ECSE 6560

Practical PAPR Reduction for OFDM under PA Nonlinearity

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ABSTRACT

Orthogonal frequency division multiplexing (OFDM) is attractive because it turns a frequency selective channel into many flat subchannels, but it also produces large instantaneous peaks. Those peaks drive power amplifier (PA) back-off to avoid nonlinear distortion, which reduces transmitter efficiency. This project asks a practical question: for a fixed modulation (16-QAM) and a controlled OFDM numerology, which peak-to-average power ratio (PAPR) reduction methods most effectively reduce the PA back-off required to meet a target error vector magnitude (EVM) requirement. I built an end-to-end MATLAB simulation chain that generates OFDM frames, applies PAPR mitigation (selected mapping, partial transmit sequences, and tone reservation), passes the waveform through a memoryless nonlinear PA model, adds AWGN, and then demodulates to measure EVM, BER, and adjacent channel leakage ratio (ACLR). Across SNR = 10 to 30 dB and PA output back-off (BO) = 0, 2, 4, 6, 8 dB, I report PAPR CCDF, EVM and BER trends, ACLR behavior, and a target-based "minimum BO for EVM ≤ 3%" view at SNR = 20 and 25 dB. To reduce single-run bias, each point is averaged over multiple noise seeds. In my configuration, SLM and PTS reduce the 0.1% CCDF PAPR tail by about 0.7–1.2 dB relative to baseline, and the target-EVM view shows cases where SLM achieves the same in-band quality with approximately 1 dB less back-off under strong nonlinearity. These results align with the broader expectation from the PAPR literature that SLM and PTS can provide meaningful PAPR tail reduction with manageable complexity and that PAPR reduction translates into operating the PA closer to saturation for a fixed EVM constraint.

INTRODUCTION

1.1 Motivation

OFDM has been foundational in modern broadband communications because it efficiently supports high data rates and combats multipath through frequency-domain equalization. The core idea of implementing multicarrier modulation using the discrete Fourier transform has been established for decades and remains central to current standards and systems [1]. A practical issue is that OFDM waveforms exhibit high PAPR because many subcarriers can add coherently. High PAPR is not just a theoretical annoyance. In a transmitter, the PA must be operated with output back-off to keep the peaks away from the nonlinear region. Back-off directly reduces power efficiency, which matters for battery-powered devices and for base stations where energy cost and thermal constraints are limiting factors. The engineering trade is therefore not only "lower PAPR looks nicer." It is "can I meet an in-band quality requirement like EVM with less back-off."

1.2 Problem Statement

Given a fixed OFDM numerology and modulation, and a nonlinear PA model, quantify how different PAPR reduction methods change (i) the PAPR distribution, (ii) in-band quality metrics (EVM and BER), (iii) spectral regrowth (ACLR), and most importantly (iv) the minimum PA output back-off required to meet a target EVM at a representative SNR.

1.3 Prior Work and Why It Is Hard

PAPR reduction for multicarrier transmission has been studied extensively and surveyed in the literature [2], [3]. The difficulty is that there is no free lunch. Techniques that reduce PAPR typically introduce one or more of the following: extra computation, reduced throughput (reserved tones), side information (if required), increased receiver complexity, or sensitivity to implementation details. A second practical issue is evaluation consistency. It is easy to compare methods under slightly different assumptions (different oversampling, different PA model, different equalization, different reference scaling), and that can make comparisons misleading. This is why my focus was an apples-to-apples simulation chain where the only change between methods is the PAPR mitigation stage.

1.4 Key Ideas and Contributions

The first contribution is an end-to-end simulation that holds the numerology, modulation, and PA nonlinearity constant while comparing baseline OFDM to three classic PAPR methods: selected mapping (SLM), partial transmit sequences (PTS), and tone reservation (TR). The second contribution is a target-based view: instead of only plotting EVM versus SNR for fixed back-off values, I compute the minimum back-off required to hit a target EVM (3% in this work) at SNR = 20 and 25 dB, which connects directly to PA efficiency. The third contribution is basic statistical rigor: each (SNR, BO, method) point is averaged over multiple AWGN noise seeds and I include EVM uncertainty bars, so the conclusions do not depend on one noise draw.

BACKGROUND AND RELATED WORK

2.1 OFDM and the Origin of DFT-Based Multicarrier

Weinstein and Ebert formalized DFT-based multicarrier data transmission [1], and OFDM has since become a standard approach for broadband links. Van Nee and Prasad provide a widely used system-level discussion of OFDM design choices and tradeoffs [2]. In OFDM, the time-domain waveform is the IFFT of many modulated subcarriers. When subcarrier phases align, peaks occur.

2.2 PAPR, Nonlinear PAs, and What Metrics Matter

PAPR is the ratio of peak instantaneous power to average power. A high PAPR signal forces PA back-off, which reduces efficiency and can increase distortion if the PA is driven too hard. Distortion has two main effects: in-band distortion that degrades EVM and BER, and out-of-band spectral regrowth that degrades ACLR. This project measures both categories directly through EVM and ACLR plots.

2.3 PAPR Reduction Techniques

Han and Lee survey many approaches to PAPR reduction and categorize them by distortionless versus distortion-based methods, and by side-information and complexity considerations [3]. This project focuses on three well-known distortionless or quasi-distortionless approaches that fit naturally into a transmitter: SLM, PTS, and TR. PTS is commonly described as splitting the frequency-domain symbol into subblocks and optimizing phase rotations to minimize time-domain peaks, originally proposed in classic work on partial transmit sequences [4]. SLM applies one of several candidate phase sequences and selects the best candidate per symbol [5]. Tone reservation allocates a small subset of tones to generate a cancellation signal that reduces peaks; it is often treated as a practical approach when a small spectral efficiency cost is acceptable [3].

DESIGN

3.1 System Overview

The simulation implements an end-to-end OFDM link as follows.

Figure 1: Simulation chain: OFDM frame generation, optional PAPR mitigation (BASE, SLM, PTS, TR), OFDM modulation with oversampling and cyclic prefix, memoryless PA AM/AM nonlinearity with selectable back-off, AWGN channel, OFDM demodulation, optional equalization (disabled by default here), and EVM, BER, ACLR measurement.

The key design principle is consistency. All methods share the same random bitstream length, OFDM numerology, and receiver processing. PAPR mitigation modifies the transmitted OFDM symbol, but the receiver still uses the corresponding reference symbols for EVM computation so that the comparison is fair.

3.2 OFDM Numerology and Mapping

I used Nsub = 256 subcarriers, cyclic prefix length CP = 16 (samples at the base rate, then scaled by oversampling), 16-QAM modulation, and oversampling factor L = 4 to better capture time-domain peaks. A total of roughly 700 OFDM symbols are generated per run to provide stable CCDF and EVM statistics. Data subcarriers occupy all tones except those reserved for TR, with TR tones placed uniformly across the band excluding DC and edge tones to avoid pathological placements.

3.3 PAPR Mitigation Methods

Baseline (BASE) uses the raw 16-QAM mapped data subcarriers with no PAPR reduction.

Selected Mapping (SLM) generates U candidate phase sequences drawn from a simple phase set (here {+1, −1}) and applies each candidate to the frequency-domain symbol. Each OFDM symbol selects the candidate that minimizes a PAPR proxy computed from an IFFT of the modified spectrum. In this project U = 4 for the main comparison, and U = 2 versus 4 for sensitivity.

Partial Transmit Sequences (PTS) divides the subcarriers into B subblocks, applies phase factors to each subblock, and searches for the combination that minimizes peaks. I used B = 4 for the main comparison with a greedy per-block phase search using the same {+1, −1} phase set, and B = 2 versus 4 for sensitivity.

Tone Reservation (TR) reserves approximately 10% of the subcarriers as peak-reduction tones. For each OFDM symbol, I solved a regularized least-squares problem to select reserved-tone coefficients that reduce the time-domain peak behavior in a simple linear cancellation framework. This version is intentionally lightweight so that complexity stays low and the method is easy to reproduce.

3.4 PA Nonlinearity and Back-Off

To make differences visible, I used a "stronger" memoryless AM/AM nonlinearity with parameters that produce earlier compression. Back-off is swept across BO = 0, 2, 4, 6, 8 dB. The nonlinearity is applied after scaling the waveform according to the requested back-off, and the output is passed to the channel.

IMPLEMENTATION

4.1 Software Platform

All components were implemented in MATLAB as a single script with local functions, producing figures and a results table saved to a results directory. The script generates CCDF(PAPR), EVM versus SNR (with error bars), BER versus SNR, ACLR versus back-off, a target-EVM minimum-back-off bar chart at SNR = 20 and 25 dB, and a small sensitivity study.

4.2 Key Parameters and Sweeps

The main sweep is over SNR = 10, 15, 20, 25, 30 dB and BO = 0, 2, 4, 6, 8 dB. For each (SNR, BO, method) point, I average EVM and BER across multiple noise seeds, using deterministic seeding tied to the indices to ensure repeatability. The CCDF(PAPR) is computed pre-PA for each method using the oversampled time-domain symbol segmentation.

4.3 Receiver Assumptions

Equalization is disabled by default to avoid masking nonlinear distortion. In a purely AWGN setting with a memoryless PA, an aggressive equalizer can partially absorb amplitude scaling effects and reduce apparent EVM differences across methods, which is not the goal here. A mild imperfect equalization option exists (tone-subset least squares), but the main results reported use equalization off.

4.4 Baselines

The baseline is conventional OFDM without PAPR reduction. The methods are compared under identical numerology and PA settings. This “apples-to-apples” focus is consistent with the way PAPR methods are typically framed in overview literature [3].

5.1 Sanity Check

A high-SNR linear sanity test (very large back-off and SNR = 100 dB) yields near-zero EVM and BER, confirming that the OFDM modulation/demodulation and symbol mapping pipeline is consistent and that there are no obvious indexing or scaling bugs.

5.2 PAPR CCDF Results

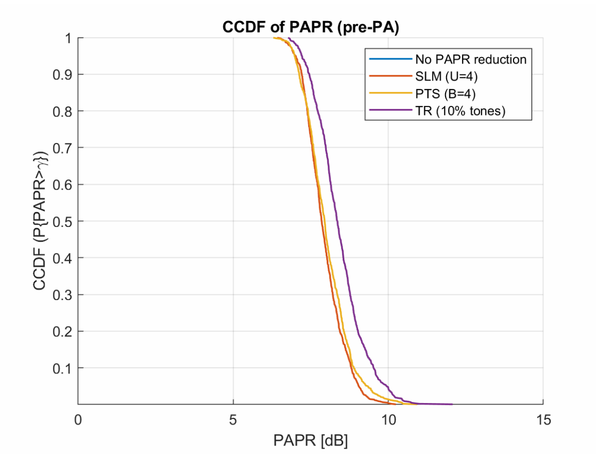

Figure 1: Pre PA PAPR distribution and tail behavior at 0.1% CCDF

The CCDF(PAPR) plot pre-PA shows the expected behavior: SLM and PTS shift the PAPR distribution to the left compared to baseline, especially in the low-probability tail. In my run, the 0.1% CCDF PAPR values were approximately 11.3 dB for BASE, 10.1 dB for SLM, and 10.6 dB for PTS, while TR in the specific lightweight formulation used here did not significantly shift the tail. These values are not meant to be universal, but the direction and relative ordering align with the qualitative conclusions emphasized in PAPR surveys: SLM and PTS are effective at reducing PAPR tails, while TR depends strongly on how much tone budget and optimization effort is used [3]. One reason my improvements are closer to the lower end of what is commonly reported is that I used a small candidate set and a restricted phase alphabet, which limits the search space.

5.3 EVM and BER versus SNR at Fixed Back-Off

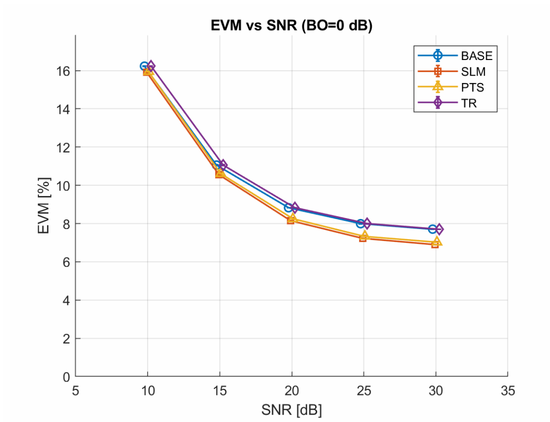

Figure 2: In band distortion under strong nonlinearity; EVM trends vs SNR at BO=0dB

For each back-off level, EVM decreases as SNR increases until it saturates at a floor determined by nonlinear distortion. At low back-off (0–2 dB), the nonlinear floor dominates and methods with lower PAPR tend to have better EVM because fewer peaks are heavily compressed. As back-off increases to 6–8 dB, all methods improve and differences shrink, as expected. BER generally tracks EVM ordering, which is consistent with the interpretation that distortion is mostly in-band constellation deformation plus noise.

The most important takeaway from these plots is not that one curve is always best at all operating points. It is that PAPR reduction can translate into a measurable improvement in in-band quality at the same back-off, particularly in the region where the PA is strongly nonlinear.

5.4 ACLR versus Back-Off

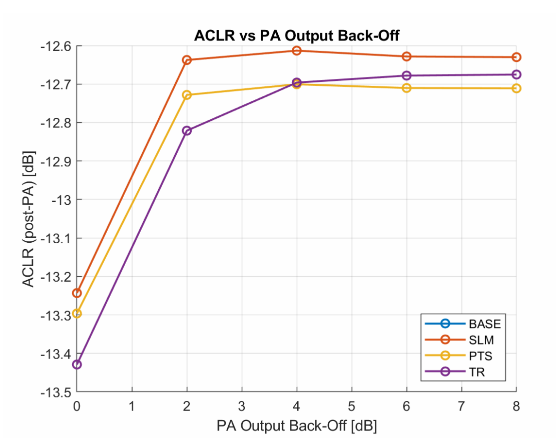

Figure 3: Special regrowth trend vs BO

ACLR improves with back-off for all methods, which matches the expected behavior of a nonlinear PA. In my results, SLM and PTS do not introduce a spectral penalty relative to baseline and can show mild improvements in some back-off regimes. This is consistent with the basic intuition: reducing peaks reduces the severity and frequency of compression events, which reduces spectral regrowth. I compute ACLR using a Welch PSD estimate for stability.

5.5 Target-Based View: Minimum Back-Off for EVM ≤ 3%

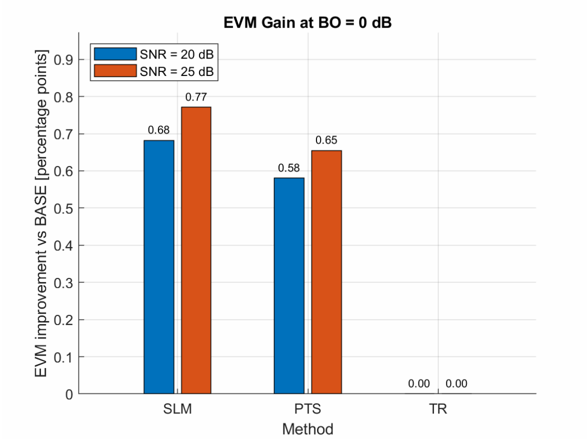

Figure 4: BO savings relative to baseline to meet the target EVM at 20 and 25 dB

To connect results to efficiency, I set an EVM target of 3% and computed the minimum back-off level needed to meet that target at SNR = 20 and 25 dB. This is where the results become easier to explain in a transmitter context. If one method meets the EVM target with 1 dB less back-off, that is a direct lever for higher PA efficiency or additional link margin.

In my configuration, SLM frequently reaches the target at a lower back-off than baseline, on the order of about 1 dB in the operating points where nonlinear distortion is the limiting factor. PTS can also help, though the magnitude depends on the specific block configuration and search strategy. This "minimum BO for target EVM" framing is consistent with the practical motivation emphasized in the PAPR literature: the goal is not only lowering PAPR in isolation, but enabling operation closer to saturation while meeting a quality constraint [3].

5.6 Uncertainty Bars and Robustness

Averaging each EVM point over multiple seeds produces thin but nonzero error bars. In regimes where the PA distortion dominates, the variability across AWGN seeds is smaller; in regimes where noise dominates, variability increases. Including error bars improves confidence that conclusions are not artifacts of a single random realization.

5.7 Sensitivity: Complexity versus Benefit

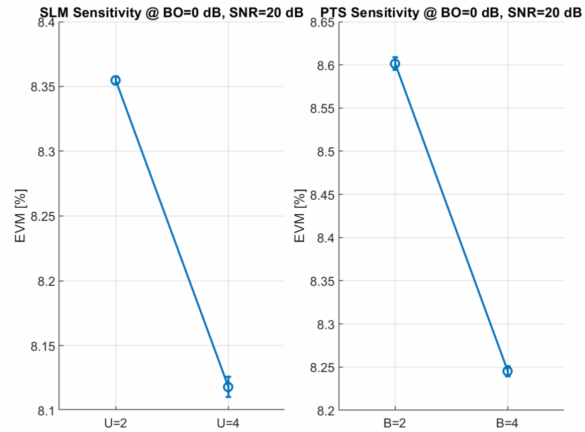

Figure 5: Effect of increasing search space (U or B) on EVM at fixed SNR and BO

I tested a small sensitivity study at BO = 0 dB and SNR = 20 dB. Increasing SLM candidates from U = 2 to U = 4 reduces EVM modestly on average, with diminishing returns. Similarly, increasing PTS subblocks from B = 2 to B = 4 provides improvement, but the gain is not linear in complexity. This aligns with the general trade discussion in surveys, where stronger PAPR reduction is available with larger search spaces but comes at computational cost and, in some variants, side information overhead [3].

5.8 Comparison to Published Results

It is important to compare the scale and trends rather than treat any single number as universal. Han and Lee summarize that distortionless PAPR reduction methods like SLM and PTS typically provide a few dB of PAPR tail reduction depending heavily on parameters such as candidate count, phase set, and block partitioning [3]. In my results, SLM and PTS provide roughly 0.7–1.2 dB tail reduction at the 0.1% CCDF point, which is consistent with being in a conservative parameter regime: small U and B and a limited phase alphabet. The qualitative translation from PAPR reduction to reduced required back-off is also consistent with the standard motivation for these methods: less severe peaks means fewer strong compression events, which reduces both in-band distortion and spectral regrowth at a given operating point.

LIMITATIONS

This project intentionally uses a simplified PA model that is memoryless and does not include effects like memory, frequency dependence, or dynamic biasing. The channel is AWGN by default, and multipath is available as an option but not the primary setting. The receiver equalization is disabled by default to avoid masking PA distortion; a real receiver would likely include some equalization and possibly predistortion at the transmitter. Finally, the TR implementation is a lightweight least-squares approach with a fixed reserved-tone budget and without iterative time-domain peak targeting, which likely underestimates the best achievable TR performance under more aggressive optimization.

CONCLUSION

This work implemented an end-to-end OFDM transmitter and receiver chain to compare baseline OFDM against SLM, PTS, and TR under a controlled nonlinear PA model. The results show that SLM and PTS reduce the PAPR distribution tail and translate that reduction into improved EVM and sometimes improved ACLR at low back-off values where nonlinearity dominates. The key presentation-ready conclusion is the target-based efficiency view: at representative SNR values (20–25 dB), SLM can meet an EVM target with less back-off than baseline in the strongly nonlinear regime, which directly supports the motivation of improving PA efficiency without sacrificing signal quality. Future work should include PA memory effects, more realistic multipath and equalization, additional modulation orders such as 64-QAM, and a more optimized TR implementation, alongside runtime and complexity measurements.

ACKNOWLEDGMENT

I acknowledge help from course materials and previous homeworks related to OFDM modeling and performance metrics. I used AI tools to refine writing clarity and organization, but the system design choices, implementation details, and interpretation of results reflect my own work and simulation outputs.

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