCDFs of OFDM signals with different number of subcarriers.[9] The Input-Output characteristics of an HPA are shown below

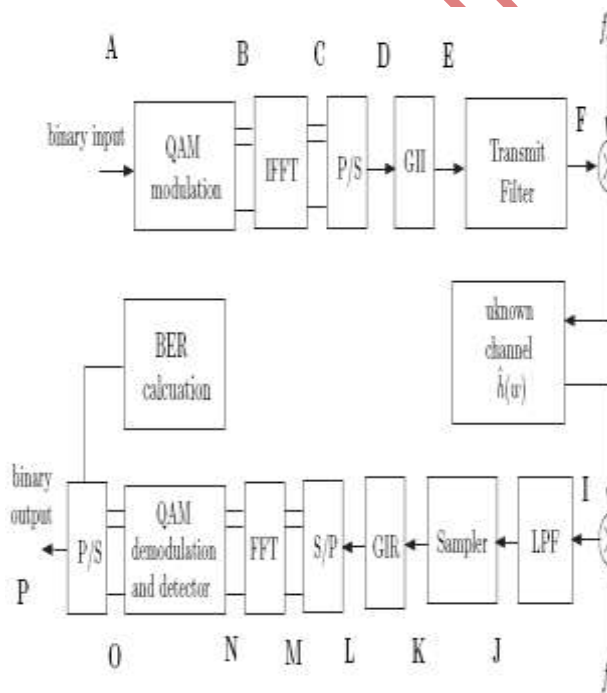


Fig-2:- OFDM Transceiver Structure

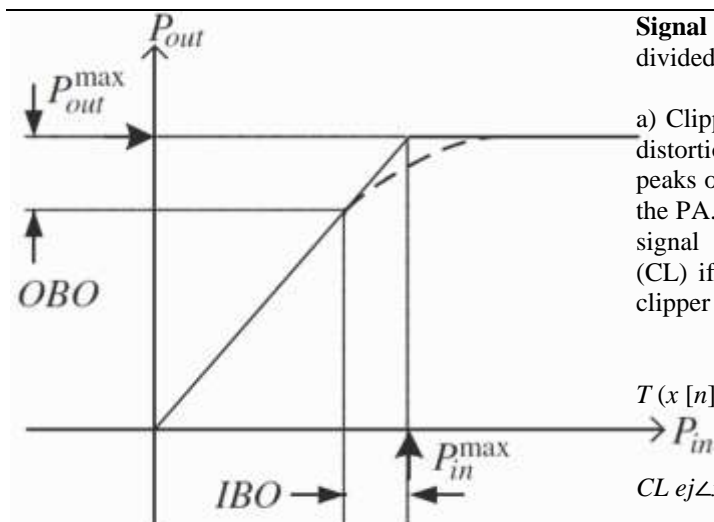


Fig-4:- Graph showing linearity between output and input power

In the graph above, the input power is denoted by P_{in} while the outputs power is represented by P_{out} . To keep the linearity, the maximum output power is limited by the value P_{outmax} and the maximum input power is bounded by $(P)in_{max}$. Both the input and output power 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 limited imposed on the maximum peak of the OFDM signal by the HPA, an increase is encountered in both the in-band and out-of-band distortions. The later causes undesirable increase in the power of the side lobes of the *power spectral density* (PSD) of the OFDM signal. This effect is referred to as spectral spreading or spectral. As shown in the figure, when the nonlinearity of the HPA is higher, IBO is smaller, and the spectral spreading is higher. Spectral spreading 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. However, this solution has the disadvantage of lowering the spectral efficiency.

B. DIFFERENT TECHNIQUES FOR PAPR REDUCTION AND THEIR COMPARISON:

. Different PAPR reduction techniques can be broadly categorized as:

Signal Distortion Techniques: These can be further divided into 4 categories:[1],[5],[7]

a) Clipping and Filtering: One of the simplest signal distortion methods is the method of clipping the high peaks of the OFDM signal prior to passing it through the PA. This method employs a clipper that limits the signal envelope to a predetermined *clipping level* (CL) if the signal exceeds that level; otherwise, the clipper passes the signal without any change.

$$T(x[n]) = x[n] \text{ if } |x[n]| \leq CL \quad \dots(3)$$

$$CL \text{ ej}\angle x[n] \text{ if } |x[n]| > CL, \quad \dots(4)$$

b) Peak Windowing: Unlike peak clipping where the peaks that exceed a predetermined threshold are hard-limited, peak windowing 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 have good spectral properties window functions include Hamming, Hanning and Kaiser Windows. 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 around the way compared to hard clipping, resulting in reduced distortion.

c) Companding : Companding[2] transforms are number of bits per sample. 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.

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

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

- 1) Selective Mapping(SLM) : The basic idea 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, and then transmitting the OFDM signal x having the smallest value of PAPR[4],[13].

- 2) Partial Transmit Sequences (PTS): In this method, an input data block of length N is partitioned into a number of disjoint sub-blocks. The IDFT for each of these sub-blocks is computed separately and then weighted by a phase factor. The phase factors are selected in such a way as to minimize the PAPR of the combined signal of all the sub-blocks[4],[13].
- 3) Interleaved OFDM: Another method to generate multiple OFDM signals is to use interleavers, which is similar to the SLM technique but here interleavers are used in place of phase sequences.[14]
- 4) Tone injection & tone reservation : In this technique, a subset of tones is reserved for reduction of PAPR. Due to their low SNR, they carry no information but reduce PAPR by statistical redistribution[8],[12].
- 5) Active Constellation Extension: In this the modulation constellation over active subcarriers in the OFD data block is modified or pre-distorted so that the PAPR is reduced but at the cost of degrading the BER[4],[14].
- 6) Constrained Constellation Shaping: In this technique, the modulation points over the data sub carriers in OFDM symbol are modified within an allowed error to reduce the PAPR, again BER is the tradeoff[4].

Coding Techniques for reduction of PAPR:

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 natural choice for reduction of PAPR. The coding pattern is modified in such a manner that the codes are not used to reduce BER but to reduce PAPR[9].

Comparison of various PAPR reduction techniques:

Before selecting a particular PAPR reduction technique[4],[9] one should bear in mind that the power required is proportional to N^2 , [4] where N is the number of sub-carriers of the OFDM system. In earlier OFDM systems, the main focus was on the simplicity of the PAPR reduction method in implementing it on hardware. Therefore, before comparing the various techniques, it becomes mandatory to analyze the computational complexity of the most common PAPR reduction techniques when it comes to hardware implementation. The table

below depicts the computational complexities of the common PAPR reduction techniques.

TABLE 1: COMPUTATIONAL COMPLEXITY ANALYSIS

Method	Complexity
Clipping and Filtering	$4NL + 2N$ multiplications, $4NL + 2N$ additions
SLM	$2MN(1 + \log_2 N) + M$ multiplications, $3MN(1 + \log_2 N) + M(N - 1) - 1$ additions
PTS	$2MN \log_2(N) + 2N + 1$ multiplications $3MN \log_2(N) + (M - 1)[2N(M + 1) - 1]$ additions

Apparently the least complex method as far as computational complexity is concerned, seems to be the Clipping and filtering technique. But a close look at the technique reveals its weakness. Let us consider the figure below which shows the time domain OFDM signal. If we look at the signal in time domain, it can be seen 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. Now, if we wish to clip the signal in time domain maintaining a fixed threshold value, we would end up in clipping peaks which may contain crucial information. The consequence in the frequency domain would be an increase in BER.[5],[9] Presently wireless systems like Wi-Max, Mobile-Wi-Max, LTE, DVB-T standards support up to 512, 2048 and 8192 sub-carriers. Thus although clipping and filtering for one or more iterations may seem least demanding, but signal transmission and reception becomes substantially erroneous. With the advent of very high integrated circuits with ever increasing computational capabilities, the focus has now switched on SLM and PTS techniques. PTS technique requires sending transmitting sub-blocks of the original data. The main drawback is the overhead data needed to be sent which can be substantially large making PTS practically non-viable for large data blocks. The SLM requires generating replicas of the same signal but with different values of PAPR attributed to different phase shifts. This creates a challenge in implementing practical systems on hardware which

would be computationally efficient. Thus research has shifted to low weight and low complexity SLM techniques and blind SLM techniques which would be less demanding in terms of data overhead and computational costs.

TABLE 2: COMPARATIVE RESULTS
 [1],[3],[5], [9]

PAPR Reduction Technique	BER Increase	Implementation Complexity	Power Incr
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 coding techn used

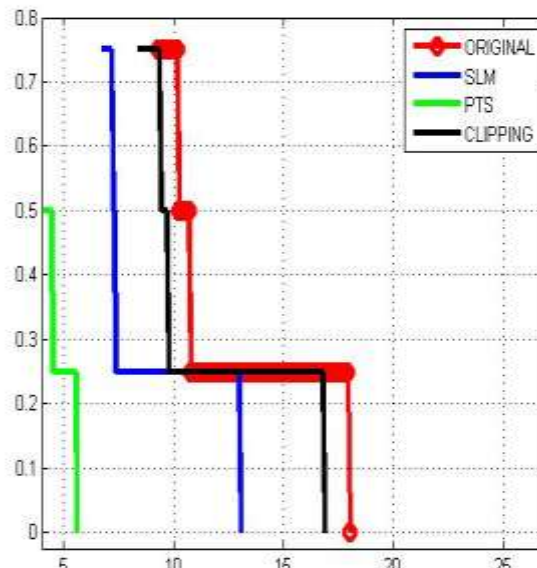


Fig 7:- Comparative CCDF plots.

SIMULATION RESULTS AND THEIR EXPLANATION

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

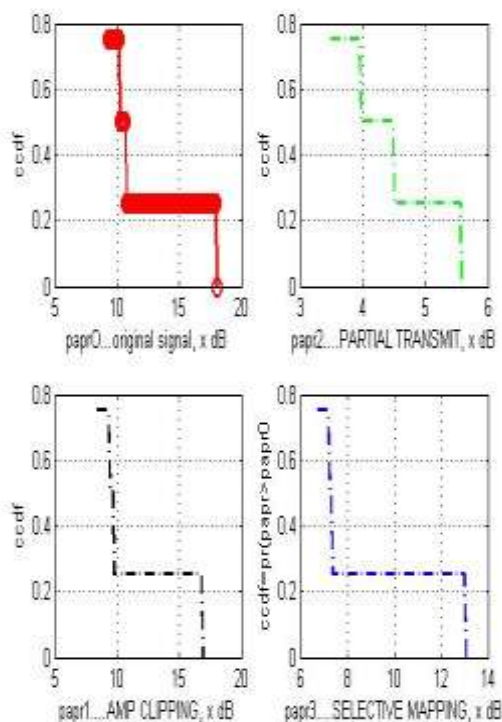


Fig 6:- CCDF plot for Different PAPR Reduction Techniques.

The simulation results clearly show that the probability 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 illustrates 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 augments the fact that PTS has the highest capability of PAPR reduction among the analyzed techniques

III. CONCLUSION

OFDM has become a natural choice due to high data rates, spectral efficiency and robustness to multipath fading. In present day situations, The challenging point is that the computational complexity increases non-linearly as the number of sub-carriers increase. A quick synopsis is the various techniques with some salient features have been tabulated for ready reference. Thus, 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. SLM can be adjudged as a technique with considerable PAPR reduction capability without exacerbating the computational complexity.

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