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Hybrid Energy Efficiency Friendly Frequency Domain TR Algorithm Based on PSO Algorithm Evaluated by Novel Maximizing HPA Efficiency Evaluation Criteria

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Abstract: Smart Grids (SGs) expedite secure, large-scale and efficient two-way communication between the power supply and management, but under a sophisticated 5G communication infrastructure, the multi carrier system is the principle system. The high peak-to-average power ratio (PAPR) is one of the significant limitations of the 5G multi carrier (MC) system, as it impedes the efficient design of the 5G analogue front end. Tone reservation (TR) is a highly efficient scheme without signal distortion, which is designed by increasing the freedom in the frequency domain for PAPR reduction. In this paper, a particle swarm optimization (PSO) based TR (PSO-TR) scheme proceeding with an optimal input power back off-modulation error ratio (IBO-MER) convergence criterion is proposed to improve high power amplifier (HPA) efficiency for OFDM systems. A probabilistic analysis of TR predistribution and freedom in the frequency domain, in relationship with the amplitude of its constituent samples, is carried out. This yields the theoretical framework employed in design of the proposed high computing-enhanced solutions. The proposed PSO-TR essentially make the frequency domain distribution and operation itself adaptive, that is, it adjusts to comply with the changing HPA efficiency and redundant cost during application runtime.

Keywords: OFDM; PAPR; HPA; TR; PSO; 5G; IBO; MER; energy efficiency

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1. Introduction

The 5th communication system supports a wide range of wireless services by applying a millimeter-Wave and multicarrier modulated system, which significantly improves data rate and time delay [1]. However, the demand for higher carrier frequency and broader bandwidth with limited energy efficiency sacrifice is the major challenge in 5G communication systems and SGs [2]. The power amplifier (PA) is the most power-consuming device among traditional transmission components in general, which takes 50%~80% of total power consumption from a base station [3]. Therefore, HPA improvement is significant for enhancing the energy efficiency of the base station.

Orthogonal frequency division multiplexing (OFDM) has been widely chosen for 5G wireless communication standards due to many desirable properties such as high spectral efficiency, simple channel estimation, and robustness against multipath fading [4]. The major drawback of OFDM is the high peak-to-average power ratio (PAPR) characteristic caused by the superposition of peaks from a large number of subcarriers [5]. High PAPR can drive the signal beyond the linear region of the HPA, which can cause serious signal distortion [6], modulation error rate (MER) decreases, demodulation errors and deterioration of PA efficiency. The minimum (complementary cumulative distribution function) CCDF curve is the most common criterion to evaluate PAPR method function [7].

However, due to the low probability of peak value appearance, CCDF improvement does not necessarily imply optimising PA efficiency. Signal peak can be optimization with a variety of approaches and schemes: clipping and filtering (CF) [8]; coding [9]; adaptive symbol selection [10]; partial transmit sequence (PTS) [11] and interleaving [12]; tone reservation/injection [13]; active signal constellation extension (ACE) [14], companding, and so forth [15]. Predistortion and coding schemes are no longer sufficient for modern communication systems; the tone distortion algorithm is considered one of the most potential approaches. TR is a commonly used PAPR reduction technique in 5G communication systems; many optimization TR algorithms have been proposed to obtain a global optimized PAPR reduction result. Refs. [16–18] combined PTS, ACE, and clipping schemes with TR, PAPR reduction performance has been improved at the cost of increased computational complexity and SNR. Refs. [19,20] applied machine learning (PRNet, deep neural network) with the TR scheme which can minimize PAPR by training examples; a lack of training data and extensive training time is the main concern of such algorithms.

By increasing the freedom of a signal in the frequency domain space and its space, signals in frequency domain QAM coordinates can expand freely within an allowable range, which acquires a higher level of freedom than conventional multi carrier systems, so that the probability of the phase superposition of high peak signal can be reduced, and PAPR can be reduced effectively [21]. Therefore, the TR distortion process can be advanced to the frequency domain as F-TR. To describe and optimize the distortion of HPA, we proposed a novel maximizing HPA efficiency evaluation criteria IBO-MER to statistically analyze the amplitude and occurrence probability of the signal level, balance considered distortion influence from each subcarrier, and obtain the best CCDF curve distribution of OFDM signal. To achieve the dual optimization targets of HPA energy consumption reduction and system energy efficiency improvement and reach a compromise between signal freedom and HPA power amplifier efficiency, we proposed an optimal particle swarm optimization based (PSO) algorithm to analyze the global boundary. By PSO algorithm, global maximum/minimum optimization objectives can be searched, the global boundary of the objective function can be determined [22]. Specifically, we proposed a novel scheme based on the continuous PSO genetic algorithm to achieve the best OFDM signal distribution. FPSO-TR can reach theoretical boundaries in the continuous infinity domain. Compared with conventional TR, FPSO-TR has reached optimal PAPR reduction and MER results within reasonable complexity.

This paper is arranged as follows: descriptions of MIMO-OFDM and its inherent PAPR characteristics are presented in Sections 2.1 and 2.2. The HPA model and its characteristics are described in detail in Sections 2.3 and 2.4. In Section 3, the conventional TR scheme is shown. Analytical evaluations of the F-TR and FPSO-TR algorithms are contained in Section 4. Finally, simulations and concluding remarks are given in the last section.

2. Massive MIMO-OFDM Model

2.1. MIMO-OFDM Model

In this section, we present the MIMO-OFDM system and its PAPR characteristic. The continuous-time domain OFDM with N subcarriers could be expressed as [23]:

$$x(t) = \sum_{k=0}^{N-1} X_k(t) e^{j2\pi k \Delta f t}, 0 \leq t \leq T, \quad (1)$$

where $X(k)$ is OFDM complex signals in k -th subcarrier, T is signal duration, OFDM signals are modulated with 16 QAM in this paper.

Similarly, the discrete-time domain OFDM signals can be represented as [23]:

$$x(n) = \frac{1}{\sqrt{NL}} \sum_{k=0}^{NL-1} X_k(n) e^{j2\pi f_k n / LN}, n = 0, 1, \dots, NL - 1, \quad (2)$$

where L is the oversample times.

An OFDM-MIMO system composed of a base station (BS) with M transmitter (TX) and receiver (RX) antennas has Q users. After inverse discrete Fourier transform (IDFT), the frequency domain signal $\mathbf{Y}[k] = [Y_0[k], Y_1[k], \dots, Y_{M-1}[k]]^T$ of k -th subcarrier can be represented as [24]:

$$\mathbf{Y}[k] = \sqrt{\rho} \mathbf{H}[k] \mathbf{X}[k] + \mathbf{N}[k], 0 \leq k \leq N-1 \quad (3)$$

where $\mathbf{Y}[k]$ is $M \times 1$ received vector, ρ is the total TX power for a downlink signal, $\mathbf{H}[k]$ denotes the $M \times M$ independent identically distributed channel matrix between TX and RX, $\mathbf{X}[k]$ represents the $M \times 1$ signal vector with each data symbol modulated by quadrature amplitude modulation (QAM), and $\mathbf{N}[k]$ represents the $M \times 1$ additive white Gaussian distribution.

The discrete-time t -th OFDM-MIMO signal of TX antenna $\mathbf{x}_t = [x_t[0], x_t[1], \dots, x_t[N-1]]^T$ can be represented as [25]:

$$\mathbf{x}_t = \mathbf{F}_q^H \mathbf{X}_t, \quad (4)$$

where $\mathbf{X}_t = [X_t[0], X_t[1], \dots, X_t[N-1]]^T$ is the frequency domain signal after IDFT, $\mathbf{F}_q^H \in \mathbb{C}^{Nq \times N}$ represents IDFT matrix as $[\mathbf{F}_q]_{i,k} = \frac{1}{\sqrt{qN}} e^{-j2\pi ik/qN}$ with its (i, k) -th element.

2.2. PAPR Definition

The definition of PAPR is the ratio of the peak and average power of the multi carrier system, which is the character of the signal peak's superposition caused by amplitude Rayleigh distribution. PAPR can be represented as [26]:

$$\text{PAPR} = \frac{\max_{0 \leq n \leq qN-1} \{ |\mathbf{x}_t[n]|^2 \}}{E[|\mathbf{x}_t[n]|^2]}, \quad (5)$$

where $E\{\cdot\}$ is the expectation operator.

Complementary Cumulative Distribution Function (CCDF) is the primary evaluation criterion of PAPR in OFDM signals only to seek for the minimize PAPR value, which counts the probability that the PAPR of OFDM symbol $x_t[n]$ exceeds a particular threshold value Z_0 , which can be shown as [27]:

$$\begin{aligned} \text{CCDF}_{\text{PAPR}}(\text{PAPR}_0) &= \Pr(\text{PAPR} > \text{PAPR}_0) \\ &= 1 - F(Z) \\ &= 1 - (1 - e^{-Z_0})^N. \end{aligned} \quad (6)$$

CCDF measures a sparse clipping probability, which represents the high peak sample is likely to undergo severe distortion but ignores the information on how many samples are distorted [27]. Moreover, the secondary peaks with considerable statistical quantity are more important in evaluating the HPA energy efficiency. Indeed, CCDF alone cannot predetermine the optimal target of each sub-carrier and entire distribution in HPA. In practical scenarios, it is essential to consider a more refined analysis considering all the signal samples.

2.3. HPA Model

Excessive PAPR would force HPA operation in the saturated region. To evaluate OFDM transmitter system, it's crucial to represent HPA models. The discrete signal $x_t[n]$ can be represented as:

$$x_t[n] = |x_t[n]| e^{jy_t[n]}, \quad (7)$$

where $|x_t[n]|$ and $e^{jy_t[n]}$ is the amplitude phase of signal $x_t[n]$, respectively. Amplified signal $y_t[n]$ can be represented as follows:

$$y_t[n] = A[|x_t[n]|]e^{j\{y_t[n] + \phi[|x_t[n]|]\}}, \quad (8)$$

where $A[\cdot]$ and $\phi[\cdot]$ is Amplitude/Amplitude (AM/AM) and Amplitude/Phase (AM/PM) conversion, respectively.

This paper adopted a nonlinear Rapp model without memory for the HPA. The Rapp model for a solid-state power amplifier (SSPA) was developed in [28], which is a memoryless HPA model with only an AM/AM function. The Rapp model can be represented as:

$$\tilde{x}_t[n] = \frac{\sqrt{G}x_t[n]}{(1 + (\frac{x_t[n]}{A_{sat}})^{2p})^{\frac{1}{2p}}} \quad (9)$$

$$\phi[|x[n]|] \approx 0,$$

where A_{sat} is the amplifier saturation voltage, p is the parameter that controls the AM/AM sharpness of the saturation region, and G is the amplifier voltage gain, considered as unitary in this paper for simplicity.

It is known that the characteristic of AM/AM is more benign than that of AM/PM when high order modulations are employed [29].

2.4. Power Consumption Model

In practical communication systems, the total power consumption contains the power radiated to the environment for signal transmission and an independent transmission power representing the power consumed by circuit dissipation and signal processing. We suppose that the constant power is proportional to the transmit antenna number, then the realistic total power consumption is given as [30]:

$$P_{\text{total},\ell} = \sum_{a \in \ell} \frac{P_a}{\eta_a} + \ell \cdot P_{\text{cir}} + P_{\text{sta}}, \quad (10)$$

where η_a denotes the PA efficiency for the a -th antenna, P_a is the maximal HPA output power for the a -th transmit antenna, ℓ denotes the active transmit antenna set of the BS, and $\ell \subseteq \{1, \dots, M\}$. $\ell \cdot P_{\text{cir}}$ denotes the circuit power consumption proportional to the number of the active transmit antennas. P_{sta} denotes the static power independent of both P_a and ℓ , which accounts for the power consumption of the baseband processing, and so forth.

2.5. Performance Metrics

The power amplifier's distortion can be classified as nonlinear distortion (amplitude distortion) and cut-off saturation distortion (frequency and phase distortion). To optimize the dynamic range of the power amplifiers, the signal power from the transmitter of HPA can be backed off.

The input back-off (IBO) is defined as the operating point of the HPA, which can be represented as [31]:

$$IBO = 10\log_{10} \frac{A_{sat}^2}{P_{avg}} = 10\log_{10} \gamma^2, \gamma = \frac{A_{sat}}{\sqrt{P_{avg}}}, \quad (11)$$

where P_{sat} denotes the average input power.

It has been well investigated that the OFDM signal converges to a complex Gaussian random process when N is large enough according to the central limit theorem. For the Gaussian input $x_t(n)$, the Bussgang theorem can be employed. Alternatively, the output signal of the HPA $\tilde{x}_t[n]$ can be disassembled into two uncorrelated signals based on

Bussgang theorem, that is, $\tilde{\mathbf{x}}_t[n] = \alpha \mathbf{x}_t[n] + \mathbf{d}_t[n]$ where α represents an attenuation factor and the distortion term $\mathbf{d}_t[n]$ is uncorrelated with $\mathbf{x}_t[n]$ ($\mathbf{d}_t[n]$ and $E[\mathbf{d}_t[n]\mathbf{x}_t^*[n]] = 0$). The attenuation factor α is depend on the IBO level is as follows:

$$\alpha = \frac{E(\mathbf{x}_t^* \mathbf{d}_t[n])}{E[|\mathbf{x}_t[n]|^2]} = 1 - e^{-\gamma} + \frac{\sqrt{\pi}\gamma}{2} \text{erfc}(\gamma), \quad (12)$$

where $\text{erfc}(\gamma) = \frac{2}{\sqrt{\pi}} \int_{\gamma}^{\infty} e^{-x^2} dx$ is the error function.

The distortion induced by the Rapp function ($p \rightarrow \infty$) impacts the tail of the Rayleigh distribution. Hence, the variance of $\mathbf{d}_t[n]$ can be easily obtained as follows:

$$\begin{aligned} \sigma_d^2 &= E[|\tilde{\mathbf{x}}_t[n]|^2] - \alpha^2 E[|\mathbf{x}_t[n]|^2] \\ &= (1 - e^{-\gamma^2} - \alpha^2) \sigma^2, \end{aligned} \quad (13)$$

where $(1 - e^{-\gamma^2}) \sigma^2$ represents the variance of $\tilde{\mathbf{x}}_t[n]$.

In this paper, the signal-to-distortion ratio (SDR) is due to distortion noise caused by the HPA, which can be defined as follows [32]:

$$\begin{aligned} \text{SDR}(\hat{\mathbf{x}}) &= 10 \lg \left\{ \frac{\alpha^2 E[|\mathbf{x}_t[n]|^2]}{E[|\tilde{\mathbf{x}}_t[n] - \mathbf{x}_t[n]|^2]} \right\} \\ &= 10 \lg \frac{\alpha^2 \sigma^2}{\sigma_d^2} \\ &= 10 \lg \frac{\alpha^2}{(1 - e^{-\gamma^2} - \alpha^2)}, \end{aligned} \quad (14)$$

where $E[|\mathbf{x}_t[n]|^2] = \sigma^2$ is the power of the input signal. The SDR is relevant to the reception quality. Most importantly, the utilized definition is a wideband SDR, that is, covering both in-band and out-of-band frequencies. Notice that SDR depends on the IBO level γ^2 , and the attenuation α . Signal power is calculated only for data symbols.

Distortion power is sparse and distributed in the time domain, uniform in the frequency domain receiver. HPA distorted symbols in the frequency domain can be shown as:

$$\tilde{\mathbf{Y}}[k] = [\tilde{Y}_0[k], \tilde{Y}_1[k], \dots, \tilde{Y}_{M-1}[k]]^T, \quad (15)$$

where

$$\begin{aligned} \tilde{\mathbf{Y}}[k] &= \sqrt{\rho} \mathbf{H}[k] \tilde{\mathbf{X}}[k] + \mathbf{N}[k] \\ &= \sqrt{\rho} \mathbf{H}[k] (\alpha \mathbf{X}[k] + \mathbf{D}[k]) + \mathbf{N}[k] \end{aligned} \quad (16)$$

and $\mathbf{D}[k] = [D_0[k], D_1[k], \dots, D_{M-1}[k]]^T$ represents the frequency domain version of the nonlinear distortion terms.

Energy efficiency (EE) is one of the key metrics to evaluate HPA performance, which is defined as the number of information bits transmitted per unit of energy. Assuming that IBO is appropriately set, and distortion due to the nonlinear devices is negligible, the EE can be represented as [30]:

$$EE \approx \frac{\kappa \cdot E \left[\log_2 \det \left(\mathbf{I}_M + \frac{\rho \mathbf{H}[k] \mathbf{H}^H[k]}{\ell N_0 B} \right) \right]}{P_{\text{total}, \ell}} \quad (17)$$

$$\text{s.t. } \xi \leq \vartheta, \ell \leq M,$$

where $\mathbf{I}_M$ is the $M \times M$ identity matrix, $N_0 B$ is the noise power at a given bandwidth, B . κ is the scaling factor for the signaling overhead and guard interval, which can be shown as:

$$\kappa = (1 - \xi), \quad (18)$$

where κ represents pilot ratio.

HPA efficiency η_a is usually defined to measure the EE based on HPA operation. High η_a offers low power consumption, in an ideal HPA model, η_a is modelled by a constant, and the total power consumption is a linear function of the radiated power of the HPA. However, η_a has a dependence on the radiated power HPA in practical systems. According to [33], a more accurate HPA model can be described as follows:

$$\eta_a = \left(\frac{P_a}{P_{a, \max}} \right)^\beta \eta_{\max}, \quad (19)$$

where P_a is the maximal HPA output power for the a -th transmit antenna, $\eta_{\max}$ is the maximal HPA efficiency. β is the efficiency exponent depending on the type of the HPA where $\beta \in [0, 1]$. For class B and class A non-ideal HPAs, the typical value of β is 0.5 and 1, respectively. From (14), it has known that the efficiency of HPA decreases with the decline of HPA output power.

Modulation error rate (MER) is a significant criterion for measuring signal quality by quantifying signal to noise ratio (SDR), defined as the ratio of the received symbol location and the difference between received symbol location and ideal one. HPA efficiency and distortion have a tradeoff relationship, as mentioned previously. The lower IBO leads to higher output signal power and, thus, higher HPA efficiency, but it may also cause severe nonlinear distortion. The in-band SDR contribution in (11) can be calculated by computing the quantity MER, which can be shown as follows [34]:

$$\begin{aligned} \text{SDR}(\hat{\mathbf{x}}) &\approx \text{MER}(\hat{\mathbf{S}}_{\mathbf{n}}) \\ &= 10 \lg \left\{ \frac{\alpha^2 \sum_{k=1}^N (|s_k|^2)}{\sum_{k=1}^N (|s_k - \hat{s}_k|^2)} \right\} \\ &= 10 \lg \left\{ \frac{\alpha^2 \sum_{k=1}^N (I_k^2 + Q_k^2)}{\sum_{k=1}^N (\Delta I_k^2 + \Delta Q_k^2)} \right\}, \end{aligned} \quad (20)$$

where N is the number of data samples, I and Q are the real and imaginary ideal locations, ΔI and ΔQ are the real and imaginary difference between received symbol locations and the ideal one. MER can indirectly evaluate the performance of OFDM acceptance.

3. Conventional TR System

In single-antenna OFDM systems, the TR-based scheme reserves N_R peak reduction tones (PRTs) set for PAPR reduction and rest $N - N_R$ subcarriers for data transmission. The time domain kernel $c = [c_0, c_1, \dots, c_{Nq-1}]^T$ is generated as the peak-canceling signal by the R reserved tones, which can be calculated as [13]:

$$\mathbf{c} = \mathbf{F}\mathbf{C}, \quad (21)$$

where $\mathbf{F}$ represents the inverse fast Fourier transform matrix, $\mathbf{C} = [C_0, C_1, \dots, C_{N-1}]^T$ represents the reserved frequency domain kernel with nonzero tones at positions in $\mathbf{R}$, which can be shown as:

$$C_k = \begin{cases} 0, & k \notin \mathbf{R} \\ 1, & k \in \mathbf{R}, \end{cases} \quad (22)$$

where R is the number of reserved tones, and $\mathbf{R} = [r_0, r_1, \dots, r_{R-1}]^T$ denotes the set of the reserved tones.

So that the time domain signal in (2) after TR peak cancelling transfer into:

$$\mathbf{a} = \mathbf{x} + \mathbf{c} = \mathbf{F}(\mathbf{X} + \mathbf{C}), \quad (23)$$

where $\mathbf{a}$ is the peak reduced time domain signal, and $\mathbf{X}$ and $\mathbf{C}$ are orthogonal in the frequency domain. To be specific, the frequency domain n -th subcarrier peak-cancelling signal can be represented as:

$$X_n + C_n = \begin{cases} X_n, & n \notin \mathbf{R} \\ C_n, & n \in \mathbf{R}. \end{cases} \quad (24)$$

The structure of the conventional TR scheme is given in Figure 1.

Figure 1. The structure of the conventional TR scheme.

In MIMO-OFDM systems, each antenna transmits a modulated OFDM signal. To avoid tones' contamination of the MIMO receiver, the same $\mathbf{C} = [C_0, C_1, \dots, C_{N-1}]^T$ can be utilized to generate the peak-cancelling signal on the m -th transmit antenna. Therefore, the TR scheme can reduce the PAPR of MIMO-OFDM systems by performing the TR iterations independently on every transmit antenna. Then, the PAPR reduced signal $\hat{\mathbf{x}}_t$ of t -th antenna is generated by the peak-cancelling signal $\mathbf{c}$ plus the original signal $\mathbf{x}_t$ in the time domain, which can be shown as:

$$\hat{\mathbf{x}}_t = \mathbf{x}_t + \mathbf{c} = \mathbf{F}_q^H(\mathbf{X}_t + \mathbf{C}). \quad (25)$$

To further improve the dispersion of the signal, the PAPR signal $\hat{\mathbf{x}}_t^i$ is updated during the i -th iteration as follows:

$$\begin{aligned} \hat{\mathbf{x}}_t^{i+1} &= \hat{\mathbf{x}}_t^i + \sum_{l=0}^{L-1} \partial_l (A_l e^{j \arg(x_{n_l}^i)} - x_{n_l}^i) \mathbf{c}[(n - n_l)] \\ &= \hat{\mathbf{x}}_t^i + \sum_{l=0}^{L-1} a_l \mathbf{c}_l[(n),] \end{aligned} \quad (26)$$

where ∂_l is a scaling factor, and $\mathbf{c}(n - n_l)$ is the cyclically shifted of $\mathbf{c}$ to n_l , n_l denotes the position of whose value exceeds the amplitude A_l in the i -th iteration, and L is the number

of the positions. The time-domain OFDM symbol of the t -th antenna $\mathbf{x}_t$ to be transmitted can be represented as follows:

$$\begin{aligned}\hat{\mathbf{x}}_t &= \mathbf{x}_t + \sum_{i=1}^M \sum_{l=0}^{L-1} \mathbf{c}_{i,l} \\ &= \mathbf{F}_q(\mathbf{X}_t + \mathbf{C}_t),\end{aligned}\quad (27)$$

where $\mathbf{c}_i$ is the updated time domain kernel during the i -th iteration, and M is the adaptive iteration number, and $\mathbf{C}_t$ represents the frequency domain kernel of t -th antenna.

The PAPR of TR-OFDM signals can be transferred into:

$$\text{PAPR} = \frac{\max_{0 \leq n \leq N-1} \left\{ |\mathbf{x}_t[n] + \mathbf{c}_t[n]|^2 \right\}}{\mathbb{E} \left[|\mathbf{x}_t[n]|^2 \right]}.\quad (28)$$

Moreover, the optimum PAPR reducing performance can be selected as follows:

$$\begin{aligned}\arg \min_{\mathbf{C}_t} \max \mathbf{F}_q(\mathbf{X}_t + \mathbf{C}_t)_\infty \\ \text{s.t.} \quad \sum_{i=0}^{N-1} \mathbf{C}_{t,i}^2 \leq \beta\end{aligned}\quad (29)$$

where β is the maximum allowed power increasing imposed on reserved tones to avoid dramatically increasing the transmit power caused by reserved tones superposition.

The essential algorithm of conventional TR is exhaustively searching in the time domain kernel to find the minimal secondary peaks at the expense of high computational complexity and time delay. Meanwhile, TR has an unsatisfactory performance when a high power peak is unlikely to appear because TR cannot distinguish the maximum peak in this scenario.

4. Proposed Frequency-Particle Swarm Optimization-Tone Reservation Scheme with Novel Maximizing HPA Efficiency Evaluation Criteria

This section proposed a novel FPSO-TR algorithm, saving much IFFT progress by conducting TR in the frequency domain. Instead of utilizing iteration to an exhaustive search for the suboptimal peak-cancelling kernel, this paper obtained the global optimal kernel by employing the PSO algorithm. To further statistically analyze the amplitude and occurrence probability of signal level, novel maximizing HPA efficiency evaluation criteria were applied and the effect of each subcarrier on the distortion of the power amplifier was taken into account.

4.1. F-TR and Maximizing HPA Efficiency Evaluation Criteria

By advancing TR into the frequency domain, F-TR can be achieved by severe clipping and frequency filtering so that the move of the correcting signal lies only on the reserved tones.

The frequency domain OFDM signal divided onto $N - L$ data transmitting signal $\mathbf{X}_t = [\mathbf{X}_t[0], \mathbf{X}_t[1], \dots, \mathbf{X}_t[N - L]]^T$ and L reserved tones $\mathbf{C} = [\mathbf{C}_0, \mathbf{C}_1, \dots, \mathbf{C}_{N-1}]^T$. Then the PAPR reduced signal $\mathbf{x}_t$ of t -th antenna is generated by the peak-cancelling signal $\mathbf{c}$ plus the original signal $\mathbf{x}_t$ in the time domain, which can be shown as:

$$\begin{aligned}\hat{\mathbf{x}}_t &= \mathbf{x}_t + \sum_{i=1}^M \sum_{l=0}^{L-1} \mathbf{c}_{i,l} \\ &= \mathbf{F}_q(\mathbf{X}_t + \mathbf{C}_t).\end{aligned}\quad (30)$$

Then the time domain signal $\hat{\mathbf{x}}_t[n] = [\hat{\mathbf{x}}_t[0], \hat{\mathbf{x}}_t[1], \dots, \hat{\mathbf{x}}_t[N-L]]$ was clipped to threshold A_{sat} as:

$$\bar{x}_t[n] = \begin{cases} \hat{\mathbf{x}}_t[n], & \text{if } |\hat{\mathbf{x}}_t[n]| < A_{sat} \\ A_{sat}e^{j\theta[n]}, & \text{if } |\hat{\mathbf{x}}_t[n]| \geq A_{sat}, \end{cases} \quad (31)$$

where $\bar{x}_t[n], n = 0, 1, \dots, N-1$ is the clipped signal, $\theta[n]$ is the phase of $\bar{x}_t[n]$ whose amplitude exceeds A_{sat} .

Evidently, the clipping noise $\mathbf{w}(\mathbf{n})$, $n = 0, 1, \dots, N-1$ can be obtained as:

$$\mathbf{w}(\mathbf{n}) = \mathbf{x}_t[n] - \bar{\mathbf{x}}_t[n]. \quad (32)$$

Transfer clipping noise $\mathbf{w}$ into the frequency domain as:

$$\mathbf{W} = \mathbf{F}_q(\mathbf{w}), \quad (33)$$

where $\mathbf{w} = [w_0, w_1, \dots, w_{qN-1}]$ is the the corresponding frequency domain clipping noise from $\mathbf{W} = [W_0, W_1, \dots, W_{qN-1}]$, respectively.

To empty the data transmission subcarriers, reserve values of PRTs only, the frequency filtering $\mathbf{H}_r(k)$ were set as:

$$\mathbf{C}(k) = \mathbf{W}(k)\mathbf{H}_r(k) = \begin{cases} \mathbf{W}(k), & k \in R \\ 0, & \text{otherwise} \end{cases} \quad (34)$$

$$\mathbf{H}_r(k) = \begin{cases} 1, & k \in R \\ 0, & \text{otherwise.} \end{cases} \quad 0 \leq k \leq qN-1$$

The distortion in the constellation cells will be decreased when the first configuration of the filter is repeated. However, the receiver can estimate the occurred clipping and compensate the received OFDM symbol accordingly because the clipping noise is generated by a known process mentioned in [11].

Finally, the F-TR signal can be converted into the time domain as follows:

$$\begin{aligned} \tilde{\mathbf{x}}(n) &= \mathbf{x}(n) + \beta \mathbf{c}(n) \\ &= \mathbf{x}(n) + \beta \mathbf{F}_q \mathbf{C}. \end{aligned} \quad (35)$$

The structure of F-TR were given in Figure 2.

Figure 2. The structure of F-TR scheme.

In this paper, the increasing power of the F-TR symbol is irrelevant to MER but significantly affects IBO's implementation. To avoid taking the additive mentioned above power into account, the IBO definition can be adapted into:

$$\text{IBO}_n = P_{in,max} - P_{in,av} - P_{TR}, \quad (36)$$

where $P_{in,av}$ is the average input power, $P_{in,max}$ is the saturation point of an ideal amplifier (Rapp factor is infinite) for the input power, and P_{TR} is the additive power with TR PAPR function. To describe the IBO gain more intuitively, P_{TR} is subtracted from IBO gain to avoid taking into account F-TR strategies. In this case, an optimization model hybrid

F-TR scheme can be adopted to minimize IBO by setting smoothness factor $p = 10$ and determining the appropriate scaling factor ∂_l , amplitude threshold $Asat$ as follow:

$$\begin{aligned} \min_{f,F} \quad & IBO(\tilde{\mathbf{x}}) \\ \text{subject to} \quad & \text{MER}(\tilde{\mathbf{x}}) \geq \varepsilon \text{dB}, \end{aligned} \quad (37)$$

where ε is the MER threshold (in dB). This paper intended to reduce PAPR to exceed the predefined threshold received MER from the F-TR scheme. (32) and IBO can be simplified as follow:

$$\min_{f,F} \quad IBO(\tilde{\mathbf{x}}) = \varepsilon \text{dB} \quad (38)$$

In this paper, we comprehensively analyzed the PAPR reduction signal level amplitude and its statistical quantity from the overall level value distribution of OFDM signal and its statistical quantity perspective, thoroughly considering the impact from each subcarrier. We proposed novel maximizing HPA efficiency evaluation criteria in this paper to evaluate the optimized OFDM signal distribution probability curve.

After introducing the little distortion with the MER criterion, a lesser IBO value would increase HPA efficiency dramatically, so reducing IBO with fixed MER was regarded as the evaluation criterion for optimizing HPA efficiency.

By adjusting the distribution of total subcarriers in the F-TR constraint space, the HPA would achieve optimal efficiency. In other words, minimized IBO would be captured by fixed MER and the appropriate setting of relevant parameters in the F-TR scheme. Maximizing HPA efficiency evaluation criteria can be shown as:

$$\tilde{X}_n^{opt} = \arg_{\tilde{X}_n} \min IBO_n, \quad (39)$$

where $\tilde{X}_n^{opt}$ is the optimum distributed subcarriers achieved minimum IBO value.

4.2. FPSO-TR

We adopted the PSO algorithm to achieve the minimum IBO values by novel maximizing HPA efficiency evaluation criteria. The PSO algorithm search optimization parameter path achieves the group optimal goal by the cooperation between individuals [35]. Suppose that the position and velocity of the i -th particle are: $\mathbf{w}_i = \{w_{i1}, w_{i2}, \dots, w_{iD}\}$, $\mathbf{v}_i = \{v_{i1}, v_{i2}, \dots, v_{iD}\}$ respectively, where $i = 1, 2, \dots, n$. Particles are updated by adaptive function $\mathbf{f}_i = \{f_i | i = 1, 2, \dots, P\}$ and velocity iteration function, the individual and population optimal location are updated as: $w_i^p \text{best} = \{w_{i1}^p \text{best}, w_{i2}^p \text{best}, \dots, w_{iD}^p \text{best}\}$, $p_i \text{best} = \{p_{i1} \text{best}, p_{i2} \text{best}, \dots, p_{iD} \text{best}\}$ and $w_i^g \text{best} = \{w_{i1}^g \text{best}, w_{i2}^g \text{best}, \dots, w_{iD}^g \text{best}\}$, respectively. In each iteration, the velocity and position are updated as the following rules:

$$\begin{aligned} v_{i+1} &= \omega_i \times v_i + c_1 \times \text{rand} \times (w_i^p \text{best} - w_i) + c_2 \times \text{rand} \times (w_i^g \text{best} - w_i) \\ w_{i+1} &= w_i + v_{i+1}, \end{aligned} \quad (40)$$

where rand is random number ranging from $[0, 25]$. The structure of the PSO algorithm is shown in Figure 3.

Figure 3. The structure of the PSO algorithm.

In this paper, F-TR iteration parameters are major parameters for predistortion adjustment, which determines the performance of MER and IBO. By setting fixed IBO, the optimal MER can be obtained by defined F-TR iteration parameters as population particles $\mathbf{w}_{i1} = \{w_{11}, w_{21}, \dots, w_{P1}\}$ and $\mathbf{w}_{i2} = \{w_{12}, w_{22}, \dots, w_{P2}\}$ respectively, the corresponding velocity defined as $\mathbf{v}_{i1} = \{v_{11}, v_{21}, \dots, v_{P1}\}$ and $\mathbf{v}_{i2} = \{v_{12}, v_{22}, \dots, v_{P2}\}$ respectively. The structure of the FPSO-TR algorithm is given in Figure 4.

Figure 4. Structure of the FPSO-TR scheme.

The FPSOPSO-TR Algorithm 1 is given in Table 1 in detail.

Algorithm 1 Particle swarm optimization based on FPSO-TR calculation.

Input: Modulated OFDM signal x , iteration times I , population size P

Output: Optimal combination of scaling factor ∂_l and amplitude threshold $Asat$

- 1: Initialize position factor $w_0 = \{w_{01}, w_{02}\}$ and the velocity $v_0 = \{v_{01}, v_{02}\}$ of each particle randomly, where w_0 is a random combination of ∂_l and $Asat$, ranging from $[0, 25]$.
 - 2: Initialize inertia weight coefficient range $\omega_{\max}$ and $\omega_{\min}$, acceleration constants c_1 and c_2 , velocity range $v_{\min}$ and $v_{\max}$, size of swarm particle P . Relationship of inertia weight coefficient and iterations times is: $\omega_i = \omega_{\max} - (\frac{\omega_{\max} - \omega_{\min}}{iter_{\max}}) * (i - 1)$, where $iter$ is current iteration times, $iter_{\max}$ is maximum iteration times.
 - 3: Initialize both personal best position $w_0^pbest = \{w_{01}^pbest, w_{02}^pbest\}$ and global best position $w_0^gbest = \{w_{01}^gbest, w_{02}^gbest\}$ as negative infinity.
 - 4: **Begin**
 - 5: **while** $iter < I$ **do**
 - 6: Calculating fitness $f_i = \{f_i | i = 1, 2, \dots, P\}$ of position w_i in (16), where i represents $iter$
 - 7: **if** $p_i^best < f_i$ **then**
 - 8: $p_i^best = f_i$
 - 9: $w_i^pbest = w_i$
 - 10: where p_i^best is personal best fitness, w_i is current location.
 - 11: **end if**
 - 12: **if** $p_g^best < \max(p_i^best)$ **then**
 - 13: $p_g^best = \max(p_i^best)$
 - 14: $w_i^gbest = position\ of\ \max(p_i^best)$
 - 15: where p_g^best is global best fitness.
 - 16: **end if**
 - 17: Update velocity as: $v_{i+1} = \omega_i \times v_i + c_1 \times rand \times (w_i^pbest - w_i) + c_2 \times rand \times (w_i^gbest - w_i)$
 - 18: Find velocity $< v_{\min}$, replace them with $v_{\min}$.
 - 19: Find velocity $> v_{\max}$, replace them with $v_{\max}$.
 - 20: Update position $w_{i+1} = w_i + v_i$.
 - 21: Update position ω_{i+1} .
 - 22: $iter = iter + 1$
 - 23: **end while;**
 - 24:
 - 25: Output the final position $w_I = \{w_{I1}, w_{I2}\}$ as the optimal scaling factor ∂_l and amplitude threshold $Asat$; output the final fitness f_I as the optimal MER
 - 26: **End**
-

Table 1. Simulations parameters of Simulation results.

amplifier voltage gain G	1
Smoothing factor p	10
PAPR reduction scheme	F-TR
Total number of subcarrier	3780
Total number of OFDM symbols	10^5
Pilot ratio	3%, 5%, 7%
Up-sample times	4
Constellation modulation mode	16 QAM
PAPR threshold	6 dB
Maximum iterations times	3

5. Simulation

To demonstrate the efficiency of the conventional TR scheme, this paper conducted a simulation that compared the PAPR reducing performance of PTS, ACE, and TR schemes with the OFDM system.

As shown in Figure 5, the original OFDM signal PAPR is almost 12 dB when the probability is 10^{-2} , while the PAPR is 8.8 dB, 8.5 dB, 8.1 dB when the PAPR reduction scheme is ACE, PTS and TR respectively. Thus, TR has a significant PAPR reduction performance in the OFDM system. The conventional TR scheme PAPR reduction performance is more evident than when other methods are used.

Figure 5. Comparison of different PAPR reduction scheme.

In this paper, performance simulations are shown for the proposed FPTS-TR. The OFDM signal modulated by 64QAM was adopted, 3780 subcarriers were generated. The original signal utilized four times upsampling. The Rapp HPA model employed $p = 10$ in this paper (regardless of the nonlinear distortion of the amplifier). The parameters of FPTS-TR are given in Table 1.

To demonstrate the efficiency of the F-TR scheme with different pilot ratios on PAPR reduction performance, Figure 6 compares F-TR PAPR reduction performance when the pilot is 3%, 5%, 7%, respectively.

As shown in Figure 6, the original OFDM signal PAPR is more than 11 dB when probability is 10^{-2} , while the PAPR is 8.1 dB, 7.1 dB, 6.5 dB when the pilot ratio is 3%, 5%, 7% respectively. Thus, F-TR has a significant PAPR reduction performance in the 64QAM OFDM system, and its performance enhanced with the increase of pilot ratio, 7% pilot F-TR gained nearly 2 dB better than 3% pilot. However, CCDF standards failed to evaluate signal performance globally, and F-TR did not achieve optimal performance.

Figure 6. CCDF of F-TR with various pilot ratio.

To achieve optimal MER performance, we adopted the FPSO-PTS scheme as in Figure 7 to study the relationship between pilot ratio and IBO gains, and Figure 7 shows the curve of the relationship mentioned above when $MER = 40$ dB; the PSO algorithm parameters setting are shown in Table 2.

It can be seen from Figure 7 that all curves have reached convergence and the optimal result has been searched; 3% pilot reached $MER = 41.03$ dB by 22 times iterations; 5% pilot reached $MER = 44.27$ dB by 14 times iterations; 3% pilot reached $MER = 41.03$ dB by 22 times iterations; 5% pilot reached $MER = 44.27$ dB by 14 times iterations; 7% pilot reached $MER = 47.56$ dB by 10 times iterations. Although 5% and 7% pilot are 3.24 dB higher than 3% pilot, 5% and 7% pilot had an almost identical performance. The FPTSO-TR searching result is given in Table 3 in detail.

To evaluate the optimized OFDM signal distribution probability curve, Figure 8 adopted maximizing HPA efficiency evaluation criteria to evaluate the signal performance of F-TR after HPA, which employed the Rapp model when $p = 10$.

Figure 8 shows that when $MER = 40$ dB, the IBO of the original signal is 7.95 dB; After F-TR scheme with 3% pilot, the IBO of the signal decreases by 6.9 dB and the gain is 1.05 dB; After F-TR scheme with 5% pilot, the IBO of the signal decreases by 6.6 dB and the gain is 0.3 dB; After F-TR scheme with 7% pilot, the IBO of the signal decreases by 6.2 dB and the gain is 0.35 dB. Thus, the IBO of F-TR can achieve more gains than the original 64QAM OFDM signal. In a specific range, the IBO gain enhanced with the increase of pilot ratio. It is clear that novel maximizing HPA efficiency evaluation criteria cannot clarify the HPA efficiency.

Table 2. FPSO-TR parameters setting.

PAPR reduction scheme	FPSO-TR
IBO	7 dB
Searching positions (D)	2
Population size	50
Iteration times	50
Dimension values	1
Position ranges	[0, 25]
$v_{\min}$	−1
$v_{\max}$	1
$\omega_{\min}$	0.4
$\omega_{\max}$	0.9
c_1	0.5
c_2	0.5

Table 3. Results of FPTSO-TR.

Pilot ratio = 3%	Optimal ∂_l	23.17
	Optimal $Asat$	14.45 dB
	Optimal MER	41.03 dB
Pilot ratio = 5%	Optimal ∂_l	22.91
	Optimal $Asat$	13.94 dB
	Optimal MER	44.27 dB
Pilot ratio = 7%	Optimal ∂_l	0.8
	Optimal $Asat$	13.7 dB
	Optimal MER	47.56 dB

Figure 7. Relationship of IBO (dB) and pilot ratio (%) in FPSO-TR scheme.

Figure 8. Novel maximizing HPA efficiency evaluation criteria.

It can be seen from Figure 9 that: the original signal IBO is 6 dB ($pilotratio = 0$); IBO decreases with the increase of pilot ratio with trend slow down. IBO is 4.4 dB, and the IBO gain is 1.6 dB when the pilot ratio reaches 20%. It further proves the effectiveness of the F-TR algorithm.

By adopting the FPSO-TR scheme and maximizing HPA efficiency evaluation criteria, the best IBO and MER can be found and the efficiency of HPA would be improved.

Figure 9. Relationship of IBO (dB) and pilot ratio (%) in F-TR scheme.

Energy efficiency and signal to noise ratio (SNR) are demonstrated in Figure 10 and 11. Simulation parameters are shown in Table 4. The energy efficiency of different pilot signals with $MER = 40$ dB is fair compared.

It can be seen that the overall energy efficiency increases first and then decreases while SNR increases; the energy efficiency reaches the peak value between $SNR = [12, 17]$ dB. The energy efficiency increases with the increases of the pilot when $pilot \leq 9\%$. $pilot = 1\%$ and $pilot = 9\%$ reaches the minimum and maximum energy efficiency values of 10.9 (s.Hz)/J and 16.5 (s.Hz)/J respectively when $SNR = 17$ dB. Then the energy efficiency decreased with the increases of the pilot when $pilot > 9\%$. $pilot = 13\%$ reaches 16.2 (s.Hz)/J when $SNR = 17$ dB. Obviously, energy efficiency peaked at $pilot = 9\%$ when $SNR = 17$ dB.

Table 4. Simulations parameters of the Rapp HPA model.

Transmit antennas TX = ℓ	64
Receive antennas RX	64
Range of SNR	1~31 dB
Circuit power consumption $\ell \cdot P_{cir}$	0.01
Static power consumption P_{sta}	0.01
Pilot ratio $\zeta = pilot$	0.1~0.3
HPA efficiency η_a	0.35

Figure 10. Energy Efficiency Trend of Pilot Under Different SNR When $MER = 40$ dB.

Figure 11 demonstrates the relationship between pilot and energy efficiency when $SNR = 17$ dB; the energy efficiency increases first and then decreases while SNR increases, peaking at $pilot = 9\%$ with the value of 16.5 (s. Hz)/J.

Figure 11. Relationship Between Pilot and Energy Efficiency when $SNR = 17$ dB.

This paper adopted an efficient PAPR reduction scheme TR to use HPA work in the linear region and saved energy for smart grids. The best MER results under different IBO conditions can be obtained by further combining FTR with the PSO algorithm, and the signal transmission accuracy of SG is improved. By the final simulation of energy efficiency, it can be concluded that the highest energy efficiency is obtained when IBO = 9 dB, which further enhances the energy efficiency of SG.

6. Conclusions

This paper studies the combination of the improved frequency domain TR method and the PSO algorithm and the novel maximizing HPA efficiency evaluation criteria of global evaluation to optimize the PAPR reduction performance and effect of FPTS-PSO high-order communication system in SGs. We adopted 3%, 5% and 7% reserved tone in the frequency domain. The IBO achieved satisfactory gain compared to the original OFDM signal, which offset the power loss of HPA and solved the PAPR issue of the multi-carrier transmitter under high-order M-QAM modulation. By combining F-TR with the PSO algorithm, the optimal pilot ratio and the optimal power amplifier efficiency is obtained. FPSO-TR applied in the high-order communication system in SGs are proven to be an energy efficiency algorithm. In further work, the compatibility of the TR method with neural network algorithm methods can be considered to explore a better PAPR suppression scheme for a future communication system in SGs.

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Abbreviations

The following abbreviations are used in this manuscript:

PAPR	Peak-to-Average Power Ratio
OFDM	Orthogonal Frequency Division Multiplexing
TR	Tone Reservation
PSO	Particle Swarm Optimization
IBO	Input Back-Off
HPA	High Power Amplifier
MER	Modulation Error Ratio
EE	Energy Efficiency

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