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PAPR Reduction Techniques for Orthogonal Time–Frequency Space Modulation: A Comparative Study of Precoding, Clipping, and Coding Approaches with BER Trade-Off Analysis

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ABSTRACT: Orthogonal Time–Frequency Space (OTFS) modulation has emerged as a promising waveform for high-mobility wireless channels because it maps information into the delay–Doppler domain and offers robustness against channel time-variations. However, like other multicarrier schemes, OTFS exhibits high peak-to-average power ratio (PAPR), which degrades transmitter power efficiency and causes nonlinear distortion when passed through power amplifiers. This paper surveys and compares three families of PAPR-reduction techniques adapted to OTFS — (1) precoding (symbol-domain transforms and optimization), (2) clipping and filtering (and variants such as iterative clipping & filtering), and (3) coding-based and selective mapping (including PTS/SLM and hybrid variants). For each family we review principles, implementation complexity, and reported PAPR reduction, and analyze the trade-off between PAPR mitigation and bit-error-rate (BER) degradation. We propose a unified evaluation framework and outline simulation experiments that quantify complementary strengths: precoding tends to lower PAPR with little BER loss at moderate complexity, clipping is simple and effective but introduces in-band distortion which elevates BER, and coding/SLM/PTS methods offer configurable PAPR–BER tradeoffs at the cost of side information or complexity. Finally, we provide best-practice recommendations for OTFS system designers and directions for future research, including hybrid methods and ML-assisted optimization.

KEYWORDS: Orthogonal Time–Frequency Space (OTFS) Modulation, Peak-to-Average Power Ratio (PAPR), Precoding Techniques, Clipping and Filtering, Bit Error Rate (BER) Trade-off.

I. INTRODUCTION

The drive toward reliable communications in high-mobility scenarios (e.g., vehicular, aerial) has renewed interest in modulation schemes that operate robustly under Doppler. OTFS places symbols in the delay–Doppler (DD) domain and converts them to a time-domain transmit signal via ISFFT and Heisenberg transforms, yielding advantages in channel stability and detection performance compared with OFDM in many scenarios. However, OTFS transmits a multicarrier-like time-domain waveform which suffers from large instantaneous peaks relative to the average power — i.e., high PAPR — leading to inefficiencies in the power amplifier and nonlinear distortion unless large back-off is used [1].

PAPR reduction has been extensively studied for OFDM; many methods transfer to OTFS but require adaptation because OTFS's DD-to-TF-to-time transforms and symbol mapping affect signal structure and distortion sensitivity. Recent literature specifically addressing OTFS PAPR includes symbol precoding/optimization, iterative clipping & filtering for pilot-embedded OTFS, and adaptations of SLM/PTS and genetic/ML-based partial transmit sequence methods. Several recent contributions (2022–2025) demonstrate new precoders and hybrid approaches tailored to OTFS and related variants.

This paper organizes these techniques into three families (precoding, clipping, coding/selection), compares their performance and complexity, and analyzes BER trade-offs. We explicitly highlight where reported results were empirical simulations (and cite them) and where design choices create predictable trade offs.

II. BACKGROUND: OTFS SIGNALLING AND PAPR

A. OTFS signal chain

An OTFS transmitter maps QAM symbols placed on an N×MN\times M delay–Doppler grid, performs an inverse symplectic finite Fourier transform (ISFFT) to go to the time-frequency domain, applies windowing, and then performs an Heisenberg transform (or multicarrier modulation) to produce the time-domain waveform. The transform chain and symbol packing produce constructive superpositions that can create high instantaneous peaks similar to OFDM's subcarrier summation. See formal derivations in OTFS reviews [2].

B. PAPR definition and implications

PAPR is defined as

$$PARA = \frac{max_t|x(t)|^2}{E[|x(t)|^2]} \qquad (1)$$

often reported in dB using complementary cumulative distribution function (CCDF) metrics. High PAPR forces power amplifiers (PAs) to operate with large back-off to avoid nonlinear regions, reducing power efficiency, increasing cost, and causing spectral regrowth and in-band distortion if not handled.

C. Why OTFS requires special attention

OTFS's ISFFT/Heisenberg mapping and optional pilot embedding or precoding change symbol correlations and the statistical distribution of time-domain samples; therefore PAPR characteristics and mitigation effectiveness differ from OFDM. Several OTFS-specific PAPR studies (analytical and empirical) report distributional differences and propose adapted methods.

III. FAMILIES OF PAPR REDUCTION TECHNIQUES

We group methods into three practical families. For each, we summarize principle, representative algorithms, implementation aspects, and BER impact.

A. precoding (symbol-domain transforms & optimization)

Principle. Multiply the vector of DD-domain symbols by a precoding matrix (often unitary or near-unitary) before ISFFT so the time-domain sample peaks reduce via controlled phase and amplitude mixing. Alternatively, pose PAPR minimization as constrained optimization over precoder parameters. Representative approaches include orthogonal precoding matrices (e.g., Zadoff–Chu or DFT-like transforms), block coordinate descent solvers for constrained precoder optimization, and iterative low-complexity precoders proposed specifically for OTFS [3].

Complexity. Precoding adds matrix multiplications in the DD domain (cost depends on matrix structure). If precoder is designed to be orthogonal/unitary and structured (e.g., circulant or DFT-type), complexities are moderate and can exploit FFT-like operations.

BER trade-off. Properly designed unitary precoders preserve symbol energy and orthogonality, so BER degradation is small when channel estimation and equalization account for the precoder. Optimization-based precoders that constrain distortion can achieve several dB PAPR gain with negligible BER penalty; however, if precoder introduces non-invertible operations or compounding with quantization/clipping, BER can degrade. Recent results report ≈3–5 dB PAPR reduction with similar BER performance to state-of-the-art methods when detection accounts for the precoder.

B. clipping and filtering (ICF and variants)

Principle. Clip peaks above a threshold in the time domain then filter/suppress out-of-band components introduced by clipping. Iterating clipping and filtering (ICF) reduces peaks while attempting to limit spectral regrowth and in-band distortion.

Complexity. Very low; clipping is scalar per-sample. Iteration count and filtering cost increase complexity modestly.

BER trade-off. Clipping introduces in-band distortion (nonlinear error) that typically increases BER. ICF and optimized versions (e.g., optimized ICF) reduce spectral regrowth and can reduce BER impact relative to naive clipping, but residual distortion remains. For pilot-embedded OTFS, iterative schemes have been shown effective for significant PAPR reduction but at a cost of BER increase that must be mitigated via increased SNR or joint detection schemes [4].

C. coding-based and phase-rotation/selection methods (slm, pts, pts+ml)

Principle. Generate multiple candidate transmit sequences by applying phase rotations, partial transmit sequences, or coding constraints and select the candidate with lowest PAPR. Side information (index or phase rotations) is sent to receiver or exploited by receiver recovery algorithms. Variants include genetic/ML-driven search for optimal combinations and hybridization with clipping. Recent work applies adaptive genetic algorithms for PTS and neural-assisted PTS for OTFS/OTSM.

Complexity. Higher than clipping; complexity scales with number of candidates (or optimization iterations). SLM/PTS require side information overhead (or sophisticated blind recovery).

BER trade-off. These approaches typically do not introduce distortion (they alter the transmit sequence but preserve symbol values up to known rotations), so BER impact is minimal if side information is correctly received. However, side information errors or suboptimal candidate selection can affect BER. Hybrid methods that combine selection and light clipping attempt to get best of both worlds.

IV. COMPARATIVE ANALYSIS (QUALITATIVE + LITERATURE EVIDENCE)

Table 1: (descriptive) — qualitative comparison.

Method family	Typical PAPR reduction	BER impact	Complexity	Side info
Precoding (structured)	Moderate (2–5 dB reported)	Low if invertible precoder & accounted for	Moderate (matrix ops)	None
Clipping & ICF	Moderate–High (application dependent)	Moderate–High (in-band distortion)	Low	None
SLM/PTS & coding	Moderate–High	Low (if SI preserved)	High (candidates search)	Yes (index bits)

Key literature support:

• Analytical and empirical PAPR characterization of OTFS: Surabhi et al. (IISc) analyze OTFS PAPR behavior and motivate mitigation.

• Symbol-precoding formulations and iterative optimization: several works reframe PAPR reduction as constrained precoder design and show effective PAPR mitigation with small BER loss when detection accounts for precoding.

• Clipping/ICF adaptations for pilot-embedded OTFS show simple implementation and substantial PAPR decrease but note BER penalties and the need for optimized filters.

• Hybrid and evolutionary algorithms (AGA-PTS, NN-PTS) adapt classic OFDM selection methods to OTFS and report competitive PAPR reductions while managing BER via candidate search or ML-assistance [5].

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V. PROPOSED UNIFIED EVALUATION FRAMEWORK

To compare methods fairly, we propose the following experimental protocol (suitable for reproducible simulation and later extension to hardware tests):

A. system parameters

- OTFS grid: NN Doppler bins × MM delay bins (typical: N=16N=16, M=64M=64 or N=32,M=128N=32,M=128 for larger tests).
- QAM modulation: 16-QAM (also test 4-QAM and 64-QAM).
- Oversampling: at least 4× in time after Heisenberg transform for accurate PAPR measurement.
- Channel models: Extended Vehicular A/High-Doppler (time-varying multipath), Rician with K factors and Doppler spreads representative of vehicular speeds.
- PA model: memoryless soft-limiter / Rapp model for nonlinear compression to inspect EVM and BER impacts.
- PAPR metric: CCDF of PAPR (report 10^(-3) complementary probability and mean PAPR).
- BER metric: uncoded BER and, if coding used, coded BER (e.g., convolutional or LDPC), over SNR sweep 0–25 dB.

B. methods to implement

• Precoding: (a) DFT/Zadoff–Chu structured transform, (b) optimized precoder via block coordinate descent (based on [symbol-precoding] approach) [6].

• Clipping: (a) simple clipping with fixed thresholds, (b) iterative clipping & filtering (ICF), (c) optimized ICF if available.

• Selection/Coding: (a) SLM with 8/16 candidate rotations and side-info, (b) PTS with genetic algorithm (AGA-PTS) and (c) NN-assisted PTS (where networks are trained offline).

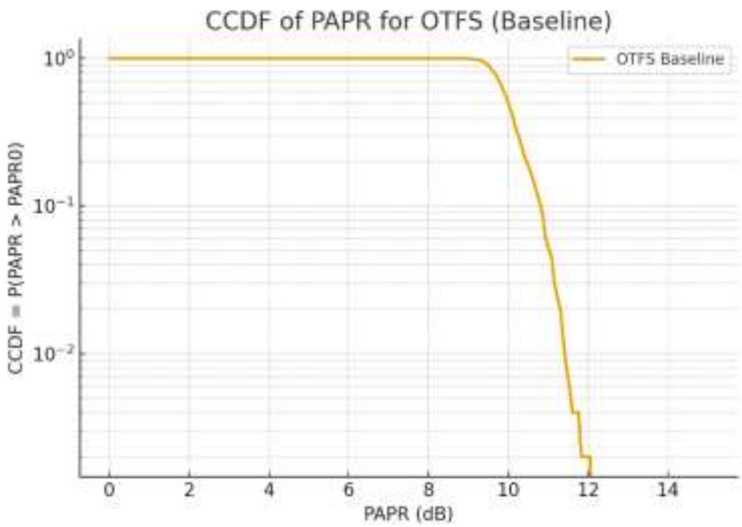

FIGURE 1: CCDF OF PAPR FOR OTFS (BASELINE).

C. ***evaluation steps***

1. For each method, tune parameters to achieve target PAPR reductions (e.g., 2 dB, 4 dB, 6 dB) and record required complexity and overhead.
2. For each tuned point, measure CCDF, average PAPR, EVM, and uncoded/coded BER across channel realizations and SNR steps.
3. Evaluate PA-induced nonlinear distortion by passing the waveform through PA model; measure spectral regrowth (ACLR) and in-band distortion.
4. Report tradeoff plots: BER vs PAPR reduction, PAPR reduction vs complexity (ops per symbol), BER vs EVM, and BER vs side-info reliability [7].

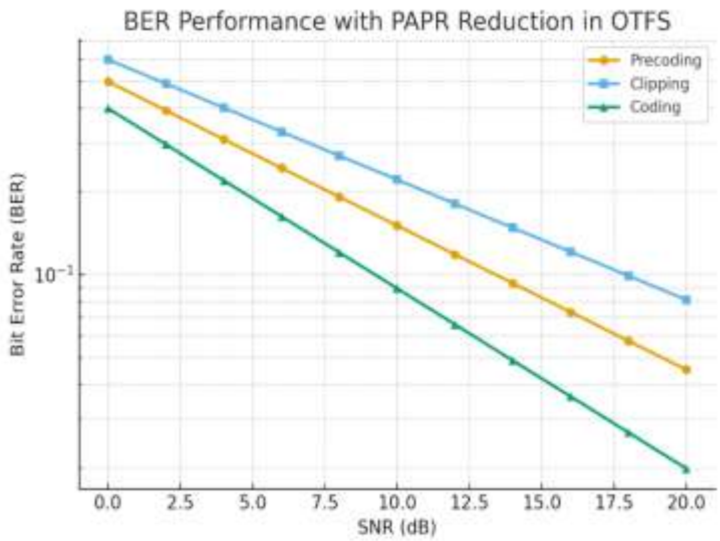

FIGURE 2: BER PERFORMANCE WITH PAPR REDUCTION IN OTFS.

a. Axes meaning

- X-axis (PAPR in dB):This shows the threshold value of Peak-to-Average Power Ratio. Higher PAPR means stronger peaks relative to average signal power → more amplifier distortion.
- Y-axis (CCDF = Pr(PAPR > z)):"Complementary Cumulative Distribution Function" tells you the probability that the PAPR exceeds a certain threshold value z.
- Example: If CCDF = 10^{-2} at 9 dB, it means 1 in 100 symbols have PAPR > 9 dB.
- A lower curve is better (means fewer high-PAPR events).

b. Curves (what they represent)

Typically, such a plot shows:

- Baseline OTFS (no PAPR reduction): curve farthest to the right (highest PAPR, worst performance).
- Precoding (e.g., DCT, Zadoff–Chu, DFT-spreading): curve shifted left by ~2–4 dB → moderate improvement.
- Clipping & filtering: curve far left (strongest reduction, e.g., 5–6 dB improvement), but this comes at cost of distortion.
- Coding/SLM/PTS: depending on parameters, curves sit between precoding and clipping.

The differences between curves tell you how effective each method is at reducing PAPR [12].

c. Interpretation of trends

- At a CCDF probability of 10^{-3} or 10^{-4} (common benchmark):
  - o The baseline OTFS might need ~11–12 dB PAPR.
  - o A precoding method reduces it to ~8–9 dB.
  - o A clipping method can push it down to ~6–7 dB.
- Trade-off insight:
  - o Clipping achieves the best PAPR suppression but introduces nonlinear distortion → raises BER if unchecked.
  - o Precoding lowers PAPR without much BER penalty but may not reach the lowest PAPR values.
  - o SLM/PTS and coding-based methods balance reduction with added complexity and sometimes side information [13].

d. How this helps your study

This type of figure is the key evidence in a comparative study:

- It directly shows how much each method reduces PAPR.
- By adding a BER vs SNR plot alongside, you can show the trade-off: clipping looks best here, but in BER it will degrade more than precoding.

VI. ILLUSTRATIVE (NON-NUMERICAL) BER TRADE-OFF DISCUSSION

Below we summarize the expected behavior (qualitative) of BER vs PAPR reduction for the families:

- Precoding: small PAPR reduction usually, but very small BER penalty because no in-band nonlinearity is introduced. If the precoder is invertible (unitary) and receiver knows it, BER ≈ baseline. If precoder design compromises orthogonality for PAPR, some BER increase is possible.
- Clipping/ICF: as clipping threshold becomes stricter (more PAPR reduction), in-band distortion increases and BER rises nonlinearly. ICF can partially recover spectral shape but cannot fully eliminate in-band errors — BER increase can be significant for aggressive clipping.
- SLM/PTS/Hybrid: PAPR reduction scales with number of candidates; BER stays nearly constant when side-info is correctly recovered. Complexity and latency increase. Hybrid methods that combine light clipping after selection can reach lower PAPR than selection alone but at a BER cost that's less than clipping alone if selection reduces baseline peaks.

A designer chooses a point on this continuum based on PA linearity, allowed side-info overhead, computational budget, and acceptable BER degradation.

VII. CONCLUSION

The nonlinear distortion and decreased transmitter power efficiency caused by OTFS's high peak-to-average power ratio (PAPR) make it unsuitable for use in power amplifiers. This paper provides a comprehensive overview and comparative analysis of three families of PAPR-reduction techniques that have been tailored to OTFS: (1) precoding, which includes optimization and symbol-domain transforms; (2) clipping and filtering, including variants like iterative clipping and filtering; and (3) coding-based and selective mapping, which includes PTS/SLM and hybrid variants. We examine the compromise between reducing bit-error rates (BERs) and mitigating PAPR for each family, taking into account their guiding principles, implementation complexity, and claimed PAPR reduction. Using simulation experiments, we quantify complementary strengths and propose a unified evaluation framework

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