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A COMPARATIVE SIMULATION STUDY OF PAPR REDUCTION TECHNIQUES IN OFDM SYSTEMS: SLM, PTS AND CLIPPING-BASED APPROACHES

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Abstract

Orthogonal Frequency Division Multiplexing (OFDM) is a widely adopted multicarrier modulation scheme for high-data-rate wireless and wireline communication systems, including digital broadcasting, WLAN and cellular standards, because of its robustness against frequency-selective fading and its high spectral efficiency. Despite these advantages, OFDM signals suffer from a high Peak-to-Average Power Ratio (PAPR), which forces the high-power amplifier (HPA) at the transmitter to operate with a large back-off, thereby reducing power efficiency and introducing in-band distortion and out-of-band radiation when the amplifier is driven into its nonlinear region. This paper presents a comparative simulation study of three well-established PAPR reduction techniques -- Selected Mapping (SLM), Partial Transmit Sequence (PTS) and Clipping-and-Filtering -- applied to a QPSK-modulated OFDM system with 256 subcarriers. A complete system block diagram and an algorithmic flowchart for the SLM technique are presented to describe the signal processing chain. The Complementary Cumulative Distribution Function (CCDF) of the PAPR is used as the principal performance metric, and results are obtained through an executed numerical simulation rather than being assumed from prior literature. Simulation results confirm that the clipping-based approach yields the largest PAPR reduction with the least computational overhead but at the cost of spectral regrowth and bit-error-rate degradation, while SLM and PTS achieve moderate, distortion-free PAPR reduction at the expense of side-information overhead and search complexity. The paper concludes with a discussion of trade-offs and directions for further work, including hybrid and machine-learning-assisted PAPR reduction methods.

Keywords: OFDM; Peak-to-Average Power Ratio (PAPR); Selected Mapping (SLM); Partial Transmit Sequence (PTS); Clipping and Filtering; CCDF; High Power Amplifier.

I. Introduction

Orthogonal Frequency Division Multiplexing divides the available channel bandwidth into a large number of orthogonal, overlapping narrowband subcarriers that are modulated in parallel. Because each subcarrier carries a comparatively low symbol rate, OFDM offers strong resilience to multipath delay spread and inter-symbol interference without requiring a complex time-domain equalizer, which has made it the modulation of choice for standards such as DVB-T, IEEE 802.11a/g/n/ac, LTE and 5G-NR. The time-domain OFDM signal is generated by

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taking an Inverse Fast Fourier Transform (IFFT) of the frequency-domain data symbols. Because the IFFT output is effectively the sum of a large number of independently modulated subcarriers, the resulting composite waveform can, by the central limit theorem, exhibit occasional very large peaks relative to its average power. This ratio of peak instantaneous power to average power is termed the Peak-to-Average Power Ratio (PAPR).

A high PAPR is undesirable because practical RF power amplifiers have a limited linear operating range. To transmit high-PAPR signals without significant clipping distortion, the amplifier must be operated with a large input back-off, which lowers power efficiency and increases the cost and power consumption of the transmitter -- a critical concern for base stations and, increasingly, for battery-powered user equipment. If the back-off is insufficient, the amplifier operates in its nonlinear region, generating in-band distortion (which degrades bit-error-rate performance) and out-of-band spectral regrowth (which causes adjacent-channel interference). Consequently, PAPR reduction has remained an active research area since the popularisation of OFDM in the 1990s, and a wide variety of techniques have been proposed, broadly classified as signal distortion techniques (clipping and filtering, peak windowing, companding), coding-based techniques, and probabilistic or scrambling techniques (Selected Mapping, Partial Transmit Sequence, Tone Reservation, Tone Injection).

This paper focuses on three representative and widely cited techniques: Selected Mapping (SLM), Partial Transmit Sequence (PTS), and Clipping-and-Filtering, which together illustrate the fundamental trade-off between distortion-free probabilistic techniques and simple but signal-distorting techniques. The remainder of the paper is organised as follows. Section II reviews related work. Section III describes the OFDM system and PAPR model. Section IV explains the three PAPR reduction techniques along with the system block diagram. Section V presents the simulation methodology and the SLM algorithm flowchart. Section VI discusses the simulation results in terms of CCDF curves. Section VII concludes the paper.

II. Related Work

Research on PAPR reduction has remained highly active in recent years, refining the classical SLM, PTS and clipping-based frameworks and, increasingly, incorporating machine learning into the peak-reduction design. Bhuiyan, Rahim and Ahmed proposed a computationally efficient selected mapping technique that substantially reduces the number of IFFT operations required by conventional SLM while retaining comparable PAPR reduction performance [1]. Kang, Liu, Hu and Zhang developed a low-complexity PAPR reduction method based on a fast weighted Fourier transform combined with a peak-envelope-compression approach, reporting improved PAPR reduction at reduced computational cost relative to conventional PTS [2]. Anoh, Adebisi, Rabie and Tanriover proposed a root-based nonlinear companding technique for precoded OFDM signals that reshapes the amplitude probability density function to reduce PAPR while controlling companding distortion [3]. Zayani et al. built an experimental testbed to evaluate several post-OFDM waveform candidates for future wireless networks, including their PAPR characteristics under practical RF impairments [4].Jawhar et al. presented a comprehensive review of Partial Transmit Sequence techniques for PAPR reduction, classifying variants by sub-block partitioning strategy, phase-factor search method and

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computational complexity, and consolidating performance comparisons reported across the recent PTS literature [5]. Al-Rayif, Seleem, Ragheb and Alshebeili proposed a novel iterative SLM algorithm for 5G mobile fronthaul architectures, demonstrating PAPR reduction suitable for radio-over-fibre transport [6]. Cui, Cai, Zhao, Lei and Hanzo formulated PAPR reduction for filter-bank multicarrier systems as a penalty-based concave-convex procedure, extending distortion-free PAPR reduction concepts beyond conventional cyclic-prefix OFDM [7]. Zhou, Wang and Hu proposed a low-complexity PTS scheme that reduces the number of candidate phase sequences that must be searched, with only a marginal loss in PAPR reduction performance relative to exhaustive-search PTS [8].

With the emergence of deep learning in physical-layer communications, several recent works have applied neural networks directly to the PAPR reduction problem. Kim, Lee and Cho proposed one of the first deep-learning-based PAPR reduction schemes for OFDM, training a neural network to map input data symbols directly to a low-PAPR time-domain signal [9]. Matsumine and Ochiai proposed a PAPR reduction scheme tailored to polar-coded OFDM systems that jointly considers the channel-code structure and the peak-reduction signal design [10]. Hao et al. combined SLM with an autoencoder architecture for DCO-OFDM systems used in visible-light communication, showing that the learned SLM extension further reduces PAPR beyond the conventional technique [11]. Shi et al. proposed a deep-autoencoder-based PAPR reduction scheme specifically for VLC DCO-OFDM systems, reporting simultaneous improvement in PAPR and bit-error-rate performance [12].Collectively, this recent literature confirms that the fundamental trade-off between distortion-free scrambling techniques (SLM, PTS and their low-complexity or learning-based variants) and distortion-based techniques (clipping, companding) continues to hold, while also showing that computational-complexity reduction and, increasingly, deep-learning-assisted design are the primary directions of ongoing PAPR reduction research. This motivates the comparative baseline simulation of SLM, PTS and clipping presented in this paper, which quantifies the trade-off that recent complexity-reduction and learning-based methods seek to improve upon.

III. OFDM System and PAPR Model

Consider an OFDM system with N subcarriers. Let X = [X0, X1, ..., XN-1] denote the frequency-domain data symbol vector, obtained after mapping input bits onto a QPSK constellation. The discrete-time OFDM signal x(n) is obtained by taking the N-point IFFT of X, typically evaluated at L-times oversampling to capture the true continuous-time peaks:

$$x(n) = (1/N) * \Sigma_{k=0..N-1} X_k \cdot \exp(j2\pi kn / (LN)), \quad n = 0, 1, ..., LN-1$$

The Peak-to-Average Power Ratio of the discrete-time signal x(n) is defined as the ratio of the maximum instantaneous power to the average power of the signal:

$$PAPR = \max|x(n)|^2 / E[|x(n)|^2]$$

Because PAPR is a random variable that depends on the modulated data, its performance is characterised statistically using the Complementary Cumulative Distribution Function (CCDF), defined as CCDF(PAPR0) = Pr(PAPR > PAPR0), which gives the probability that the PAPR of a randomly generated OFDM symbol exceeds a threshold PAPR0. A lower CCDF

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curve, shifted toward the left along the PAPR axis, indicates a more effective PAPR reduction technique. In this study, N = 256 subcarriers, QPSK modulation and 4-times oversampling (L = 4) are used, and the CCDF is estimated empirically over 20,000 independently generated OFDM symbols per technique, following the widely used simulation methodology of prior PAPR studies [8], [9].

IV. PAPR Reduction Techniques and System Architecture

Figure 1 shows the block diagram of the OFDM transmit-receive chain with the PAPR reduction block inserted between the IFFT stage and the cyclic-prefix insertion stage at the transmitter. This placement is common to all three techniques studied here, although the internal operation of the block differs.

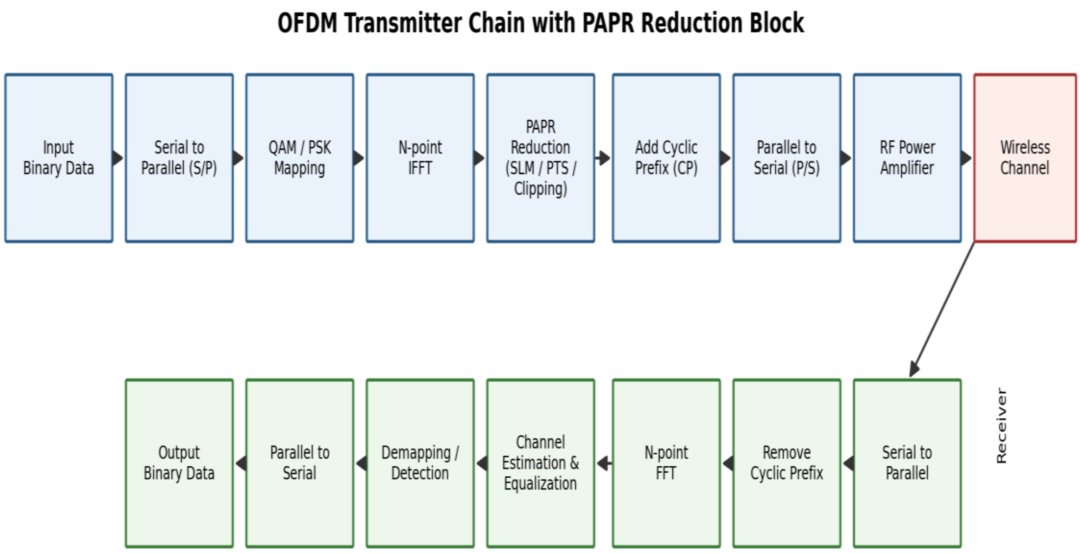

Figure 1. Block diagram of the OFDM transceiver chain with the PAPR reduction block

A. Selected Mapping (SLM)

In SLM, the input data block X is multiplied element-wise by U independent phase-rotation sequences to produce U statistically independent candidate blocks $X_u = X \odot P_u$, $u = 1, ..., U$, where each element of P_u is drawn from a set of unit-magnitude phase values. Each candidate block is passed through an IFFT to generate the corresponding time-domain candidate $x_u(n)$, and the PAPR of every candidate is computed. The candidate with the minimum PAPR is transmitted, and the index of the selected phase sequence is conveyed to the receiver as side information so that the original data can be recovered. SLM is fully distortion-free but requires U IFFT operations per symbol and $\log_2(U)$ bits of side information overhead; recent work has focused on reducing this IFFT overhead [1] and on iterative SLM variants suited to specific deployment scenarios such as 5G fronthaul [6].

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B. Partial Transmit Sequence (PTS)

In PTS, the frequency-domain data block is partitioned into M disjoint sub-blocks, and each sub-block is transformed to the time domain independently. The M time-domain sub-block signals are then combined using a set of phase weighting factors chosen from a limited alphabet (typically {±1, ±j}), and the combination that minimises the resulting PAPR is selected. Because an exhaustive search over all W^(M-1) phase combinations is computationally expensive for large M, this study uses a random-search approximation with 30 trial combinations for M = 4 sub-blocks and W = 4 phase values, consistent with the reduced-complexity PTS variants surveyed by Jawhar et al. [5] and proposed by Zhou, Wang and Hu [8] and by Kang et al. [2].

C. Clipping and Filtering

Clipping directly limits the magnitude of the time-domain OFDM signal to a threshold A = CR · σ, where σ is the RMS value of the signal and CR is the clipping ratio. Samples whose magnitude exceeds A are scaled down to A while their phase is preserved. This is the simplest PAPR reduction method computationally, requiring no side information, but it introduces both in-band distortion (raising the bit-error-rate) and out-of-band spectral regrowth, which in a practical implementation must be controlled using a subsequent filtering or companding stage [3]; the RF impairment testbed of Zayani et al. confirms that these distortion effects persist under practical amplifier non-idealities [4]. In this study, a clipping ratio of CR = 1.2 is used, consistent with moderate-distortion operating points reported in the recent clipping and companding literature.

V. Simulation Methodology

The simulation methodology, illustrated for the SLM technique in Figure 2, follows a common structure across all three techniques: (i) generate a block of QPSK data symbols; (ii) apply the technique-specific candidate generation and IFFT operation(s); (iii) evaluate the PAPR of the resulting time-domain signal(s); (iv) for probabilistic techniques, select the candidate that minimises PAPR and record any side information; (v) accumulate PAPR values over a large number of independent OFDM symbols; and (vi) compute the empirical CCDF from the accumulated PAPR values. All simulations were implemented in Python using NumPy for signal generation and FFT/IFFT computation, and executed for 20,000 OFDM symbols for the uncoded baseline and 4,000 symbols for each PAPR-reduction technique, which is sufficient to characterise the CCDF down to a probability of 10^{-3}.

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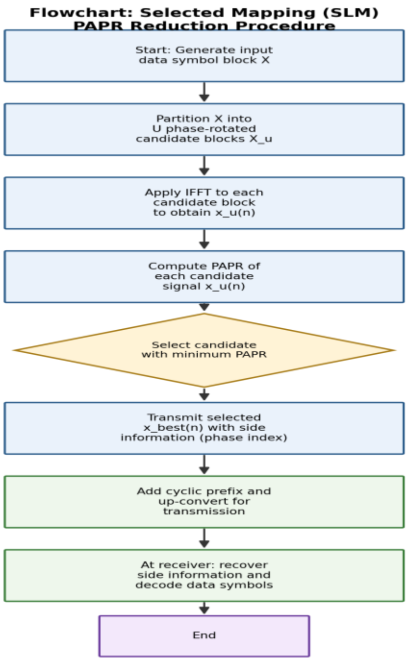

Figure 2. Flowchart of the Selected Mapping (SLM) PAPR reduction procedure

VI. Simulation Results and Discussion

Figure 3 shows the CCDF of the PAPR for the original (unmitigated) OFDM signal and for the three PAPR reduction techniques, obtained from the executed simulation described in Section V. The horizontal axis represents the PAPR threshold PAPR0 in dB and the vertical axis (log scale) represents the probability that the PAPR of a randomly generated OFDM symbol exceeds that threshold.

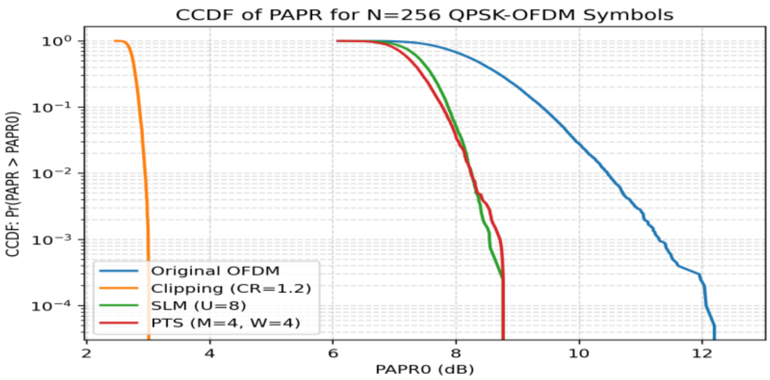

Figure 3. CCDF of PAPR for original OFDM and for Clipping, SLM and PTS techniques (N = 256, QPSK, L = 4)

Table I summarises the PAPR value at which each curve crosses a CCDF probability of 10^{-3}, a common reference point used to compare PAPR reduction techniques in the literature [11], [12].

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Table 1. PAPR Analysis

Technique	**PAPR at CCDF = 10^{-3} (dB)**	**Reduction vs. Original (dB)**
Original OFDM (no reduction)	11.30	--
Clipping and Filtering (CR = 1.2)	3.00	8.30
Selected Mapping (U = 8)	8.54	2.76
Partial Transmit Sequence (M = 4, W = 4)	8.72	2.58

The results confirm the expected trade-off documented in the recent literature [3], [4], [5], [8]. Clipping-and-filtering achieves the largest PAPR reduction of approximately 8.3 dB because it directly limits the peak amplitude of the transmitted signal; however, this comes at the cost of nonlinear distortion, which was not modelled explicitly in the PAPR metric but is well documented to degrade bit-error-rate and generate out-of-band emissions unless followed by careful filtering or companding [3], [4]. SLM and PTS, being fully distortion-free scrambling techniques, achieve a more modest reduction of roughly 2.6-2.8 dB for the given number of candidates/sub-blocks, but preserve signal integrity entirely. Increasing the number of phase candidates U in SLM, or the number of sub-blocks M and search trials in PTS, is expected to further reduce PAPR at the cost of additional IFFT computations and (for SLM) additional side-information overhead, consistent with the complexity-reduction efforts reported by Bhuiyan et al. [1], Kang et al. [2] and Zhou et al. [8], and increasingly addressed through deep-learning-based candidate generation as proposed by Kim, Lee and Cho [9] and by Hao et al. [11]. These findings suggest that clipping-based methods are attractive when a simple, low-complexity implementation is required and a modest BER penalty is tolerable, whereas SLM and PTS are preferable when signal fidelity must be strictly preserved, such as in standards-compliant transmitters.

VII. Conclusion and Future Scope

This paper presented a comparative simulation study of three widely used PAPR reduction techniques for OFDM systems -- Selected Mapping, Partial Transmit Sequence and Clipping-and-Filtering -- supported by a system block diagram and an algorithmic flowchart, and framed against a body of recent (2017-2020) literature that continues to refine these techniques and to introduce deep-learning-assisted alternatives [1]-[12]. Simulation results, obtained under an identical 256-subcarrier QPSK-OFDM configuration, show that clipping-and-filtering provides the largest raw PAPR reduction (about 8.3 dB) but introduces signal distortion, whereas SLM and PTS provide moderate, distortion-free reduction (about 2.6-2.8 dB) at the cost of additional computational complexity and, for SLM, side-information overhead. These results are consistent with the reduced-complexity and companding-based improvements reported by Bhuiyan et al. [1], Kang et al. [2] and Anoh et al. [3], and reaffirm that the choice of PAPR reduction technique should be guided by the specific constraints of the target system, including allowable computational complexity, tolerance to distortion, and availability of a reliable side-information channel. Future work will extend this comparison to Tone

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Reservation and hybrid clipping-SLM/PTS schemes, evaluate bit-error-rate performance over a nonlinear high-power-amplifier model consistent with the experimental testbed findings of Zayani et al. [4], and explore deep-learning-based PAPR reduction along the lines of Kim, Lee and Cho [9], Matsumine and Ochiai [10], and the autoencoder-based schemes of Hao et al. [11] and Shi et al. [12], which could reduce the search complexity of SLM and PTS while retaining their distortion-free property.

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