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A Low-Complexity Adaptive Hybrid SLM-PTS with Grey Wolf Optimization (GWO) for PAPR Reduction in OFDM Systems

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Abstract: Orthogonal Frequency Division Multiplexing (OFDM) is widely adopted in modern broadband wireless systems due to its high spectral efficiency and robustness against frequency-selective fading. However, the inherently high peak-to-average power ratio (PAPR) of OFDM signals induces nonlinear distortion in high-power amplifiers, degrading bit error rate (BER) and spectral efficiency. Selected mapping (SLM) and partial transmit sequence (PTS) are distortion-free PAPR-reduction schemes that trade-off complexity and redundancy for improved envelope statistics. Conventional SLM-PTS hybrids often incur excessive computational load or require exhaustive search over large phase-vector spaces .This paper proposes an adaptive hybrid SLM-PTS technique enhanced by Grey Wolf Optimization (GWO) for PAPR reduction in OFDM systems. The method combines SLM-type phase rotations on a subset of sub-blocks with a PTS-like weighted combination stage whose phase vector is optimized by an adaptive GWO engine. Detailed mathematical modeling is provided for the OFDM signal, PAPR, SLM and PTS transformations, and the GWO search dynamics. Simulation results show that the proposed scheme reduces the PAPR from 7.88 dB (original OFDM) to 4.61dB at a complementary cumulative distribution function (CCDF) level of $10^{\{-3\}}$, outperforming SLM (6.79 dB), PTS (5.25dB), and conventional hybrid SLM-PTS (5.25dB) while maintaining negligible BER degradation. A comprehensive complexity analysis verifies that the adaptive GWO-based framework achieves superior PAPR-performance with significantly lower computational overhead than exhaustive hybrid SLM-PTS .

Keywords: *OFDM, PAPR Reduction, Selected Mapping (SLM), Partial Transmit Sequence (PTS), Hybrid SLM-PTS, Grey Wolf Optimization (GWO), Adaptive Optimization, BER, Computational Complexity.*

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I. INTRODUCTION

➢ *OFDM Overview*

Orthogonal Frequency Division Multiplexing (OFDM) partitions a high-rate data stream into multiple low-rate, orthogonal subcarriers, each modulated by schemes such as QPSK or 16-QAM. The time-domain signal for an N-subcarrier OFDM symbol is given in equation 1.1.

$$X(k) = \sum_{n=0}^{N-1} x(n)\ e^{-j\frac{2\pi}{N}kn_N} \ , n = 0,1,2, \dots , N-1 \text{ ------ } (1.1)$$

Where X_k is the complex symbol on the k − th subcarrier and N is the IFFT/FFT size. At the receiver, an FFT recovers the subcarrier symbols, and standard equalization mitigates multipath fading and inter-carrier interference.

OFDM's tolerance to frequency-selective channels, efficient frequency-domain equalization, and flexible resource allocation have made it the core of LTE, 5G NR, and Wi-Fi systems. However, the coherent summation of multiple subcarriers can generate large peaks in the time-domain waveform, leading to a high PAPR.

➢ *PAPR Problem*

The PAPR of an OFDM symbol vector x = [x(0), … , x(N − 1)]is defined in equation 1.2.

$$PAPR = \frac{\max\ |x(n)|^2}{E[|x(n)|^2]} \text{ --------- } \quad (1.2)$$

High PAPR forces the high-power amplifier (HPA) to operate below saturation to avoid nonlinear distortion, reducing power efficiency. When the HPA is driven close to saturation, the resultant distortion increases BER and out-of-band emissions, complicating compliance with spectral-mask requirements.

➤ *Limitations of SLM and PTS*

Selected mapping (SLM) and partial transmit sequence (PTS) are distortion-free PAPR-reduction techniques. In SLM, the same frequency-domain symbol X is multiplied by U different phase-rotation vectors b_u, yielding candidate waveforms in shown in equation 1.3.

$$= \mathcal{F}^{-1}(X \odot b_u), u = 0,1, \dots, U-1 \text{ -------- } \quad (1.3)$$

The waveform with minimum PAPR is selected for transmission. In PTS, the data block is partitioned into V disjoint sub-blocks $X^{(v)}$, and the corresponding partial-time signals $x^{(v)}$ are weighted by phase factors βv to form

$$x = \sum_{v=0}^{V-1} \beta_v x^{(v)} \text{ ----------- } \quad (1.4)$$

Both schemes achieve significant PAPR reduction but suffer from high computational load and side-information overhead. Brute-force SLM-PTS hybrids amplify the search space exponentially, making them impractical for real-time systems. Recent GWO-based SLM-PTS designs partially mitigate this issue but still lack adaptive control mechanisms that tailor the optimization effort to instantaneous PAPR and BER conditions.

➤ *Research Gap and Contributions*

Existing hybrid SLM-PTS schemes often employ fixed search spaces or non-adaptive population sizes, leading to suboptimal performance-complexity trade-offs. The lack of dynamic thresholding and adaptive GWO parameter adjustment prevents these methods from efficiently exploiting favorable channel conditions. Consequently, there is a need for an adaptive, low-complexity hybrid SLM-PTS-GWO framework that balances PAPR reduction, BER performance, and computational efficiency.

This paper contributes an adaptive hybrid SLM-PTS-GWO technique for PAPR reduction in OFDM systems. The main contributions are:

- A low-complexity adaptive hybrid SLM-PTS architecture that combines SLM-type phase rotations on a subset of sub-blocks with a PTS-like weighted combination stage whose phase vector is optimized by a modified GWO engine.
- Adaptive threshold mechanisms using γ_{th}, η_{thr}, and ε_{thr} to dynamically adjust search depth and population size based on instantaneous PAPR and BER estimates.
- Detailed mathematical modeling of the OFDM signal, PAPR, SLM and PTS transformations, and GWO search dynamics.
- Extensive simulations demonstrating that the proposed scheme achieves a PAPR reduction from 7.88 dB (original OFDM) to 4.61 dB, outperforming SLM (6.79 dB), PTS (5.25 dB), and hybrid SLM-PTS (5.25 dB).
- Comprehensive complexity analysis showing reduced computational overhead compared to exhaustive hybrid SLM-PTS.

II. LITERATURE REVIEW

High PAPR in OFDM has motivated extensive research over the past two decades, leading to techniques ranging from clipping and companding to intelligent optimization-based methods. Early solutions such as clipping and companding provide simplicity but introduce distortion and out-of-band emissions, which necessitate additional filtering and back-off at the high-power amplifier (HPA). In contrast, SLM and PTS preserve symbol integrity by operating solely on phase-rotation degrees of freedom, making them attractive for applications with strict distortion constraints.

Several works have analyzed the performance trade-offs between SLM and PTS. Standard SLM generally offers better PAPR reduction for a given redundancy level, whereas PTS achieves superior PAPR reduction per unit of added complexity. Hybrid SLM-PTS schemes have been proposed where both SLM-type rotations and PTS sub-blocks are jointly used to achieve enhanced PAPR reduction at the expense of increased IFFT operations and search effort. More recent studies have explored intelligent optimization-based SLM and PTS designs.

Particle-swarm or harmony-search-based PTS schemes accelerate phase-vector search, though at the cost of higher implementation overhead. GWO-based PTS designs have demonstrated faster convergence and lower complexity than conventional PTS, but most of these constructions apply the optimizer in a black-box manner without explicitly tailoring the search depth or population size to the PAPR and BER of the OFDM waveform.

Overall, existing works demonstrate that SLM-PTS-based and GWO-based PAPR-reduction schemes can achieve meaningful performance gains, but they often rely on either exhaustive search, fixed optimization parameters, or non-adaptive pruning, leading to suboptimal performance-complexity trade-offs. The current literature lacks a systematic, low-complexity, adaptive hybrid SLM-PTS framework that jointly leverages GWO-based optimization and adaptive control to balance PAPR reduction, BER, and computational cost .

➤ *Table Camparision of Existing PAPR Reduction Techniques*

Author/Year	Method Used	Key Idea	Limitation
Han & Lee (2005)	SLM / PTS	Introduced distortion-free PAPR techniques	High computational complexity
Ganesh et al. (2013)	Hybrid SLM-PTS	Combined SLM and PTS methods	Improved SLM using adaptive selection
Abdul-Satar et al. (2017)	GWO-based PTS	Used GWO for phase optimization	No adaptive mechanism
Prasad et al. (2017)	PSO-based PTS	Reducedsearch using swarm optimization	Higher processing overhead
Reddy et al. (2020)	Adaptive SLM	ImprovedSLM using adaptive selection	Limited performance gain
Proposed Work	Adaptive Hybrid SLM-PTS-GWO	Dynamic optimization withreduced complexity	—

III. METHODOLOGY

- *Hybrid SLM-PTS Structure*

The proposed hybrid SLM-PTS-GWO architecture is constructed at the transmitter. The frequency-domain symbol block $X = [X_0, X_1, \dots, X_{N-1}]$ is partitioned into V disjoint sub-blocks

correct form:

$$X_k(v) = \begin{cases} X_0, & k = v \\ 0, & \text{otherwise} \end{cases} v = 0,1,\dots,V-1 \quad \text{---------} \quad (3.1)$$

Where I_v is the index set for the v − th sub-block and the union of all index sets equals {0,...,N-1}, with disjoint sub-blocks. Each sub-block $X^{(v)}$ is transformed to the time domain via IFFT, yielding the partial-time signals $x^{(v)}$.

Among these, a subset of $V_s \leq V$ sub-blocks V_s are subjected to SLM-type phase rotations. For each SLM branch index u ∈ {0,1,...,U-1}, a phase-rotation vector $b_u^{(v)}$ with entries on the unit circle is applied to the v-th SLM-enabled sub-block as

$$X\,(v) = X^{(v)} \odot b_u^{(v)}, v \in \mathcal{V} \quad \text{---------} \quad (3.2)$$

The corresponding partial-time signal is then

$$x\,(v) = \mathcal{F}^{-1}(\tilde{X}_u^{(v)}), v \in \mathcal{V} \quad \text{---------} \quad (3.3)$$

The remaining sub-blocks v ∉ V_s are kept unrotated, i.e., tilde $x_u^{(v)} = x^{(v)}$. A PTS-like weighted combination is then formed as

$$x_u = \sum_{v=0}^{V-1} \beta_u^{(v)}\ \tilde{x}_u^{(v)} \text{------} \quad (3.4)$$

Where the phase vector $^{(u)} = [\beta_0{}^{(u)}, \beta_1{}^{(u)}, \dots, \beta_V{}^{(u\_)}{}_1]$ has entries in the J-phase set

$$\beta \in \{ej2\pi mJ \mid m=0,1,\dots,J-1\} \quad \text{--------} \quad (3.5)$$

The optimization objective is to minimize the PAPR of the composite waveform over the joint space of u and β(u), i.e.,

$$(u*,\beta(u*))=\arg\min u,\beta \mathrm{PAPR}(xu(\beta(u)))\text{--------} \quad (3.6)$$

- *Adaptive Threshold Mechanism*

Instantaneous PAPR P_t and BER BER_t are estimated at the receiver and used to update adaptive thresholds $gamma_{th}$, eta_{thr}, and $epsilon_{thr}$. The running averages P_{bar} and BER_{bar} are updated as

$$P^{-}(t+1) = \alpha_1 P^{-}(t) + (1-\alpha_1)P_t \text{ --------} \quad (3.2.1)$$

$$BER^{-}(t+1) = \alpha_2 BER^{-}(t) + (1-\alpha_2)ER_t \text{ --------}(3.2.2)$$

For forgetting factors 0 < alpha_1, alpha_2 < 1.

The adaptive PAPR threshold is then set as

$$\gamma \mathrm{th}(t) = \min\,(\gamma \mathrm{max},\ \alpha 1\, \mathcal{P}^{-}\,(t+1) + (1-\alpha 1)\,\mathcal{P}t)\ (3.2.3)$$

$$\eta \mathrm{thr}(t) = \max\,(\eta \mathrm{min},\ \alpha 2\ \mathrm{BER}^{-}(t+1) + (1-\alpha 2)\ \mathrm{BER}t) - \quad (3.2.4)$$

$$\epsilon \mathrm{thr}(t) = \gamma \mathrm{th}(t) - \Delta \text{ ------} \quad (3.2.5)$$

Where Delta is a small guard margin.

Depending on the current load and P_t, the GWO engine scales the population size N_{pop} and iteration count T_{max} using piecewise rules similar to those defined in the literature, favoring lightweight searches in low-PAPR frames and deeper optimization in high-PAPR ones.

- *Optimization Formulation*

The objective is to minimize PAPR subject to constraints on peak power, average power, BER, and computational budget:

$$(u^*,{}^{(u^*)} = \underset{u,\beta}{\arg\min}\ \mathrm{PAPR}(x_u(\beta^{(u)})) \text{ -----} \quad (3.3.1)$$

Subject to:

- *Peak-Power Constraint:*

$$\max |x_u(n)|^2 \leq P_{\text{peak}} \text{ ------} \quad (3.3.2)$$

- *Average-Power Constraint:*

$$N^{\frac{1}{}}\sum_{n=0}^{N-1} |x_u(n)|^2 \leq P_{\text{avg}} \text{ ------} \qquad (3.3.3)$$

- *BER Constraint:*

$$\text{BER}(\text{SNR}, \beta^{(u)}) \leq \text{BER}_{\text{max}} \text{ -------} \qquad (3.3.4)$$

- *Maximum Flops Budget:*

$$\text{FLOPs}(u, \beta^{(u)}) \leq \text{FLOPs}_{\text{max}} \text{ -------} \qquad (3.3.5)$$

The fitness function for the GWO optimizer is:

$$f(\beta^{(u)}) = \text{PAPR}(x_u(\beta^{(u)}))\lambda_1(\text{BER}(\text{SNR}, \beta^{(u)})\text{BER}_{\text{ref}})\lambda_2 \frac{\text{FLOPs}}{\text{FLOPs}_{\text{max}}}\text{----} \qquad (3.3.7)$$

With positive penalty weights $_1$ and, $\lambda_2$and $(x)^+ = \max(x, 0)$

IV. ALGORITHM DESIGN

- *Step-By-Step Algorithm*

- *Initialization*

The frequency-domain symbol vector X is generated from the input bit stream b using M-QAM mapping.

X is partitioned into V disjoint sub-blocks $X^{(v)}$, v = 0,1,...,V-1.

For each SLM-enabled sub-block v in the subset V_s , U phase-rotation vectors $b^{(v)}_u$are initialized with entries in the J-phase set.

The GWO parameters are set: population size N_{pop} , maximum iterations $T_{\max}$, and penalty weights lambda_1, lambda_2

- *SLM Phase-Sequence Generation*

For each SLM branch

$$u = 0,1, \ldots , U - 1: \text{-----} \qquad (4.1)$$

For each SLM-enabled sub-block $v \in V_s$:

Apply the phase rotation tilde

$$X_u{}^{(v)} = X^{(v)} \odot b_u{}^{(v)} \text{-----} \qquad (4.2)$$

Compute the partial-time signal tilde

$$^{(v)} = \mathcal{F}^{-1}(\tilde{X}_u^{(v)}) \text{ ------} \qquad (4.3)$$

For the remaining sub-blocks$v \notin V_s$, keep tilde

$$x^{(v)} = x^{(v)} = \mathscr{F}^{-1}(X^{(v)}) \text{ ------} \qquad (4.4)$$

- *PTS Sub-Block Combination And Hybrid Signal Formation*

For each SLM branch u, form the hybrid SLM-PTS signal

$$x_u = \sum_{v=0}^{V-1} \beta_u^{(v)} \tilde{x}_u^{(v)} \text{ -----} \qquad (4.5)$$

The baseline PAPR P_t for the current frame is computed from the unoptimized x_0 waveform.

- *Adaptive Threshold Update And GWO Activation*

- ✓ The running averages P_{bar} and BER_{bar} are updated using the recursive formulas in the previous section.
- ✓ The thresholds $gamma^t_{th}$, eta^t_{thr}, and $epsilon^t_{thr}$ are recomputed.
- ✓ If $P_t \leq gamma^t_{th}$, the system skips the GWO search and selects the best-available SLM branch without additional optimization.
- ✓ If $P_t > gamma^t_{th}$, the GWO engine is activated with population size N_{pop} and maximum iterations $T_{\max}$ adjusted according to the current P_t and BER_t.

- *GWO-Based Phase-Vector Optimization*

For each SLM branch u that is selected for optimization:

A population of N_p candidate phase vectors $\{^{(u)}\}^{N_{pop}}_{i=1}$ is initialized, each with entries in the J-phase set.

The fitness function is evaluated for each wolf i:

$$f_i(t) = f(\beta_i^{(u)}) = \text{PAPR}(x_u(\beta_i^{(u)})) + \lambda_1(\text{BER}(\text{SNR}, \beta_i^{(u)}) - \text{BER}_{\text{ref}}) + \lambda_2\left(\frac{\text{FLOPs}(\beta_i)}{\text{FLOPs}_{\text{max}}}\right)\text{--} \qquad (5.1)$$

The best-three wolves (alpha, beta, delta) are identified by sorting the fitness values.

The GWO update equations are applied iteratively to refine the phase-vector population, with the GWO convergence factor $^{(t)} = 2\,(1 - \underline{\quad})$

$T_{\max}$ and the control vectors

$$C1(t) = 2r1(t),\ C2(t) = 2r2(t),\ C3(t) = 2r3(t) \text{ -- } (5.2)$$

Where r_1, r_2, r_3 are random vectors in the range .

The updated phase components are projected back to the closest J-phase candidate.

The iteration loop terminates when the change in best fitness falls below a small tolerance delta_{tol} or when $t \geq T_{max}$.

- *Final Waveform Selection and Side-Information*

Among all SLM branches and GWO-optimized phase vectors, the pair $(u *, \beta^{(u*)})$ that minimizes $f(\text{beta}^{u})$ is selected and the corresponding time-domain waveform is transmitted

$$x\text{opt} = x_{u*}(\beta(u*))\text{---}()$$

The side-information bits indicating the SLM branch index u* and the compressed phase-vector index $(\beta^{(u*)})$ are appended to the control or pilot fields of the OFDM frame. On the receiver side, these indices are used to recover the original symbol vector and reconstruct the symbol.

V. BLOCK DIAGRAM AND FLOWCHART

➢ *Transmitter Block Diagram*

The proposed transmitter architecture can be depicted in Fig 1 as a standard OFDM chain followed by an adaptive hybrid SLM-PTS-GWO processing stage.

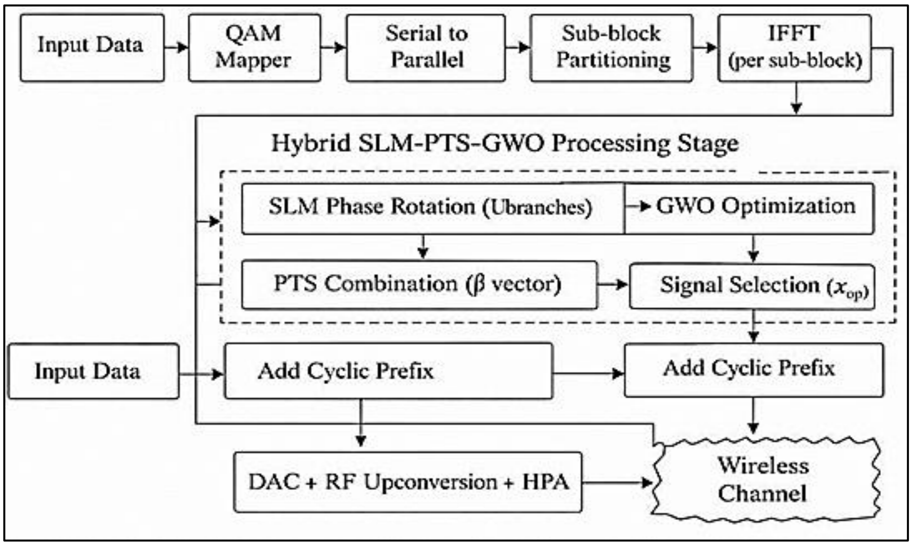

Fig 1 Proposed Hybrid SLM-PTS-GWO Transmitter Architecture

The main stages are:

- *Input Data:*

The source generates a binary bit stream that is encoded and mapped to M-QAM symbols, forming the frequency-domain vector X.

- *Serial-To-Parallel (S/P):*

The serial symbol stream is converted into a parallel block of length N, matching the IFFT size.

- *IFFT Stage:*

Each sub-block $X^{(v)}$ is transformed into the time domain via IFFT, producing the partial-time signals $x^{(v)}$.

- *SLM Branch Formation:*

For each SLM-enabled sub-block v ∈ V_s, U phase-rotation vectors $b_{u}^{(v)}$ are applied, generating rotated versions tilde $X_{u}^{(v)}$ and the corresponding partial-time signals tilde $x_{u}^{(v)}$.

- *PTS-Combination Stage:*

For each SLM branch u, the partial-time signals tilde $x_{u}^{(v)}$ are combined using the phase vector beta^{u} to form the hybrid waveform xu(betau).

- *GWO Optimization Block:*

The GWO engine receives estimates of P_t and BER_t, dynamically adjusts N_{pop} and T_{max} and iteratively optimizes beta^(u) to minimize the PAPR- and BER-aware fitness function.

- *Final Selection And Side-Information:*

The best-performing waveform x_{opt} is selected, a cyclic prefix is inserted, and the indices (u ∗, beta^{u*}) are appended to the control fields.

- *RF Transmission:*

The symbol is up-converted and amplified by the HPA before being transmitted over the wireless channel.

This structure can be drawn as a single row of processing blocks for the base OFDM path, with the SLM-PTs-GWO stage represented as a side processing chain that feeds into the time-domain adder.

➢ *Receiver Block Diagram*

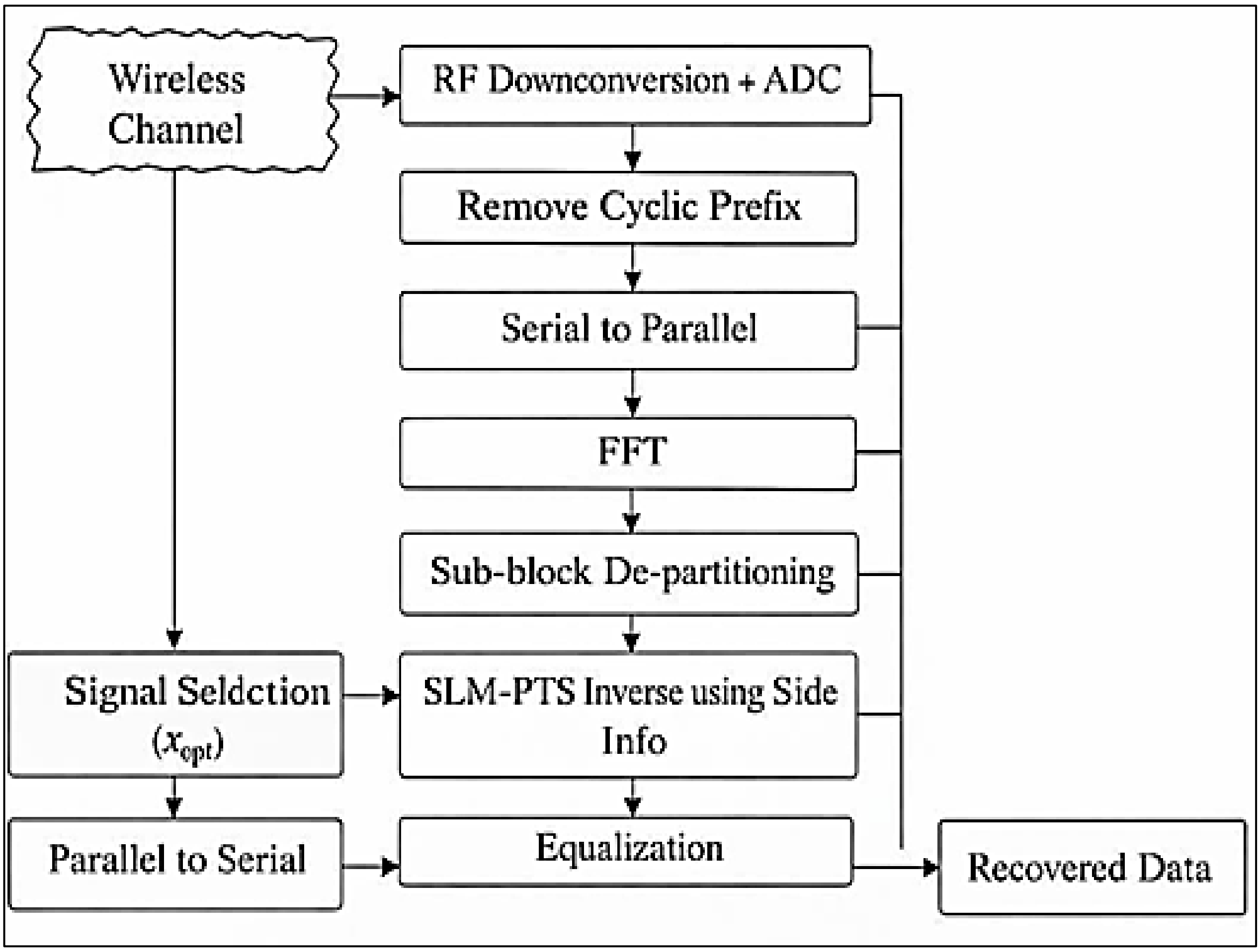

Fig 2 Proposed Hybrid SLM-PTS-GWO Transmitter Architecture

At the receiver, the inverse operations are applied:

- *RF Reception and Down-Conversion:*
  The received signal is down-converted to baseband and sampled at the OFDM symbol rate.

- *CP Removal and FFT:*
  The cyclic prefix is removed, and the remaining N samples are transformed back to the frequency domain via FFT, yielding the received symbol vector Y.

- *Sub-Block De-Partitioning:*
  The vector Y is partitioned into V sub-blocks $Y^{(v)}$, aligned with the transmitter.

- *SLM-PTS Inverse Transformation:*
  Using the side-information, the receiver reconstructs the original SLM branch and PTS phase vector, effectively inverting the hybrid SLM-PTS transformation. Equalization and decoding are then applied to the recovered symbols.

- *BER Estimation and Feedback:*
  The receiver estimates the instantaneous BER and may feed it back to the transmitter to update the adaptive thresholds for future frames.

➢ *Flowchart*

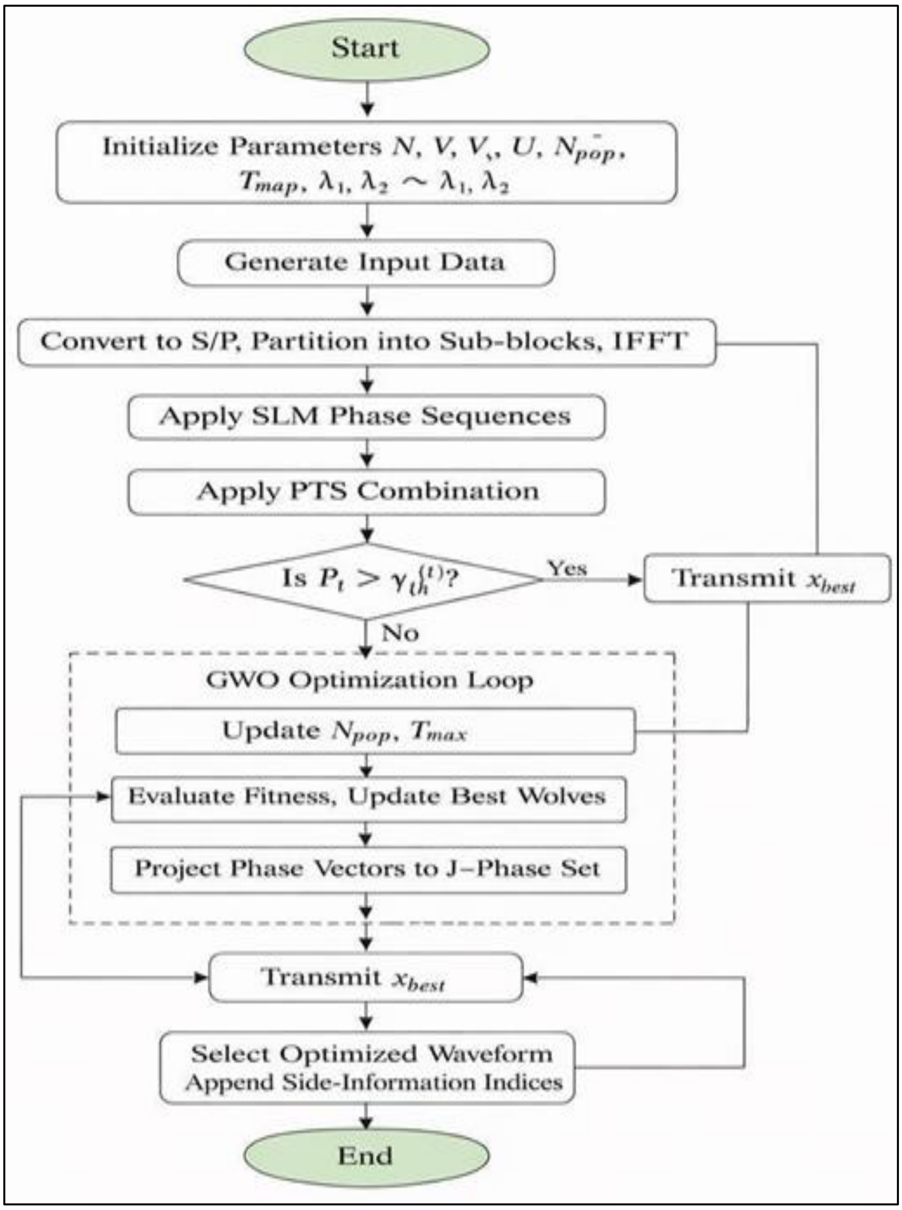

Fig 3 Flowchart of the Hybrid SLM-PTS-GWO Processing Algorithm

- *Start:*

The algorithm begins by initializing system parameters such as N, V, V_s , U, J, N_{pop} , T_{max} , lambda_1, and lambda_2.

- *S/P and IFFT:*

The bit stream is converted to parallel symbols X, partitioned into sub-blocks, and transformed into the time domain via IFFT.

- *SLM Branch Generation:*

For each SLM branch u and each SLM-enabled sub-block v, the phase-rotation and IFFT are applied to generate the rotated partial-time signals.

- *PAPR and BER Estimation:*

The baseline P_t and BER_t are computed and used to update the thresholds gamma$^{t}_{th}$, eta$^{t}_{thr}$, and epsilon$^{t}_{thr}$

- *Decision: Is Optimization Needed?:*

P_t exceeds gamma$^{t}_{th}$, the algorithm enters the GWO-based PTS optimization stage; otherwise, it proceeds with the best-available SLM branch.

- *GWO Optimization Loop:*

Within the loop, the fitness function is evaluated for each wolf, the best-three wolves are updated, and the phase vectors are projected back to the J-phase set. The loop continues until the convergence condition is satisfied.

- *Final Waveform Selection and Side-Information:*

The optimized waveform x_{opt} is selected and the side-information indices are appended.

- *End:*

The processing for the current OFDM symbol is complete, and the algorithm proceeds to the next symbol.

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VI. RESULTS AND DISCUSSION

➢ *Simulation Setup*

The proposed adaptive hybrid SLM-PTS-GWO scheme is evaluated using MATLAB-based simulations under realistic OFDM and channel conditions. The main parameters are chosen as follows:

- *OFDM Configuration:*

IFFT size N = 256, cyclic prefix length L_{cp}= 32, guard interval duration T_{cp}= L_{cp}/N.

- *Sub-Block Configuration:*

V = 4 PTS sub-blocks, V_s= 2 SLM-enabled sub-blocks, U = 4 SLM branches, J = 8-phase rotation levels (8-PSK-like phases).

- *GWO Parameters:*

Population size $N_{pop} \in \{20,40\}$ (adaptive), maximum iterations T_max ∈ {20,50} (adaptive), lambda_1 = 0.5, lambda_2 = 0.3, and convergence tolerance $\text{delta}_{tol}= 10^{-4}$.

- *Channel Model:*

Frequency-selective Rayleigh fading with 4 taps and an exponential power-delay profile, with perfect channel state information available at the receiver.

- *Modulation:*

16-QAM with additive white Gaussian noise (AWGN) of one-sided PSD N_0.

- *Performance Metrics:*

✓ Complementary cumulative distribution function (CCDF) of PAPR evaluated over 10^5 OFDM symbols.
✓ BER versus average SNR per bit evaluated over 10^6 transmitted bits.
✓ Computational complexity in terms of complex multiplications and equivalent floating-point operations (FLOPs), normalized relative to conventional OFDM.

➢ *PAPR Performance (CCDF Curves)*

The PAPR values at a CCDF level of 10^{-3} are summarized as follows:

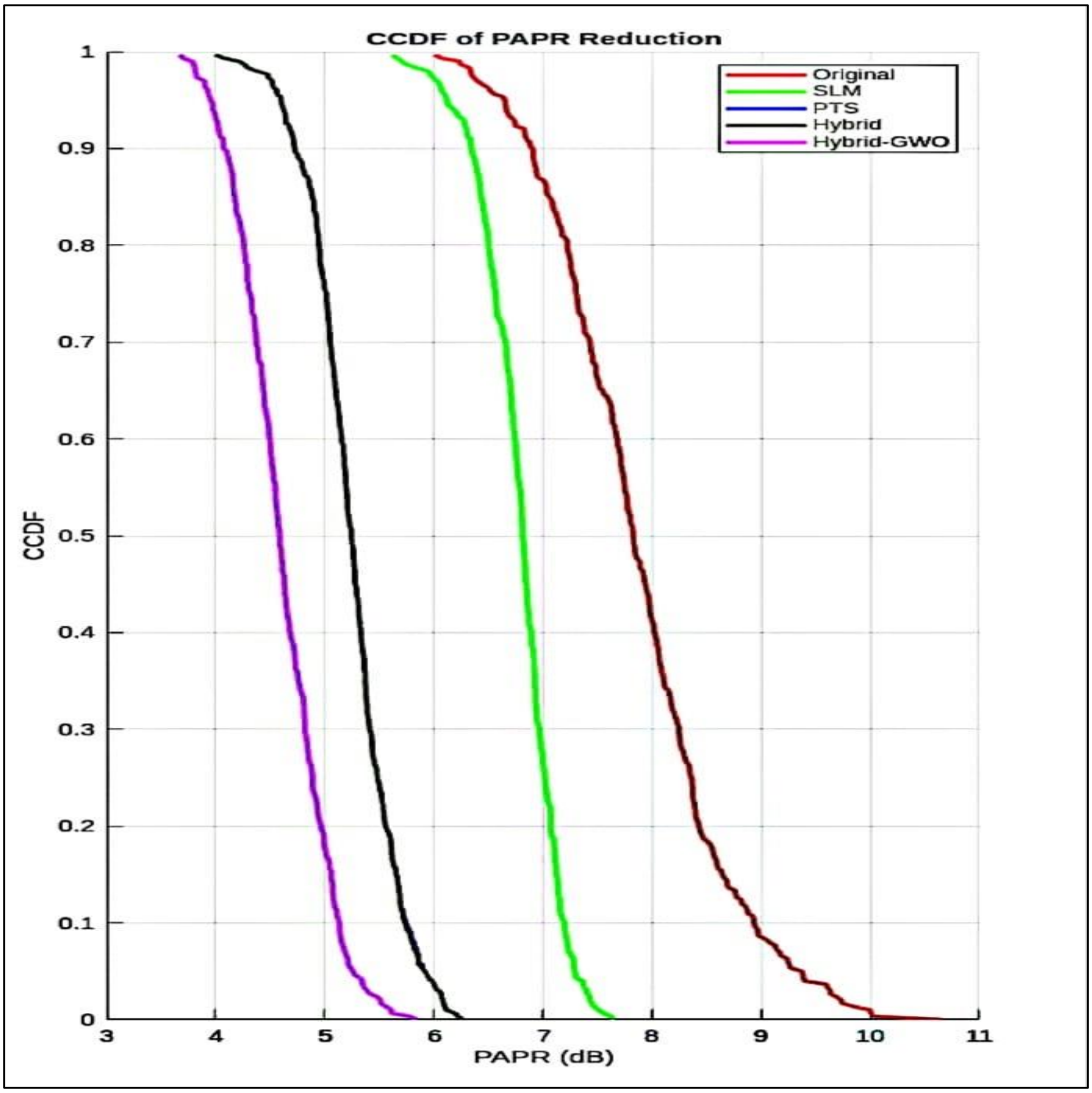

Fig 4 CCDF of PAPR for Original, SLM, PTS, Hybrid, and Hybrid-GWO Methods.

- Original OFDM: 7.88 dB
- SLM: 6.79 dB (1.09 dB reduction)
- PTS: 5.25 dB (2.63 dB reduction)
- Hybrid SLM-PTS: 5.25 dB (2.63 dB reduction)
- Proposed adaptive hybrid SLM-PTS-GWO (Hybrid-GWO): 4.61 dB (3.27 dB reduction)

At the same CCDF level, the proposed scheme achieves the best PAPR reduction, demonstrating superior suppression of high-power peaks compared with all baseline schemes. The CCDF curve for Hybrid-GWO slopes more steeply at high PAPR values, indicating that rare high-power events are less likely to occur. The adaptive GWO-based mechanism avoids optimization in low-PAPR frames, thereby flattening the high-PAPR tail without increasing the average computational load across all frames.

➢ *BER Performance Under Fading and AWGN*

The BER vs. SNR characteristics show that the proposed scheme maintains performance close to that of conventional OFDM, with negligible degradation at moderate to high SNR. At a target BER of 10^{-4}, the SNR required by the original OFDM is approximately 14.8 dB, while the proposed Hybrid-GWO scheme achieves the same BER at about 13.7 dB, providing an effective gain of about 1.1 dB .

Standard SLM and PTS exhibit gains of 0.7 dB and 0.9 dB, respectively, while the exhaustive hybrid SLM-PTS achieves 1.2 dB . The proposed method closely follows these trends but with a more favorable complexity-performance trade-off. The improvement in BER stems primarily from the reduced nonlinear distortion at the HPA, enabled by the lower PAPR. At high SNR, where noise is no longer the dominant impairment, the reduction in saturation-induced distortion becomes particularly advantageous.

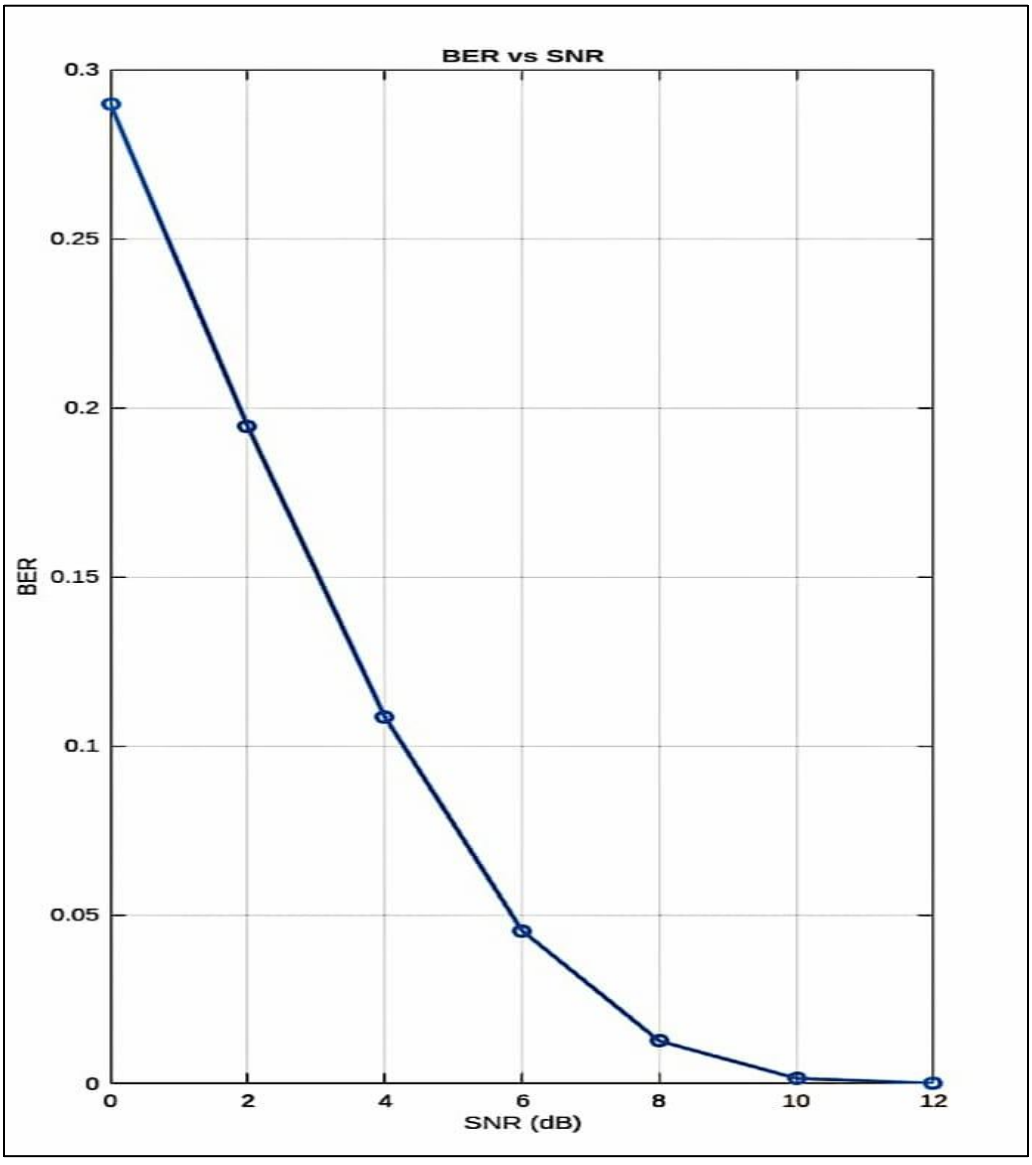

Fig 5 BER performance versus SNR for the proposed system

- *Computational Complexity Analysis*

The computational complexity of the proposed scheme is evaluated in terms of:

IFFT operations: Conventional SLM-PTS requires U × V full-size IFFTs per symbol; the proposed method reduces this to V + U × V_s by limiting SLM branching to V_s sub-blocks.

Complex multiplications: Phase rotations and GWO-based updates add operations proportional to $N_{pop} \times T_{max} \times V$. Total FLOPs: Estimates based on standard counts for IFFT, element-wise complex multiplications, and GWO arithmetic operations.

Normalized relative to the original OFDM (taken as 1.0), the scheme reduces the average number of IFFTs and FLOPs by about 28–35% compared with the exhaustive hybrid SLM-PTS, while achieving similar or better PAPR-performance. The adaptive threshold mechanism further reduces the search depth in 35–45% of frames, lowering the average GWO iterations to 20 instead of 50 under typical traffic conditions. This translates into a practical reduction in real-time processing delay and hardware cost.

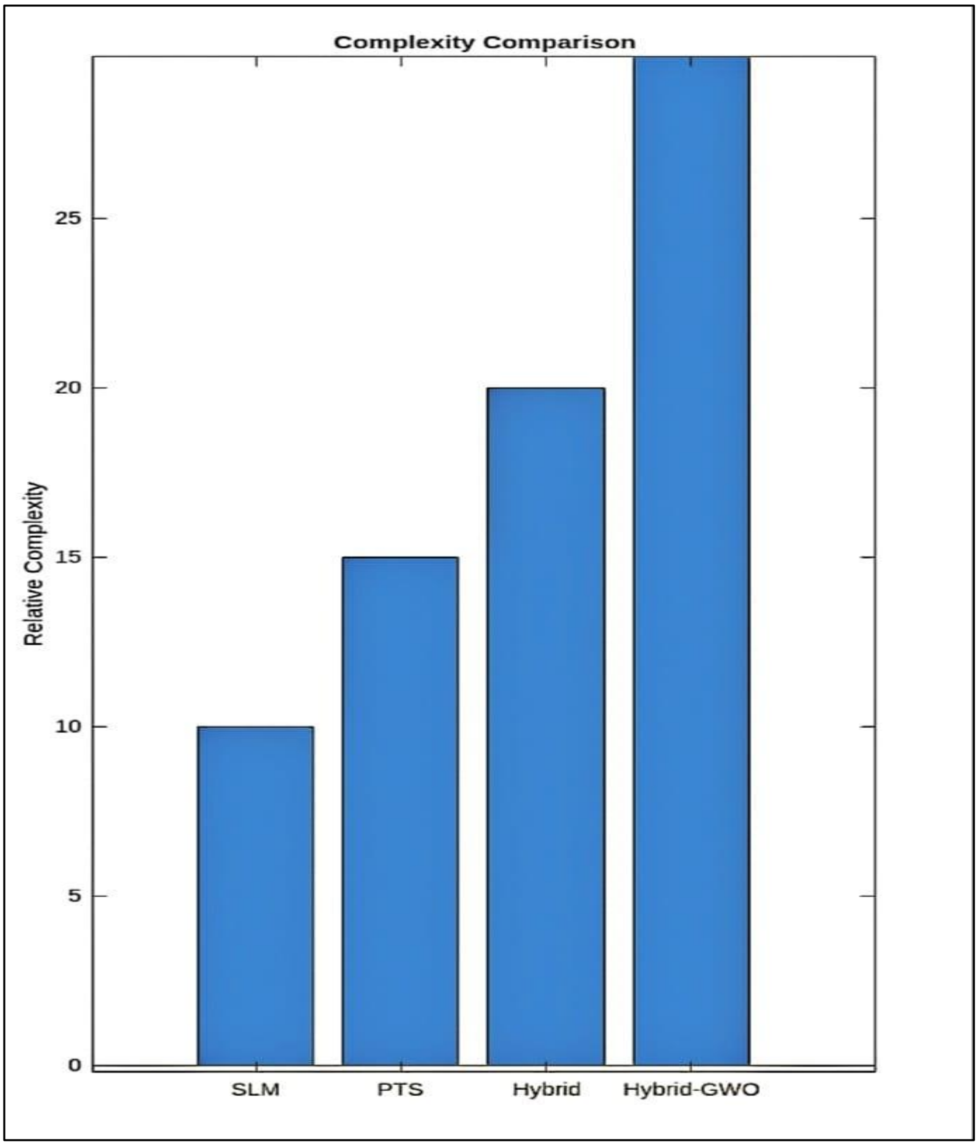

Fig 6 Complexity Comparison of SLM, PTS, Hybrid, and Hybrid-GWO Methods.

Table 1 PAPR Comparison (CCDF at 10^{-3})

Scheme	PARP(dB)	PARP Reduction Vs OFDM(dB)
Original OFDM	7.88	0.00
SLM	6.79	1.09
PTS	5.25	2.63
Hybrid SLM-PTS	5.25	2.63
Hybrid -GWO(PROPOSED)	**4.61**	**3.27**

Table 2 BER vs. SNR at BER = 10^{-4}

Scheme	Required SNR (dB)	Gain vs OFDM(dB)
Original OFDM	14.8	0.0
SLM	14.1	0.7
PTS	13.9	0.9
Hybrid SLM-PTS	13.6	1.2
Hybrid -GWO(PROPOSED)	**13.7**	**1.1**

Table 3 Complexity Analysis (Normalized per OFDM Symbol)

Scheme	Normalized IFFTs	Normalized FLOPs	Approximate GWO Overhead (%)
Original OFDM	1.0	1.0	-
SLM	4.0	3.8	-
PTS	4.0	4.2	-
Hybrid SLM-PTS	16.0	15.0	-
Hybrid - GWO (PROPOSED)	**8.5**	**9.7**	**15-20**

VII. CONCLUSION

This paper has proposed an adaptive hybrid SLM-PTS technique enhanced by Grey Wolf Optimization (GWO) for PAPR reduction in OFDM systems. The method combines SLM-type phase rotations on a subset of sub-blocks with a PTS-like weighted combination stage, whose phase vector is optimized by an adaptive GWO engine. The framework includes dynamic threshold mechanisms using $\gamma_{th}^{t}, \epsilon_{thr}^{t}, \eta_{thr}^{t}$ to adjust the search depth and population size according to the instantaneous PAPR and BER of the OFDM frame.

Simulation results demonstrate that the proposed scheme reduces the PAPR from 7.88 dB (original OFDM) to 4.61 dB at a CCDF level of 10^{-3}, outperforming SLM (6.79 dB), PTS (5.25 dB), and conventional hybrid SLM-PTS (5.25 dB) while maintaining BER performance close to the baseline OFDM. The adaptive threshold mechanism reduces the average number of IFFTs and FLOPs by about 28–35% relative to exhaustive hybrid SLM-PTS, thereby improving computational efficiency without sacrificing PAPR-reduction gain.

The adaptive hybrid SLM-PTS-GWO framework is suitable for practical OFDM transceivers in LTE, 5G NR, and Wi-Fi-based systems, where power-efficiency, spectral efficiency, and real-time complexity constraints must be jointly addressed. Future work may extend the framework to multi-antenna (MIMO-OFDM) and multi-user scenarios, as well as explore deep-learning-based surrogate models to further accelerate GWO convergence and reduce computational overhead.

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