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# Review Paper on Peak to Average Power Reduction (PAPR) Techniques in OFDM

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**Abstract: OFDM is being considered as the modulation scheme. The objective of this survey is to provide the readers and practitioners in the industry with a broader understanding of the high peak-to-average power ratio (PAPR) problem in orthogonal frequency division multiplexing (OFDM) systems and generate taxonomy of the available solutions to mitigate the problem. OFDM (Orthogonal Frequency Division Multiplexing) is generally preferred for high data rate transmission in digital communication. OFDM system has a major shortcoming of high peak to average power ratio (PAPR) value. The rapid growth in multimedia-based applications has triggered an insatiable thirst for high data rates and hence increased demand on OFDM-based wireless systems that can support high data rates and high mobility. As the data rates and mobility supported by the OFDM system increase, the number of subcarriers also increases, which in turn leads to high PAPR. As future OFDM-based systems may push the number of subcarriers up to meet the higher data rates and mobility demands, there will be also a need to mitigate the high PAPR that arises, which will likely spur new research activities. This paper explains different PAPR reduction techniques and discusses the advantages and limitations of several important PAPR reduction techniques such as Coding, Partial Transmit Sequence, Clipping, Selective Mapping, Tone Reservation, Tone Injection, and Active Constellation Extension. It also presents a comparison of the various techniques based on theoretical results.**

**Keywords: Orthogonal Frequency Division Multiplexing (OFDM); Peak-to-Average Power Ratio (PAPR); High Power Amplifiers (HPAs); Selected Mapping (SLM); Partial Transmit Sequences (PTS); Tone Reservation (TR); Complementary Cumulative Distribution Function (CCDF), Coding, Clipping, Tone Injection, Active Constellation Extension,**

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## 1. INTRODUCTION

The Modern day phenomenon of increased thirst for more information and the explosive growth of new multimedia wireless applications have resulted in an increased demand for technologies that support very high speed transmission rates, mobility and efficiently utilize the available spectrum and network resources. OFDM is one of the best solutions to achieve this goal and it offers a promising choice for future high speed data rate systems. OFDM (Orthogonal Frequency Division Multiplexing) is being widely used for wireless applications as it provides high data rate and helps to improve spectral efficiency [1,2].OFDM has been standardized as part of the IEEE 802.11a and IEEE 802.11g for high bit rate data transmission over wireless LANs. It is incorporated in other applications and standards such as digital audio broadcasting (DAB), digital video broadcasting (DVB), the European HIPERLAN/2 and the Japanese multimedia mobile access communications (MMAC). Also, OFDM is the transmission scheme of choice in the physical layer of the worldwide interoperability for microwaveaccess (WiMAX) and long term evolution (LTE) standards. It has also been used by a variety of commercial applications such as digital subscriber line (DSL),digital video broadcast handheld (DVB-H). OFDM is a multicarrier digital communication scheme where the whole available bandwidth is divided into many streams of low data rate and then modulated with various sub-carriers. OFDM was first presented in the late 1950's and characterized in the mid 1960's [3, 4]. In OFDM modulation scheme, multiple data bits are modulated simultaneously by multiple carriers. This procedure partitions the transmission frequency band into multiple narrower sub bands, where each data symbol's spectrum occupies one of these sub bands. As compared to the conventional frequency division multiplexing

(FDM), where such sub bands are non-overlapping, OFDM increases spectral efficiency by utilizing sub bands that overlap (Fig. 1). To avoid interference among sub bands, the sub bands are made orthogonal to each other, which means that sub bands are mutually independent. By breaking the wide transmission band into narrower, multiple sub bands, OFDM schemes effectively combat the effect of frequency-selective fading usually encountered in wireless channels.

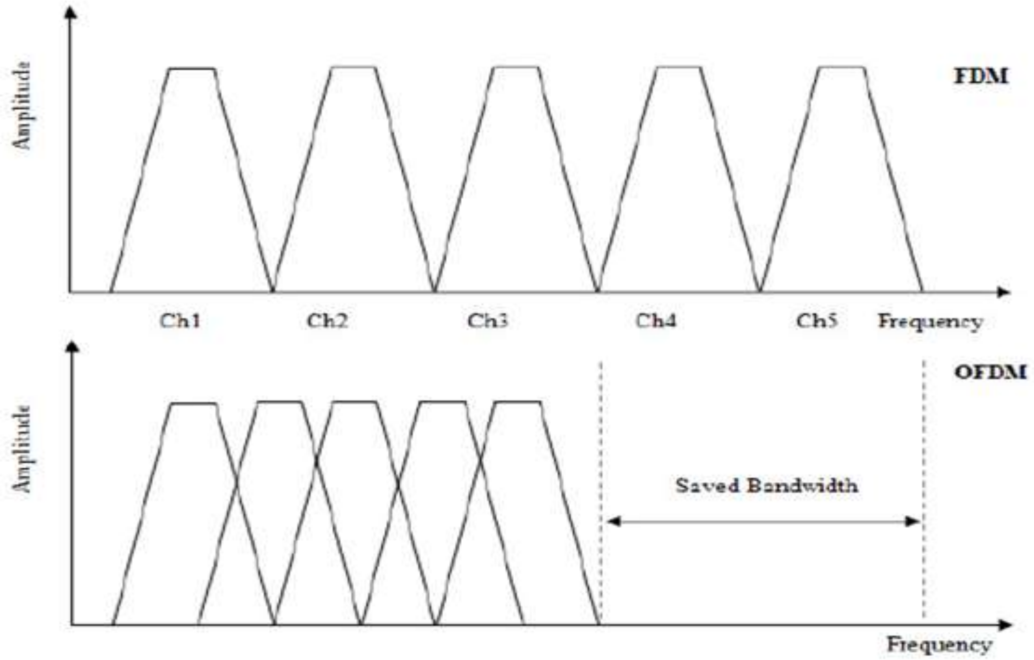


Fig. 1. Comparison of the spectral utilization efficiency between FDM and OFDM schemes.

Frequency-selective fading is a consequence of the phenomenon called multipath propagation, where multiple copies of the transmitted signal traveling along different paths combine at the receiver. To overcome the frequency-selective fading, each sub band should be narrow enough such that its bandwidth B satisfies [3].

$$\boxed{B < 1/2\ \pi\tau_{av}}$$

where $\tau_{av}$ is the average delay spread defined as the average value of the exponentially distributed random variable used to model the incremental delays of the multiple received rays of the transmitted signal. OFDM converts the frequency-selective fading channel into multiple flat-fading sub channels, thereby allows the use of simple frequency-domain equalizers to overcome the problem. However, OFDM introduces inter-symbol interference (ISI) and inter-carrier interference (ICI). ISI is the effect adjacent OFDM symbols exert on each other due to delay spread and ICI is the effect subcarriers exert on each other. Both of these problems can be reduced significantly by introducing a guard interval between OFDM symbols. This interval is a cyclic extension of the signal itself concatenated at the beginning of the OFDM symbol, called the cyclic prefix (CP). Detailed discussion of the problems of ISI and ICI and the mitigation techniques used to overcome them are beyond the scope of this paper and will not be discussed further. Currently, OFDM systems are expected to assume greater importance in high speed wireless telecommunications systems, both fixed and mobile. The evolution of the physical layer of such high speed networks points to the use of OFDM systems with a large number of subcarriers with potentially high PAPR. Consequently, mitigation solutions are expected to gain increased interest and spur further research. This paper is well-suited to serve as an all-in-one information source to the topic of PAPR reduction in OFDM systems. Its comprehensive and thorough treatment of the topic makes the paper a valuable tool to new researchers who wish to acquire wide knowledge as well as a categorized guide to extensive contributions available in the literature.

## 2. OFDM PAPR PROBLEM

Multi-carrier transmission systems have an inherent problem: high PAPR [5]. PAPR is the ratio of the instantaneous peak signal power to its time-averaged value. It can be expressed by :

$$\mathrm{PAPR} = (|x|\infty)^2/E[(|x|2)^2]$$

To obtain efficient output power, we operate the high power amplifier (HPA) near to the saturation region. Signals with high PAPR suffer from nonlinear distortion which impairs the orthogonally between sub-carriers when passing through a Power Amplifier (PA) at the transmitter side and a Low Noise Amplifier (LNA) at the receiver side. High instantaneous peaks introduce significant in band noise and also drive the PA into compression generating out-of-band spectrum content. In order to ensure low distortion, high voltage power rails are required. But this leads to high power consumption which results in reduction of battery life.

OFDM can be generated using multiple modulated carriers transmitted in parallel. However, this method involves implementation problems and makes transmitters more complex and expensive. This problem can be avoided by the use of the Discrete Fourier transform (DFT) technique. The mathematical equations takes exactly the same form as the inverse discrete Fourier transform (IDFT) and can be implemented efficiently using the inverse fast Fourier transform (IFFT) algorithm. IFFT reduces the computational complexity in comparison to IDFT. DSP chip implementations of IFFT and FFT are readily available. An interesting alternative of implementing the OFDM scheme, though less popular than the IFFT approach, is the use of wavelet filter banks. Orthogonality property of some wavelet bases makes them suitable to be used as coefficients of a set of orthogonal digital filter banks. However, such implementation also faces the problem of high PAPR. It is worth mentioning here that PAPR is evaluated per OFDM symbol. Figure 2 illustrates how a high peak is obtained by adding four sinusoidal signals with different frequencies and phase shifts coherently.

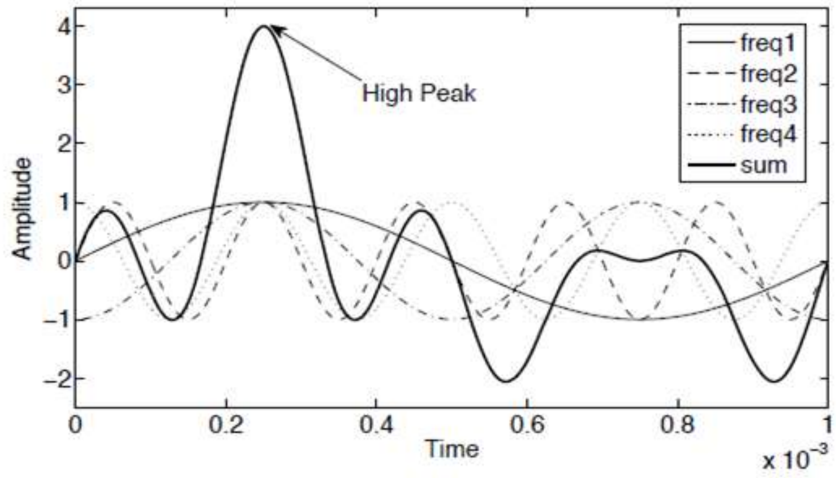


**Figure 2. High peaks in OFDM signal generated by summing multiple sinusoids**

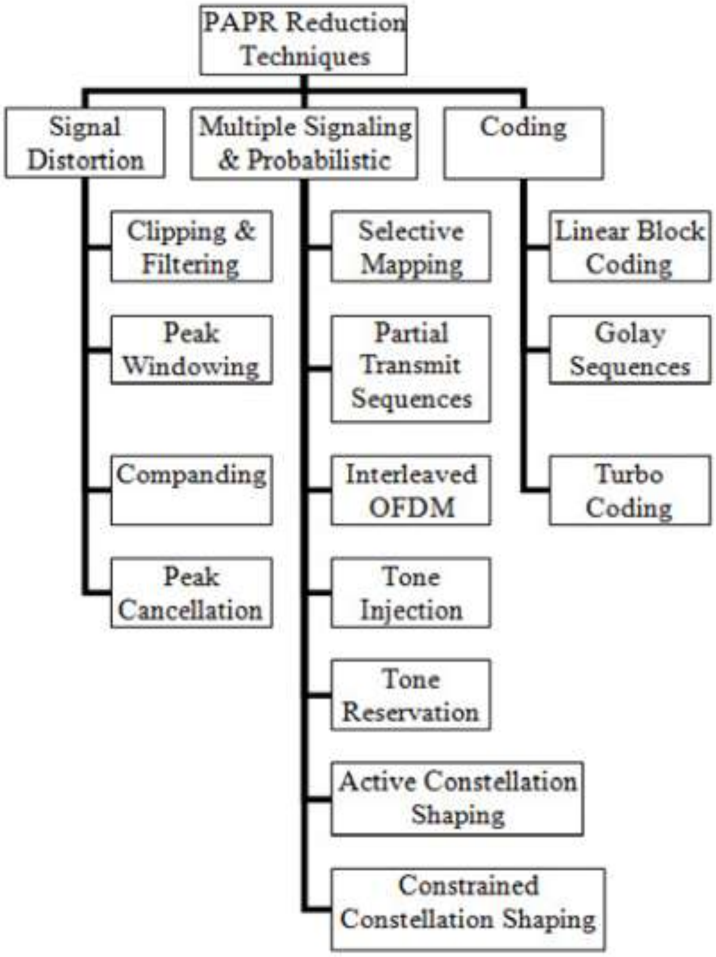
The resulting signal's envelope exhibits high peaks when the instantaneous amplitudes of the different signals have high peaks aligned at the same time. Such high peaks will produce signal excursions into nonlinear region of operation of the power amplifier (PA) at the transmitter, thereby leading to nonlinear distortions and spectral spreading. Oversampling by a factor greater than 1 is used to increase the accuracy. It is found that the PAPR of the oversampled discrete-time signal offers an accurate approximation of the PAPR of the continuous-time OFDM signal if the oversampling factor is at least 4. The performance of a PAPR reduction scheme is usually demonstrated by three main factors: the complementary Cumulative Distributive Function (CCDF), Bit Error Rate (BER), and Spectral Spreading. While CCDF is independent of the characteristics of the PA used at the transmitter, the other two factors are considerably affected. There are also other factors to be considered such as transmitted signal power, computational complexity, and bandwidth expansion and data rate loss.

1. PAPR reduction capability is measured by the amount of CCDF reduction achieved.
2. Although the main focus of PAPR reduction techniques is to reduce the CCDF, this is usually achieved at the expense of increasing the BER.
3. The undesirable increase in the power of the side lobes is the power spectral density (PSD) of the OFDM signal.
4. Some PAPR reduction techniques cause some data rate loss due to extra bandwidth required to send side information.

Many PAPR reduction techniques have been investigated in the past. However, many of them are computationally expensive and others provide minimal PAPR reduction. Generally, techniques with increased complexity have better PAPR reduction capability with less undesirable effects than simple ones. However, complex techniques require additional hardware, processing power and time. In practice, both hardware and processing complexity should be as minimum as possible to support real-time system operations and minimize.

## 3 PAPR REDUCTION TECHNIQUES

A large PAPR would drive PAs at the transmitter into saturation, producing interference among the subcarriers that degrades the BER performance and corrupts the spectrum of the signal. To avoid driving the PA into saturation, the average power of the signal may be reduced. However, this solution reduces the signal-to-noise ratio and, consequently, the BER performance [6]. Therefore, it is preferable to solve the problemof high PAPR by reducing the peak power of the signal. Many PAPR reduction techniques have been proposed in the paper. These techniques can be broadly classified into three main categories: Signal distortion techniques, multiple signaling and probabilistic techniques, and coding techniques. We will review some key methods under each category and point out the main advantages and disadvantages of each.



**Taxonomy of PAPR reduction techniques**

### 1. Coding

PAPR reduction researchers have investigated coding. The main idea is to select those codewords that minimize or reduce the PAPR for transmission [7]. For example, Complementary Golay Sequences have peak-to-average power ratios less than 2. These methods are not practical for a 60 GHz system because their complexity increases exponentially with the subcarrier number and requires very significant computation capability to successfully operate at 5 Gbps.

1. Linear Block Coding

2. Golay Complementary Sequences
3. Turbo Coding

### 4. Clipping and Filtering

Amplitude clipping is a very basic technique to reduce PAPR. 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 change. It clips the amplitude of a signal outside the specified region. Clipping is a nonlinear process that leads to both in-band and out-of-band distortions. While the latter one causes spectral spreading and can be eliminated by filtering the signal after clipping, the former can degrade the BER performance and cannot be reduced by filtering.

### 5. 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 . The most commonly used 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 peaks. This action attenuates signal peaks in a much smoother way compared to hard clipping, resulting in reduced distortion.

### 6. Companding Transforms

Companding transforms are typically applied to speech signals to optimize the required number of bits per sample. Since OFDM and speech signals behave similarly in the sense that high peaks occur infrequently, same companding transforms can also be used to reduce the OFDM signal's PAPR. Besides having relatively low computational complexity compared to other PAPR reduction techniques, companding complexity is not affected by the number of subcarriers. Also, companding does not require side information and hence does not reduce bit rate. Their simplicity of implementation and the advantages they offer make companding transforms an attractive PAPR reduction technique. The PAPR reduction obtained by companding transforms comes though with the price of increasing the BER. Companding transforms can be generally classified into four classes: Linear Symmetrical Transform (LST), Linear Asymmetrical Transform (LAST), Nonlinear Symmetrical Transform (NLST) and Nonlinear Asymmetrical Transform (NLAST).

### 7. Selective Mapping (SLM)

In this technique, different data blocks are generated while the information of the blocks is same as that of the original data block. These blocks are combined with different phase sequences and then transformation is performed with IFFT. Out of these signals, the signal with least PAPR is chosen. SLM technique provides significant reduction in PAPR[8]. As we increase the number of phase factors, more combinations are formed which increase the number of iterations and we get better PAPR reduction. Bit error rate (BER) degradation is not a very noticeable value. However, this results into bandwidth expansion due to the side information of the phase sequences.

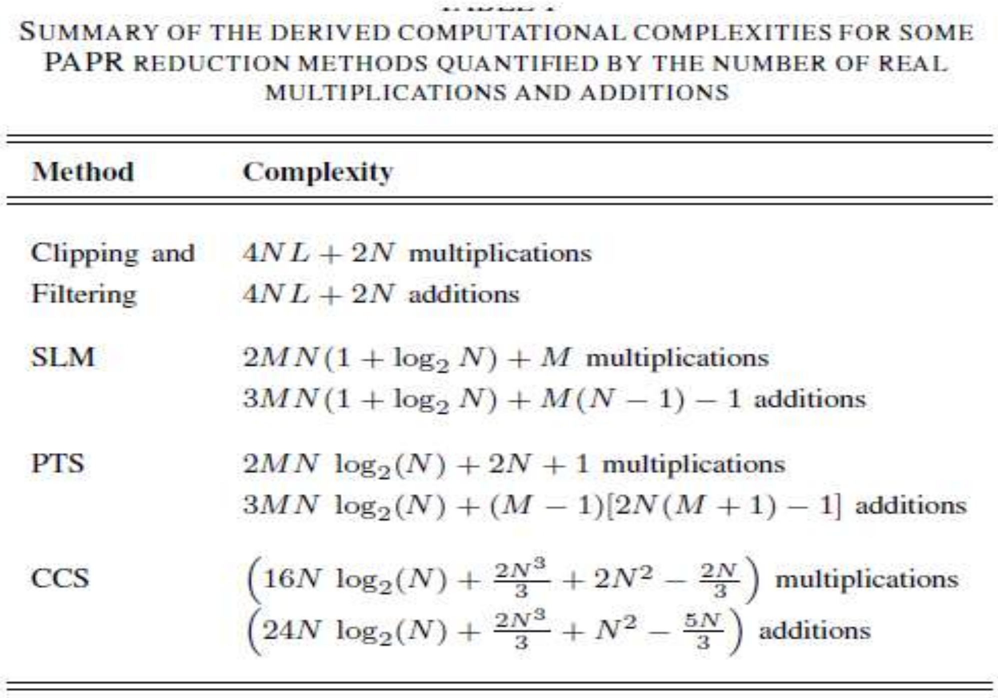
For implementation simplicity, the M phase sequences, each of length N, are set to $\{\pm1,\pm j\}$ as these values can be implemented in hardware without multiplication. Therefore, MN additions are required to apply the phase sequences. Then, M-IFFT blocks are required, adding $2MN \log_2(N)$ real multiplications and $3MN \log_2(N)$ real additions. PAPRs for the M permutations of the OFDM signal are computed by $M(2N+1)$ real multiplications and $M(3N-2)$ real additions. Finally, $(M-1)$ subtractors/adders are necessary to find the minimum PAPR. Total complexity is $2MN(1+\log_2 N)+M$ real multiplications and $3MN(1 + \log_2 N) + M(N - 1) - 1$ real additions.

### 8. Tone Reservation (TR)

Tone reservation works on the idea of reserving a number of tones to produce a signal that has reduced peak-power[9]. It has few reserved sub- carriers which are not used for transmission purpose. These sub-carriers are termed as reserved tones. This technique reduces more overhead as compared to PTS and SLM. As there is no need to include the tones information separately to the signal which is ready for transmission. It is sufficient for the receiver to be aware of the positions of these tones and simply ignore them. Mathematically,

$$x = I + T$$

The receiver only needs to be aware of the positions of these tones and ignore where I is the information signal, T is the additive signal such that PAPR of x is minimized. The advantage of this technique is that it is less complex; at the receiver end, no separate processing is needed. Also, there is no need to transmit the tones information beside the data signal. On the contrary, signal power requirement increases as some of the power must be used for reservation of tones.



SUMMARY OF THE DERIVED COMPUTATIONAL COMPLEXITIES FOR SOME PAPR REDUCTION METHODS QUANTIFIED BY THE NUMBER OF REAL MULTIPLICATIONS AND ADDITIONS

| Method | Complexity |
|---|---|
| Clipping and Filtering | $4NL + 2N$ multiplications<br>$4NL + 2N$ additions |
| SLM | $2MN(1+\log_2 N) + M$ multiplications<br>$3MN(1+\log_2 N) + M(N-1) - 1$ additions |
| PTS | $2MN\ \log_2(N) + 2N + 1$ multiplications<br>$3MN\ \log_2(N) + (M-1)[2N(M+1)-1]$ additions |
| CCS | $\left(16N\ \log_2(N) + \frac{2N^3}{3} + 2N^2 - \frac{2N}{3}\right)$ multiplications<br>$\left(24N\ \log_2(N) + \frac{2N^3}{3} + N^2 - \frac{5N}{3}\right)$ additions |

## 9. Partial Transmit Sequences

Generally, using exhaustive search to find optimal phase factors which give minimum PAPR in PTS methods[10] is expensive and unsuitable for real-time implementations. There are many PTS algorithms available in the literature that yield a suboptimal solution with reduced complexity. We consider the simple iterative flipping PTS scheme proposed in with M partial sequences for the computational complexity analysis.

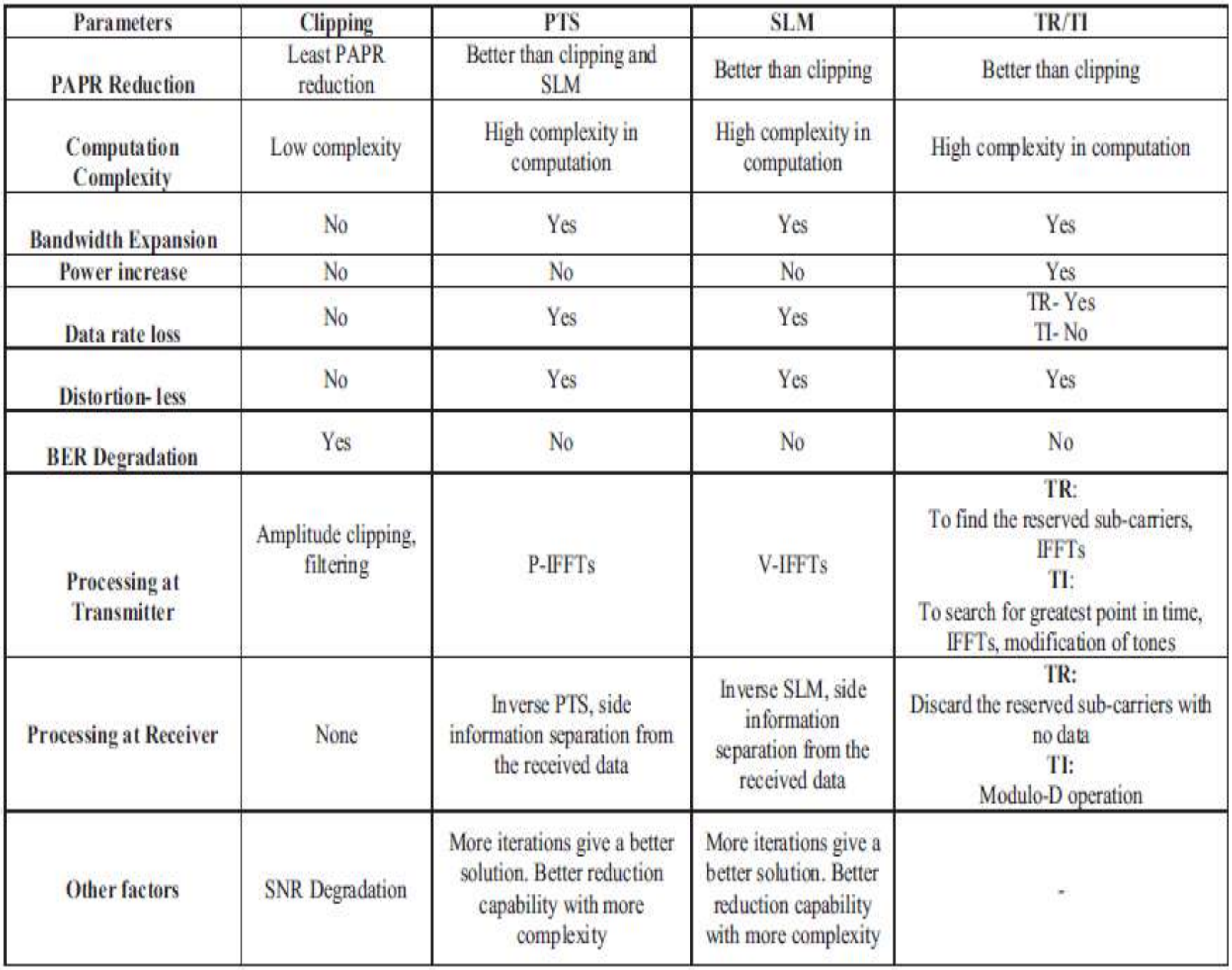
First, M-IFFT blocks are required with a complexity of 2MN $\log_2$(N) real multiplications and 3MN $\log_2$(N) real additions. Second, the next phase factor (the first phase is kept 1 and iterative flipping starts from the second) is flipped and the partial sequences are combined. This requires N(2M−1) real additions. Third, PAPR is computed and compared with the previous one to keep the phase factor that achieves the minimum. These steps require (2N + 1) real multiplications and (3N − 1) real additions. The second and third steps are repeated (M −1) times, where by the end, a suboptimal solution is reached. Therefore, the total computational complexity in this case is 2MN $\log_2$(N) + 2N + 1 real multiplications and 3MN $\log_2$(N)+(M−1)[2N(M+1)−1] real additions.

## CONCLUSIONS

This segment illustrates the overall study of the work proposed so far and it also highlights the advantages and disadvantages of the different techniques on the basis of various performance factors. An analysis for different PAPR reduction techniques on the basis of the parameters like computational complexity, bandwidth expansion and performance is shown in Table 1. The techniques discussed are: Clipping, partial Transmit Sequence, selective mapping, coding schemes, TR and TI, Nonlinear Companding transforms. This paper briefs about the above mentioned technologies and provides results of the comparison in terms of PAPR reduction. Few important PAPR reduction techniques for multicarrier, It mentions that the selection of a technique is based upon many factors. These factors comprise of PAPR reduction capability, data rate loss, and increased transmitted power etc. The amplitude clipping clips the signal peaks but introduces distortion. Implementation complexity is other significant factor while selecting a PAPR reduction technique. In PTS technique, by using more combinations of the phase factors, a better solution for the PAPR reduced signal can be obtained. New methods are being proposed for PTS and SLM techniques [11]. The results show that the proposed methods for PTS and SLM give improved PAPR reduction. Here, we are presenting a comprehensive comparison based on our study of the state of art and few points of our observations. A comparative table representing the difference between the various techniques is shown in Table I. In this table, a detailed comparison of the techniques is presented. Along with the differences, limitations of each technology are also given.

Finally, we have analyzed PAPR reduction techniques - Partial Transmit Sequence, Selective Mapping, Clipping and Tone Reservation etc which reduce PAPR to a significant amount. Out of these, PTS performs better PAPR reduction while increasing the complexity of the system. The clipping scheme is the simplest to implement but introduces distortion in the signal. However, there have been few more PAPR reduction techniques proposed e.g. Coding schemes, Non-Linear Companding Transforms (NCT). Also, a combination of above two or more techniques is being explored which may give better results[12].

TABLE I. COMPARISON OF VARIOUS TECHNIQUES



| Parameters | Clipping | PTS | SLM | TR/TI |
|---|---|---|---|---|
| **PAPR Reduction** | Least PAPR reduction | Better than clipping and SLM | Better than clipping | Better than clipping |
| **Computation Complexity** | Low complexity | High complexity in computation | High complexity in computation | High complexity in computation |
| **Bandwidth Expansion** | No | Yes | Yes | Yes |
| **Power increase** | No | No | No | Yes |
| **Data rate loss** | No | Yes | Yes | TR- Yes<br>TI- No |
| **Distortion- less** | No | Yes | Yes | Yes |
| **BER Degradation** | Yes | No | No | No |
| **Processing at Transmitter** | Amplitude clipping, filtering | P-IFFTs | V-IFFTs | **TR:**<br>To find the reserved sub-carriers, IFFTs<br>**TI:**<br>To search for greatest point in time, IFFTs, modification of tones |
| **Processing at Receiver** | None | Inverse PTS, side information separation from the received data | Inverse SLM, side information separation from the received data | **TR:**<br>Discard the reserved sub-carriers with no data<br>**TI:**<br>Modulo-D operation |
| **Other factors** | SNR Degradation | More iterations give a better solution. Better reduction capability with more complexity | More iterations give a better solution. Better reduction capability with more complexity | - |

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