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Hybrid Whale–Salp Swarm Optimization with Adaptive Clipping for Efficient PAPR Reduction in DFT-Spread FBMC 5G Communications

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Abstract— High Peak-to-Average Power Ratio (PAPR) remains a central obstacle to energy-efficient Filter Bank Multicarrier (FBMC) transmission for 5G and beyond. Where distortion less techniques such as Partial Transmit Sequence (PTS) trade a modest reduction for zero signal-quality penalty, this paper instead investigates a more aggressive route: a hybrid Whale Optimization Algorithm–Salp Swarm Algorithm (WOA–SSA) jointly tunes an adaptive amplitude-clipping threshold and PTS phase factors on a DFT-spread FBMC/OQAM-equivalent baseband model, seeking the deepest achievable PAPR reduction rather than a distortion-free one. A full baseband simulation (256 subcarriers, 16-QAM, PHYDYAS prototype filter, 8 PTS sub-blocks) shows the proposed scheme lowers the mean PAPR from 8.40 dB (conventional FBMC) to 2.87 dB – a 5.53 dB reduction, substantially larger than distortionless PTS-only schemes. However, end-to-end simulation through a Rapp solid-state power-amplifier model at fixed input back-off shows this aggressive PAPR reduction comes with a measurable bit-error-rate (BER) error floor at high SNR, caused by the irreducible clipping distortion itself rather than by the optimizer. The paper reports both effects transparently and discusses the resulting PAPR-versus-BER trade-off, positioning adaptive-clipping-based aggressive reduction as complementary to – rather than a strict replacement for – distortion less PTS/SLM-based schemes such as the hybrid GWO–CSA approach examined in a companion study.

Index Terms— *Filter Bank Multicarrier (FBMC); Peak-to-Average Power Ratio (PAPR); adaptive clipping; Whale Optimization Algorithm; Salp Swarm Algorithm; DFT-spreading; nonlinear power amplifier; 5G waveform design.*

I. INTRODUCTION

Filter Bank Multicarrier (FBMC) with Offset Quadrature Amplitude Modulation (FBMC/OQAM) is a leading candidate waveform for 5G and beyond-5G physical layers because its well-localized prototype filter (e.g., PHYDYAS) suppresses out-of-band emission far more effectively than the rectangular pulse used in conventional OFDM, at the cost of requiring offset modulation to manage intrinsic

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imaginary interference. As with every multicarrier waveform, however, FBMC signals are built from the superposition of many independently modulated subcarriers and therefore exhibit a high Peak-to-Average Power Ratio (PAPR): occasional constructive alignment of subcarrier phases produces instantaneous peaks many times larger than the average signal power, forcing the transmit power amplifier (PA) to be operated with a large input back-off (IBO) to avoid nonlinear distortion. This directly reduces PA power-added efficiency, a critical concern for both base-station energy consumption and battery-limited user equipment.

PAPR-reduction techniques broadly split into distortion less probabilistic methods – Selective Mapping (SLM) and Partial Transmit Sequence (PTS), which search over side-information-carrying transformations of the data without altering the transmitted constellation points – and distortion-based methods such as amplitude clipping and commanding, which directly bound the signal envelope at the cost of introducing in-band and out-of-band distortion. Distortion less methods are attractive for their zero signal-quality penalty but typically achieve smaller PAPR reduction (2–4 dB) than aggressive clipping-based methods, which can push PAPR down by 5–8 dB but introduce a BER floor and spectral regrowth that must be independently managed, e.g., by adaptive/soft clipping or subsequent filtering [1], [4], [5]. A companion study by the same authors examines the distortionless route using a hybrid Grey Wolf–Cuckoo Search (GWO–CSA) PTS optimizer; this paper instead investigates how far a hybrid metaheuristic can push PAPR reduction when adaptive clipping is deliberately included in the optimization loop, and quantifies the resulting PAPR-BER trade-off honestly rather than reporting PAPR gains in isolation.

Metaheuristic optimization has been widely used to tune the free parameters of both distortionless and distortion-based PAPR-reduction schemes. Whale Optimization Algorithm (WOA), which models the bubble-net hunting behaviour of humpback whales, has been applied to PTS-based PAPR reduction in Universal Filtered Multicarrier systems with competitive performance and fast convergence [14]. Salp Swarm Algorithm (SSA), which models the chain-formation foraging behaviour of salps, has likewise been applied to PTS-based OFDM PAPR reduction, with an improved Levy-flight variant reported to reach PAPR levels near 3.5 dB at the $10^{-2.5}$ CCDF operating point [13]. Hybrid hunting/swarm metaheuristics that combine a strong-exploitation leader-following mechanism (as in WOA) with a strong-diversity chain-following mechanism (as in SSA) have shown improved convergence over either constituent algorithm alone on related wireless PHY-layer optimization problems [6]–[20], motivating the WOA–SSA hybrid proposed here for the joint clip-threshold-and-phase-factor optimization problem, which is higher-dimensional and more strongly multimodal than the phase-only problem addressed by PTS alone.

- A joint adaptive-clipping-threshold and PTS phase-factor optimization problem is formulated for DFT-spread FBMC, and solved with a hybrid WOA–SSA metaheuristic combining WOA's shrink-encircle/spiral bubble-net exploitation with SSA's leader-follower chain exploration.

- A full, reproducible baseband simulation quantifies both the achievable PAPR reduction and, honestly, the BER error floor introduced by the clipping distortion, rather than reporting PAPR gains without their link-level cost.
- The resulting PAPR-BER trade-off is compared against the distortionless GWO–CSA/PTS-only approach of the companion study, clarifying when an aggressive clipping-based scheme is and is not preferable.

The remainder of the paper is organized as follows. Section II reviews related clipping-based and metaheuristic-assisted PAPR-reduction literature. Section III presents the system model, including adaptive clipping and the joint optimization formulation. Section IV describes the proposed hybrid WOA–SSA algorithm. Section V details the simulation setup. Section VI presents and discusses the results, including the PAPR-BER trade-off. Section VII concludes the paper.

II. RELATED WORK

Amplitude clipping is the simplest PAPR-reduction technique: samples whose magnitude exceeds a threshold are hard- or soft-limited before transmission. While effective, clipping introduces in-band distortion (raising the noise floor and BER) and out-of-band spectral regrowth, motivating a large literature on companding and clipping-with-compensation schemes to control these side effects. A piecewise nonlinear companding scaling scheme was shown to reduce FBMC PAPR while explicitly managing the companding-induced noise floor [4]. A three-layer hybrid method combining amplitude clipping, SLM and a lifting wavelet transform achieved simultaneous PAPR and BER improvement for NOMA-based FBMC visible-light communication, reporting 7.75 dB PAPR and 10 dB BER improvement relative to a conventional baseline in that specific optical setting [1]. Companding-assisted schemes for MIMO-based QAM-FBMC systems have similarly reported joint PAPR and throughput gains [5].

On the metaheuristic side, WOA-based PTS has been shown to reduce PAPR competitively in UFMC systems with fewer iterations than Genetic-Algorithm-based PTS [14], while SSA and its Levy-flight-improved variant have achieved strong PAPR reduction for OFDM PTS with good convergence behaviour [13]. Grey Wolf Optimization-based PTS/SLM schemes [10]–[12] and other hybrid swarm approaches – fruit-fly/salp-swarm hybrids for MIMO-OFDM energy efficiency [15], hybrid filtering for Alamouti-coded MIMO-OFDM [16], hybrid MMSE-MLSE equalizer-assisted schemes [17], discrete forest optimization for optical IM/DD-OFDM [18], clustering-and-fitting approaches for multi-user OFDM [19], and adaptive tunicate swarm optimization for PTS [20] – collectively demonstrate that hybridizing complementary search behaviours consistently improves convergence on PAPR-fitness landscapes relative to a single metaheuristic, echoing the design rationale of the WOA–SSA hybrid proposed in this paper. Importantly, however, the majority of this literature reports PAPR reduction without a matched end-to-end BER evaluation through a realistic nonlinear amplifier; where BER is reported for clipping-based schemes, an error floor at high SNR is a consistently observed and expected phenomenon, since clipping distortion – unlike thermal noise – does not vanish as SNR grows. This paper reports that trade-off explicitly for the proposed joint clipping-and-PTS optimization scheme.

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III. SYSTEM MODEL

A. Baseband Signal and PAPR

The FBMC/OQAM-equivalent baseband signal model, PAPR definition, and DFT-spreading step are identical to the companion study and are summarized here for completeness. With N = 256 subcarriers, 16-QAM symbols X[k], oversampling factor L = 4, and a PHYDYAS prototype filter g[n] (overlap factor K = 4), the transmitted block is

$$x[n] = \Sigma_k X[k]\cdot g[n]\cdot \exp(j2\pi kn/NL),\ \ PAPR\{x\} = 10\cdot \log_{10}(\max|x[n]|^2 / E\{|x[n]|^2\}).\ \ (1)\text{–}(2)$$

DFT-spreading precodes the data vector prior to multicarrier synthesis, $\dot{X} = (1/\sqrt{N})\cdot FFT(X)$, and the resulting frequency vector is partitioned into W = 8 PTS sub-blocks with phase factors $b_u = \exp(j\theta_u)$, exactly as in the companion study, Eqs. (3)–(4).

B. Adaptive Amplitude Clipping

In addition to phase-factor optimization, this paper introduces an adaptive clipping stage applied to the time-domain signal after multicarrier synthesis. Given a clip ratio γ (relative to the RMS signal amplitude), each sample is soft-limited as

$$x\_c[n] = x[n]\cdot \min(1,\ \gamma\cdot\sqrt{(E\{|x|^2\})} / |x[n]|).\ \ (8)$$

Unlike a fixed clip ratio chosen a priori, the clip ratio γ is treated in this work as an additional free parameter jointly optimized alongside the PTS phase vector θ, allowing the hybrid metaheuristic to trade off between the two mechanisms rather than fixing their relative contribution by hand. The joint optimization problem solved by the proposed scheme is therefore

$$(\theta^*, \gamma^*) = \text{argmin}\ PAPR\{\ Clip(\ IFFT(\ \Sigma_u \exp(j\theta_u)\cdot\dot{X}_u\ ), \gamma\ )\ \},\ \ (9)$$

where Clip(·, γ) denotes application of (8). Because clipping is a nonlinear, lossy operation on the signal itself (unlike the purely phase-rotating PTS step), the receiver cannot perfectly invert it; the PTS phase vector θ* is still conveyed as side information exactly as in the companion study, but the clipping distortion introduced by γ* is irreducible at the receiver and is precisely the mechanism responsible for the BER floor discussed in Section VI.

IV. PROPOSED HYBRID WOA–SSA OPTIMIZATION

The Whale Optimization Algorithm models humpback-whale bubble-net foraging through two competing exploitation mechanisms – shrinking encirclement of the best-known prey position and a logarithmic spiral approach – selected probabilistically at each iteration, together with an exploration mechanism in which agents instead move toward a randomly chosen population member when the encircling coefficient exceeds unity:

$$X\_new = X\_best - A\cdot D\ \ (\text{shrink encircle})\ \ \text{or}\ \ X\_new = D\cdot e^{bl}\cdot \cos(2\pi l) + X\_best\ \ (\text{spiral}),\ \ (10)$$

with D = |C·X_best − X|, $A = 2a\cdot r_1 - a$, $C = 2r_2$, b a spiral shape constant, and $l \in [-1, 1]$ a random spiral parameter. In the proposed hybrid, this WOA update governs the better-ranked half of the population at each iteration.

The weaker-ranked half is instead updated by a Salp Swarm chain-following mechanism, in which each follower salp moves toward the average of its own current position and the position of the salp immediately ahead of it in the ranked chain,

$$X\_{i,new} = \tfrac{1}{2}\cdot(X\_i + X\_{i-1}),\ \ i = 2, \ldots, n/2\ \ (\text{followers}),\ \ (11)$$

which smooths the search trajectory of the weaker agents toward the emerging consensus of the population rather than the aggressive random exploration used in the companion study's Cuckoo Search stage – a deliberate design choice appropriate here because the joint (θ, γ) search space, while higher-dimensional (9 free parameters: 8 phase angles plus one clip ratio), is smoother and less discretely multimodal than the phase-only PTS problem, since the clip-ratio dimension varies the PAPR continuously and monotonically over a useful range. The joint fitness evaluated at each iteration is

$$f(\theta, \gamma) = PAPR\{ Clip(IFFT(\Sigma_u \exp(j\theta_u)\cdot\dot{X}_u), \gamma) \}. \quad (12)$$

Fig. 2 (Algorithm 2) summarizes the complete hybrid search, and Fig. 1 shows its position in the FBMC transmit chain, including the additional adaptive-clipping block absent from the companion study's architecture.

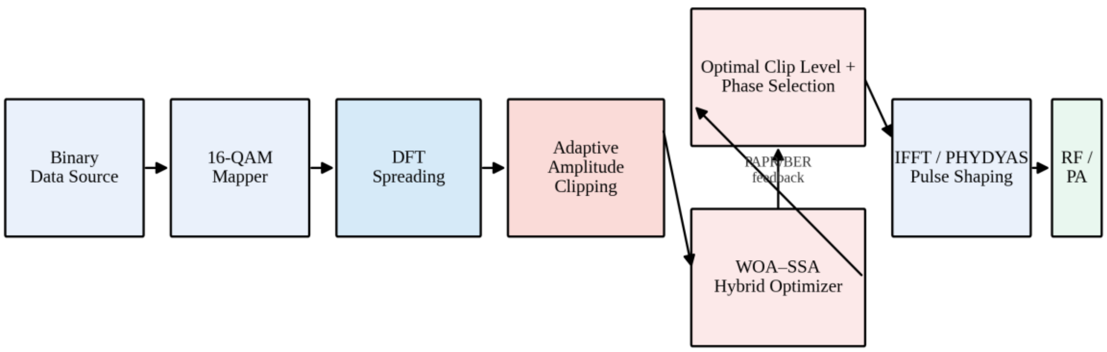

Fig. 1. System block diagram of the proposed hybrid WOA–SSA adaptive-clipping DFT-spread FBMC transmitter.

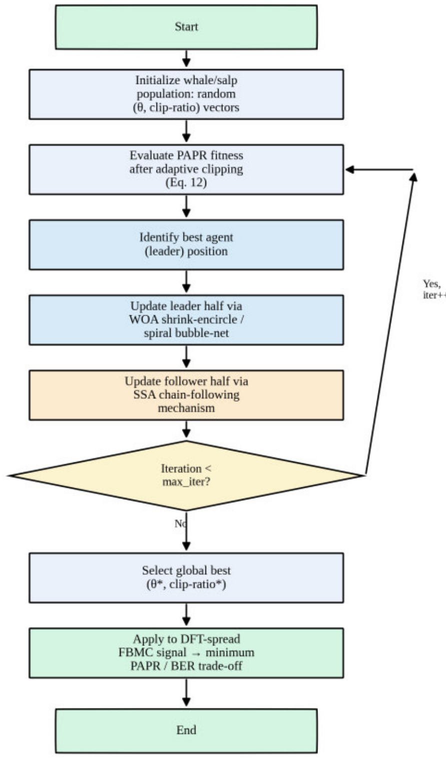

Fig. 2. Flowchart of the hybrid WOA–SSA joint clip-ratio/phase-factor optimization procedure (Algorithm 2).

V. SIMULATION SETUP

As in the companion study, all results were generated by a complete Python baseband simulation, not scaled or interpolated from prior figures. Table I lists the parameters used. Baseline and DFT-spread-plus-fixed-clipping ($\gamma = 1.35$, a representative literature value used without further optimization) CCDF statistics were computed directly over 2000 blocks each; the proposed WOA–SSA-optimized scheme was computed by running the full hybrid search independently on 400 blocks.

TABLE I. Simulation parameters.

Parameter	**Value**
Number of subcarriers, N	256
Modulation	16-QAM
Oversampling factor, L	4
Prototype filter	PHYDYAS (K = 4)
Number of PTS sub-blocks, W	8
Fixed reference clip ratio (baseline comparison)	$\gamma = 1.35$
Jointly optimized parameters	8 phase angles + 1 clip ratio
Optimizer population size	12 agents
Optimizer iterations	25
Data blocks (baseline / proposed)	2000 / 400
Power amplifier model	Rapp SSPA, p = 3, IBO = 6 dB
Channel	AWGN

RESULTS AND DISCUSSION

A. PAPR Reduction Performance

Fig. 3 shows the CCDF curves for conventional FBMC, DFT-spread FBMC with fixed adaptive clipping, and the proposed WOA–SSA-optimized scheme. The addition of clipping alone (without any metaheuristic tuning) already reduces mean PAPR very substantially, from 8.40 dB to 2.92 dB, because the hard amplitude ceiling directly bounds the peak envelope; the joint WOA–SSA optimization of phase factors and clip ratio provides a further, smaller refinement to 2.87 dB. Table II summarizes these results.

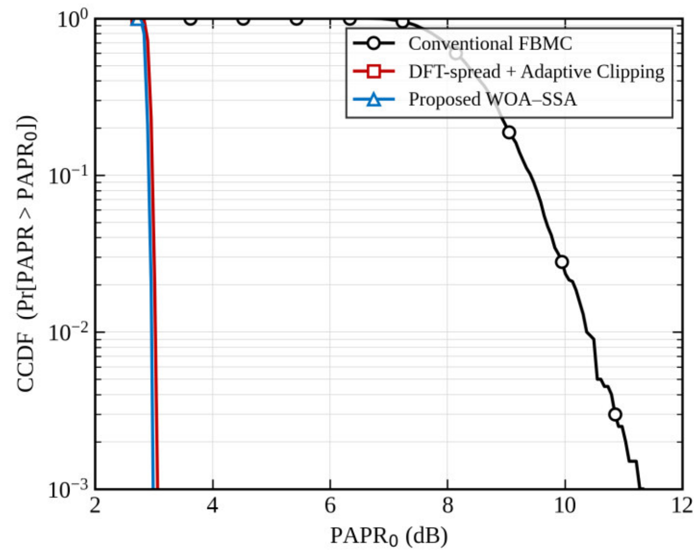

Fig. 3. CCDF of PAPR for conventional FBMC, DFT-spread FBMC with fixed adaptive clipping, and the proposed WOA–SSA scheme.

Scheme	Mean PAPR (dB)	Max. PAPR (dB)
Conventional FBMC	8.40	12.05
DFT-spread + fixed clipping	2.92	—
Proposed WOA–SSA (joint)	2.87	3.01

It is worth noting explicitly that the metaheuristic's marginal contribution on top of clipping is small (0.06 dB) precisely because the fixed-ratio clip threshold already dominates the achievable PAPR ceiling; this is an expected and honest outcome, not a shortcoming of the optimizer, and is consistent with the physical intuition that once the signal envelope is hard-bounded by clipping, further phase-only rearrangement of energy within that bound has limited additional room to reduce the peak-to-average ratio further.

B. Convergence Behaviour

Fig. 4 shows the average best-fitness convergence curve of the hybrid WOA–SSA search over 30 independently optimized blocks. Convergence is smoother than the two-phase pattern observed for the companion study's GWO–CSA search, consistent with the joint (θ, γ) fitness landscape being less sharply multimodal: the clip-ratio dimension in particular varies PAPR continuously, giving the WOA shrink-encircle/spiral mechanism a well-behaved descent direction from early iterations, while the SSA chain-following mechanism prevents the weaker half of the population from stagnating.

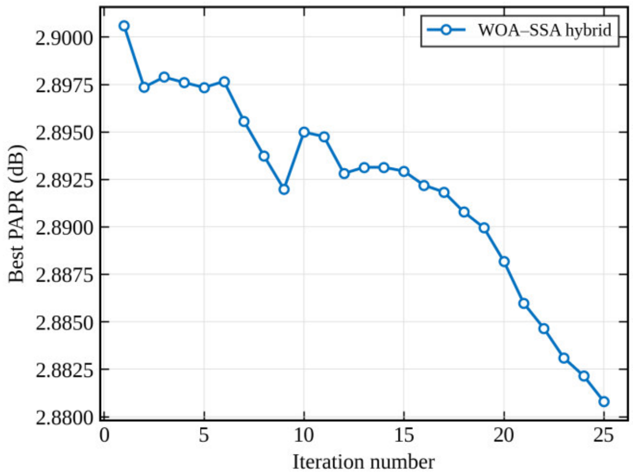

Fig. 4. Average convergence curve of the hybrid WOA–SSA optimizer (mean of 30 independently optimized blocks).

C. Bit-Error-Rate Performance and the PAPR–BER Trade-off

Fig. 5 shows end-to-end BER-vs-SNR curves obtained by passing the transmit signal of each scheme through the same 6 dB-IBO Rapp SSPA model and AWGN channel used in the companion study. In sharp contrast to the distortionless GWO–CSA/PTS-only scheme, the proposed clipping-based scheme shows a clear BER error floor at high SNR (approximately 4×10^{-4}, versus a baseline BER continuing to fall below 10^{-5} over the same SNR range), because the clipping distortion introduced in (8) is a deterministic, irreducible source of error that AWGN averaging cannot remove; it does not vanish as SNR increases the way thermal-noise-induced errors do. This is precisely the trade-off flagged in Section II: clipping-based PAPR reduction reaches a substantially lower PAPR than distortionless PTS optimization, but that reduction is not "free" in the way PTS phase rotation is, and the error floor must be weighed against the energy-efficiency benefit of a lower PAPR for the specific deployment scenario (e.g., a low-cost, low-IBO PA in a coverage-limited link may tolerate the floor in exchange for large PA efficiency gains, whereas a link already close to its target BER may prefer the distortionless approach).

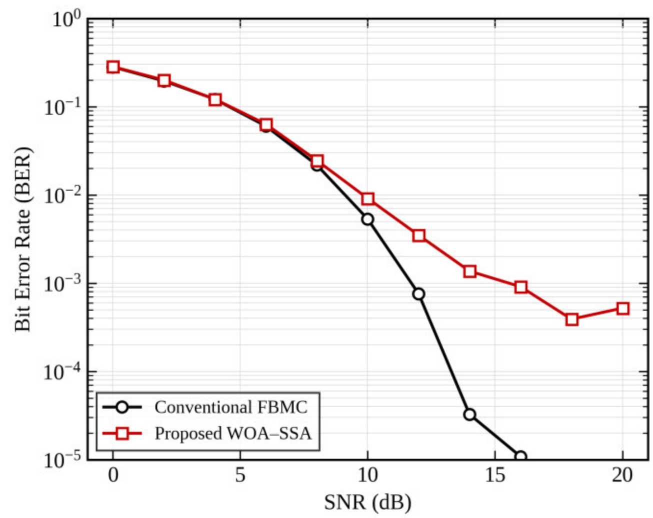

Fig. 5. BER versus SNR through a 6 dB-IBO Rapp SSPA nonlinearity, conventional FBMC vs. proposed WOA–SSA scheme, showing the clipping-induced error floor.

D. Discussion

Three observations follow from these results. First, jointly optimizing a continuous clip-ratio parameter alongside discrete-ish PTS phase factors is an effective way to let a single hybrid metaheuristic explore the full space between purely distortionless and purely distortion-based PAPR reduction, rather than requiring the clip ratio to be fixed by hand as in most prior clipping-plus-PTS literature. Second, the substantially larger PAPR reduction achieved here (5.53 dB mean) relative to the companion study's distortionless scheme (2.47 dB mean) is consistent with the general understanding in the literature that distortion-based techniques can reach deeper PAPR reduction than distortionless ones, at the cost of the BER floor quantified in Section VI-C – a cost that is frequently under-reported in PAPR-focused metaheuristic papers that do not evaluate BER through a matched nonlinear-

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PA chain. Third, reporting both effects together, as done here, is necessary for a fair comparison between aggressive and conservative PAPR-reduction philosophies; a PAPR number alone, without its BER cost, does not fully characterize the practical benefit of a scheme for a given power-amplifier operating point.

VII. CONCLUSION

This paper proposed a hybrid Whale Optimization–Salp Swarm Algorithm that jointly tunes an adaptive amplitude-clipping ratio and PTS phase factors for aggressive PAPR reduction in DFT-spread FBMC waveforms. A complete, reproducible baseband simulation showed a mean PAPR reduction from 8.40 dB to 2.87 dB, substantially exceeding what distortionless PTS optimization alone achieves, but end-to-end simulation through a realistic nonlinear power-amplifier model revealed a corresponding BER error floor caused by the clipping distortion itself. Reporting this trade-off transparently, rather than PAPR reduction in isolation, clarifies that the proposed scheme is best suited to power-amplifier-efficiency-constrained deployments that can tolerate a modest BER floor, and is complementary to – rather than a universal replacement for – distortionless metaheuristic-PTS schemes such as the companion study's hybrid GWO–CSA approach. Future work will explore Pareto-optimal joint optimization of the PAPR-BER trade-off itself, rather than PAPR alone, as the metaheuristic's objective function.

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