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ADAPTIVE PAPR REDUCTION USING TONE RESERVATION AND CLIPPING IN OFDM TRANSMISSION OVER FADING CHANNELS

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Abstract. The high peak-to-average power ratio (PAPR) inherent in orthogonal frequency-division multiplexing (OFDM) signals forces the high-power amplifier (HPA) to operate with substantial input back-off (IBO) value, severely degrading transmitter power efficiency. This paper investigates the joint application of adaptive tone reservation (TR) and clipping for PAPR reduction in OFDM transmission over frequency-selective fading channels. The adaptive TR scheme employs channel state information to dynamically allocate reserved tones to subcarriers that experience poor signal-to-noise ratio (SNR) and are therefore of limited utility for data transmission. Four configurations have been systematically compared: a baseline without PAPR reduction, clipping only, adaptive TR only, and the proposed joint adaptive TR and clipping scheme. Simulations for the case of a measurement-based underwater acoustic channel with a hard-limiter HPA model demonstrate that adaptive TR alone achieves a 2.8 dB SNR gain over the baseline at a target bit error rate of 10^{-3} , without introducing in-band distortion. The joint scheme yields a total SNR gain of 4.6 dB, combining the benefits from distortionless peak suppression by TR with the aggressive clipping action. Relative to clipping-only operation, the joint scheme decreases out-of-band emission by 3.5 dB and compresses the 99.5% occupied bandwidth by 40%. These results confirm that the combination of SINR-based adaptive TR and clipping provides simultaneous improvements in power efficiency and spectral containment, making it a compelling solution for communication systems subject to both power and spectral mask constraints.

Keywords: PAPR, tone reservation, power allocation, adaptive systems, out-of-band emission suppression

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АДАПТИВНОЕ СНИЖЕНИЕ ПИК-ФАКТОРА КОЛЕБАНИЙ С ПОМОЩЬЮ РЕЗЕРВИРОВАНИЯ ТОНОВ И КЛИППИРОВАНИЯ ДЛЯ СИГНАЛОВ С OFDM В КАНАЛАХ С ЧАСТОТНО-СЕЛЕКТИВНЫМИ ЗАМИРАНИЯМИ

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Аннотация. Высокий пик-фактор, присущий сигналам с ортогональным частотным уплотнением (OFDM), вынуждает выбирать рабочую точку усилителя вдали от насыщения его передаточной характеристики, что существенно снижает энергетическую эффективность передатчика. В данной работе исследуется совместное применение адаптивного резервирования тонов и клиппирования для снижения пик-фактора в системах связи с OFDM при работе в частотно-селективных каналах с замираниями. В предлагаемой адаптивной схеме при резервировании тонов используется информация о состоянии канала для динамического выделения поднесущих частот с низким отношением сигнал/шум, которые мало пригодны для передачи данных, для излучения служебного сигнала коррекции пик-фактора. В работе сравниваются четыре конфигурации: базовый вариант без снижения пик-фактора, только клиппирование, только адаптивное резервирование тонов и предлагаемая совместная схема с адаптивным резервированием тонов и клиппированием. Моделирование, выполненное для гидроакустического канала с моделью усилителя с жестким ограничением, показывает, что адаптивное резервирование тонов обеспечивает выигрыш в помехоустойчивости по отношению сигнал/шум в 2,8 дБ по сравнению с базовым вариантом при целевой вероятности битовой ошибки 10^{-3} , не внося дополнительных искажений. Совместная схема дает суммарный выигрыш по отношению сигнал/шум в 4,6 дБ, сочетая подавление пиков с помощью резервирования тонов и клиппирования. Совместная схема снижает уровень внеполосных излучений на 3,5 дБ и сокращает занимаемую полосу частот по уровню 99,5% мощности на 40% по сравнению с отдельным использованием клиппирования. Полученные результаты подтверждают, что комбинация адаптивного распределения тонов и клиппирования обеспечивает одновременное повышение энергетической эффективности и улучшение спектральных характеристик, что делает предлагаемое решение привлекательным для систем связи, работающих в условиях ограничений как по мощности, так и по уровню внеполосного излучения.

Ключевые слова: пик-фактор, резервирование тонов, распределение мощности, адаптивные системы, подавление внеполосного излучения

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Introduction

Orthogonal frequency-division multiplexing (OFDM) has been widely adopted in modern wireless communication standards due to its robustness against multipath fading and high spectral efficiency. Nevertheless, one of the inherent drawbacks of OFDM signals is the high peak-to-average power ratio (PAPR), which forces the high-power amplifier (HPA) to operate with a large value of input back-off (IBO), thereby degrading the overall power efficiency of the transmitter.

To mitigate this issue, numerous PAPR reduction techniques have been extensively investigated. Clipping is a straightforward and effective approach; however, it causes in-band distortion and out-of-band (OOB) radiation [1–3]. In contrast, tone reservation (TR) is a distortionless technique that reserves a subset of subcarriers for a peak-canceling signal [1, 4, 5]. While effective, TR comes at the cost of spectral and power efficiency due to the allocation of reserved tones.

Recent literature has explored both hybrid combinations and adaptive strategies for these techniques. A combination of TR based on the projected conjugate gradient (PCG) algorithm with conventional clipping is proposed in [6]. While this work demonstrates the viability of joint PAPR reduction, the TR component operates statically and does not exploit channel state information (CSI). On the other hand, research on adaptive TR has gained traction in multi-user and resource-constrained scenarios in fading channels. An adaptive TR scheme provides PAPR reduction subject to throughput constraints by allocating reserved tones within resource blocks. In [7], authors investigated joint optimization of subcarrier allocation and TR for OFDM access, further highlighting the benefits of adaptive tone selection. However, these adaptive TR studies [2, 3] focus exclusively on PAPR reduction without considering the impact of additional non-linear operations such as clipping on system performance.

A distinct yet complementary direction was explored in [4], where the focus of TR was shifted from pure PAPR reduction towards improving bit error rate (BER) performance. Specifically, the authors demonstrated that adaptively selecting the reserved tones based on the signal-to-interference-plus-noise ratio (SINR) of the fading channel yields significant gains in error robustness. Nevertheless, the work does not address PAPR reduction itself, nor does it evaluate the combined effect of TR with clipping distortion.

From the above review, a clear research gap emerges. Hybrid TR-clipping schemes have been proposed in [1], and adaptive TR schemes exist for PAPR reduction [4–8] and for BER improvement [9]. However, none of these works has investigated the joint operation of SINR-based adaptive TR and clipping specifically for PAPR reduction over fading channels. Consequently, the potential power efficiency gains – as well as the spectral containment benefits – achievable by combining channel-aware TR with controlled non-linear distortion remain unexplored.

The primary objective of this work is to enhance the power efficiency and spectral containment of OFDM transmission over fading channels through the intelligent combination of adaptive TR and clipping. Unlike conventional approaches that apply PAPR reduction agnostically to channel conditions, we aim to demonstrate that exploiting SINR knowledge for TR allocation yields a more favorable trade-off between PAPR suppression, error rate degradation, and OOB radiation. By cascading distortionless peak suppression (adaptive TR) with a subsequent clipping stage, we target a simultaneous reduction in required HPA IBO and OOB radiation [10].

To evaluate the extent of this improvement, we benchmark the proposed joint scheme and three reference configurations under identical frequency-selective fading conditions:

- 1) *No PAPR reduction*: Baseline OFDM transmission without PAPR mitigation.
- 2) *Clipping only*: Conventional amplitude clipping applied to the OFDM signal.
- 3) *Adaptive TR only*: SINR-based TR as proposed in [4], applied for peak power reduction.
- 4) *Proposed joint scheme*: adaptive TR combined with subsequent clipping.

The analysis specifically quantifies the reduction of BER. Simulation results confirm that the proposed joint scheme transmission with higher power efficiency.

PAPR reduction techniques

The problem of high PAPR in OFDM systems is well explained in the literature [1–5]. The large envelope fluctuations of multicarrier signals force the HPA to operate with a significant power back-off, severely degrading transmitter power efficiency. A comprehensive review of PAPR mitigation

strategies can be found in [1] and references therein. Among the available techniques, this work focuses on TR and clipping, described in detail below.

TR

The concept of TR emerged from the observation that, in frequency-selective fading channels, certain subcarriers experience such poor SINR that they become unusable for reliable data transmission. Rather than leaving these degraded subcarriers idle, TR repurposes them to carry a peak-canceling signal, thereby improving the PAPR characteristics of the transmitted waveform without sacrificing useful data throughput [11, 12].

Formally, TR is a distortionless PAPR reduction technique wherein a subset of subcarriers is exclusively allocated to carry a peak-canceling signal rather than user data. Let R denote the set of reserved tone indices, and let D denote the complementary set of data-bearing subcarriers, such that

$$R \cap D = \emptyset; \quad R \cup D = [0, 1, \dots, N-1], \quad N_R + N_D = N, \quad (1)$$

where N is the total subcarriers number in OFDM symbol, N_R and N_D are reserved and data set sizes, respectively. The transmitted frequency-domain symbol is then

$$x_k = \begin{cases} d_k, & k \in D \\ c_k, & k \in R \end{cases}, \quad (2)$$

where d_k is the data symbol drawn from a modulation constellation (e.g., QAM), and c_k is the peak-canceling coefficient on k -th subcarrier.

The objective of TR is to find the optimal correction vector C that minimizes the peak magnitude of the resulting time-domain signal $IFFT(x_k)$. The optimization problem is formally stated as:

$$\min_C \max_k |IFFT(x_k)|^2, \quad \text{subject to } \sum_{k=0}^{R-1} c_k \leq P_{TR}, \quad (3)$$

where the constraint limits the total power injected into the reserved tones to a predefined power budget P_{TR} .

Adaptive TR

Conventional TR allocates reserved tones at fixed, predetermined positions (typically equally spaced across the available spectrum) without regard for the underlying channel conditions. This static assignment, while simple to implement, is inherently suboptimal in frequency-selective fading environments, as demonstrated in [9].

The core principle of adaptive TR is to exploit CSI to select which subcarriers should serve as reserved tones. The key insight, introduced in [9], is that subcarriers experiencing poor SINR are of limited utility for data transmission, as they would require excessive power or low-order modulation to achieve reliable communication. Rather than wasting the degraded subcarriers on unreliable data, they can be repurposed for peak cancellation.

In this work, we adopt the SINR-based allocation strategy of [9]. The adaptive TR scheme employed in this work departs from the conventional approach in two fundamental respects. First, the number of reserved tones N_R is not fixed a priori but is determined dynamically based on the instantaneous channel state. Second, the selection of which subcarriers serve as reserved tones follows directly from a bit-loading procedure [13] rather than from a predefined rule.

This adaptive allocation strategy ensures that spectrally efficient subcarriers are preserved for user data, while the peak-canceling function is offloaded to subcarriers that would otherwise contribute little to the overall system throughput.

Clipping

Clipping is a memoryless non-linear operation that limits the envelope of the time-domain OFDM signal to a predefined threshold. Despite its conceptual simplicity, clipping remains one of the most widely studied PAPR reduction techniques due to its low computational complexity and deterministic peak suppression capability.

Mathematically, the clipping operation is defined as:

$$\bar{x}_n = \begin{cases} x_n, & |x_n| \leq A \\ A \exp(j\phi(x_n)), & |x_n| > A \end{cases}, \quad (4)$$

where x_n is the n -th sample of the discrete-time baseband OFDM signal, A is the clipping threshold, and $\phi(x_n)$ is the phase of x_n .

The deep of clipping is conventionally parameterized by the clipping ratio (CR), defined as the ratio of the clipping threshold to the root mean square (RMS) amplitude σ of the OFDM signal:

$$CR = \frac{A}{\sigma}. \quad (5)$$

In a practical transmitter chain, the clipped signal is subsequently fed to an HPA. The operating point of the HPA is characterized by the IBO, which quantifies the margin between the average input power and the amplifier saturation threshold A_{sat} .

$$IBO = \frac{A_{sat}^2}{\sigma^2} \text{ or } IBO_{dB} = 10 \log_{10} \left(\frac{A_{sat}^2}{\sigma^2} \right). \quad (6)$$

The CR and IBO parameters are inherently coupled. When the clipping threshold A is set below the amplifier saturation level A_{sat} , the clipper effectively enforces a more stringent amplitude limit than the HPA itself. In this configuration, the clipping stage reduces the PAPR of the signal before it reaches the HPA. Consequently, for a fixed saturation level A_{sat} , a lower clipping threshold (smaller CR) allows the HPA to operate with reduced IBO while maintaining the same level of nonlinear distortion. The selection of appropriate CR and IBO values is therefore a joint design problem that directly determines the trade-off between PAPR reduction, BER degradation, and power efficiency. In this work, the clipping threshold is parameterized directly in terms of the target IBO reduction rather than an abstract CR value.

Unlike TR, clipping is not a distortionless technique. The hard amplitude limitation introduces two distinct categories of impairment:

- 1) In-band distortion: The non-linear operation corrupts the transmitted constellation, raising the error vector magnitude (EVM) and introducing an error floor in the BER performance [14].
- 2) OOB radiation: The sharp amplitude truncation broadens the power spectral density (PSD) of the transmitted signal, causing interference to adjacent frequency channels. In practical systems, regulatory spectral masks impose strict limits on such emissions, making OOB radiation a critical design constraint [15].

A standard approach to mitigate OOB radiation is to apply linear filtering after the clipping stage. However, filtering modifies the signal envelope and inevitably causes peak regrowth – a partial restoration of the peaks that clipping was designed to suppress [1]. This cyclical trade-off between peak suppression, in-band distortion, and OOB containment constitutes the fundamental limitation of

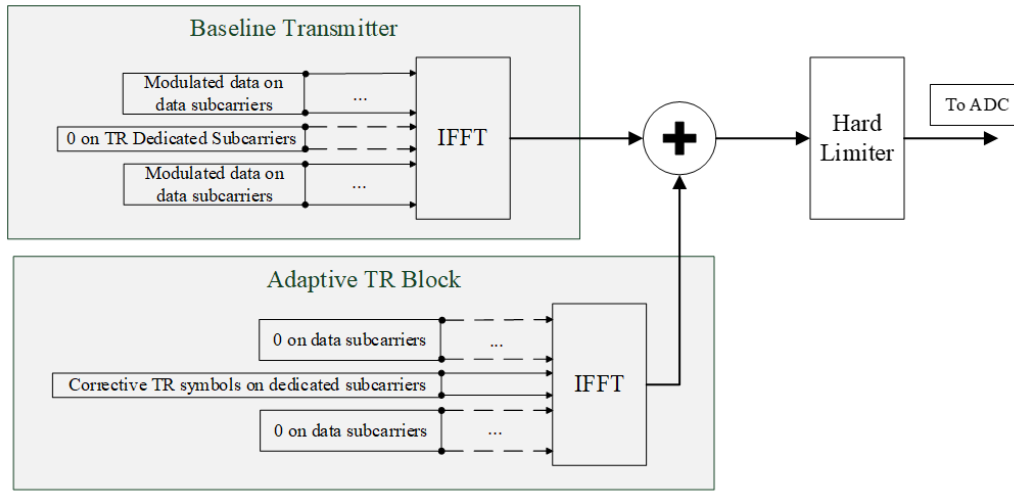


Fig. 1. Joint PAPR reduction scheme

standalone clipping and motivates its combination with distortionless techniques such as adaptive TR, as explored in this work.

Joint adaptive TR and clipping

The preceding subsections have established that adaptive TR and clipping offer complementary mechanisms for PAPR reduction. Adaptive TR is distortionless but provides limited peak suppression, constrained by the number of reserved tones.

The concept of combining TR with clipping to improve PAPR reduction performance was discussed in [6], which proposed a hybrid scheme that cascades TR based on the PCG algorithm with conventional amplitude clipping.

However, the TR component employed in [6] operates statically: the reserved tones are allocated to fixed, predetermined subcarrier positions without any consideration of the underlying channel conditions. The present work extends this concept by introducing channel awareness into the TR stage. Specifically, the fixed TR allocation of [6] is replaced by the SINR-based adaptive TR strategy.

The resulting joint scheme combines these two techniques in a cascaded architecture, as illustrated conceptually in Fig. 1. The signal processing chain proceeds as follows.

Both the adaptive TR block and the clipping block are active, arranged in cascade. The signal is first preconditioned by the adaptive TR stage, and the resulting peak-reduced signal is then clipped. The benefits of this cascade directly address the limitations of each individual technique:

1) *Enhanced PAPR reduction beyond standalone TR*: adaptive TR alone is constrained in its peak suppression capability by the number of reserved tones N_R and the allocated correction power budget P_{TR} . In practice, this means that a residual fraction of high-amplitude peaks remains after the TR stage. By cascading a clipping stage after the TR block, these residual peaks are forcibly limited, achieving a PAPR reduction that is substantially greater than what TR can deliver in isolation. This is the primary motivation for including the clipping stage: it compensates for the inherent peak suppression ceiling of the TR method.

2) *Suppressed OOB radiation compared to standalone clipping*: clipping alone introduces significant OOB spectral regrowth due to the frequent and sharp amplitude truncations. In the joint scheme, the TR preconditioning stage reduces the number and amplitude of signal samples that exceed the clipping threshold A . Consequently, the clipper is activated less frequently and on peaks of lower amplitude, leading to an adjacent channel leakage ratio (ACLR) measurably superior to that of clipping only.

System model

System overview

The performance of the proposed PAPR reduction schemes is evaluated using a Monte Carlo simulation of a complete OFDM communication link operating over frequency-selective fading channel. The simulation chain models passband OFDM modulation, application of one of the four PAPR reduction configurations, high-power amplification with a hard-limiter characteristic, transmission through a multipath fading channel, and receiver processing including equalization and symbol detection.

A key enabler for the adaptive TR scheme is the availability of CSI at the transmitter. In this study, perfect CSI is assumed at the transmitter side. The CSI is used as input to the greedy bit-loading algorithm, which determines the modulation assignment and, consequently, the reserved tone set c_k for each channel realization. This assumption isolates the performance gains attributable to the adaptive allocation strategy from any degradation due to channel estimation errors.

The main simulation parameters are summarized in Table 1.

Table 1

Communication system parameters

Parameter	Value
Mapper constellations	QPSK, QAM-16
FFT size	8192
Payload per OFDM symbol, bit	304
Number of data subcarriers (without TR)	152
Equalizer type	Zero-Forcing
Target BER	10^{-3}
Channel encoding type / code rate	Convolutional / 0.5

Channel overview

The performance of the proposed PAPR reduction schemes is evaluated over a frequency-selective underwater acoustic (UWA) communication channel. This propagation environment is chosen for two reasons directly relevant to the present study.

First, UWA channels are characterized by strong and persistent frequency-selective fading caused by multipath propagation arising from surface and bottom reflections [16, 17]. The low speed of sound in water (approximately 1500 m/s) results in delay spreads that are orders of magnitude larger than those encountered in terrestrial radio channels, producing deep spectral nulls on a subset of OFDM subcarriers. This creates precisely the conditions under which a bit-loading algorithm will identify a subset of subcarriers as unsuitable for data transmission and therefore available for TR.

Second, the UWA channel exhibits quasi-static behavior over the duration of a typical transmission packet. While the channel varies over longer time scales due to surface motion and platform displacement, the coherence time is typically much longer than the duration of an OFDM packet, particularly for moderate carrier frequencies (tens of kilohertz) and short packet lengths [16]. This stability is essential for the adaptive TR scheme: the CSI obtained at the start of a packet remains valid throughout its duration, allowing the reserved tone assignment to be fixed for all OFDM symbols within that packet without re-estimation [18].

The channel parameters are derived from experimental measurements reported in the UWA communications literature [13].

The channel is assumed to be quasi-static: the impulse response $h(t)$ remains constant for the duration of one transmission packet (comprising all OFDM symbols).

Signal-to-noise ratio metric

In the presence of clipping and hard-limiter amplification, the conventional E_b/N_0 metric – which is based on the average signal power – becomes dependent on the PAPR reduction scheme and the operating IBO. To enable fair comparison across all four configurations, we adopt a scheme-independent signal-to-noise ratio (SNR) reference based on the maximum available transmit power.

Let $P_{\max} = A_{\text{sat}}^2$ denote the saturation power of the HPA, and let N_0 denote the single-sided noise PSD. The reference SNR is defined as:

$$SNR_{\text{ref}} = \frac{P_{\max}}{N_0} = \frac{A_{\text{sat}}^2}{N_0}. \quad (7)$$

This metric represents the best-case SNR achievable when the HPA operates at saturation. For a given IBO, the actual average transmit power is:

$$P_{\text{avg}} = P_{\max} \cdot 10^{-\text{IBO}/10}. \quad (8)$$

The conventional E_b/N_0 can be recovered from SNR_{ref} as:

$$\frac{E_b}{N_0} = \frac{SNR_{\text{ref}}}{\log_2 \bar{M}} \cdot 10^{-\text{IBO}/10}, \quad (9)$$

where $\bar{M}$ is the average modulation order across data-bearing subcarriers. For the baseline case with uniform bit loading $\log_2 \bar{M} = 2$.

Performance metrics

Two categories of performance metrics are employed to evaluate the proposed schemes: link-level reliability and spectral containment. The primary metric for assessing end-to-end communication

quality is the BER as a function of the reference SNR ratio $SNR_{\text{ref}} = \frac{P_{\max}}{N_0}$.

In addition to link reliability, the spectral properties of the transmitted signal are of critical importance in practical systems subject to regulatory spectral masks. Two complementary metrics are employed to quantify spectral containment:

1. Peak OOB emission level is defined as the maximum value of the PSD measured outside the assigned signal bandwidth.
2. Occupied bandwidth at 99.5% energy is defined as the frequency interval that contains 99.5% of the total transmitted power.

Simulation results

Before evaluating the comparative performance of the four PAPR reduction configurations, it is necessary to establish a fair operating point for the clipping-based schemes. The clipping threshold A – equivalently expressed through the HPA IBO – governs the trade-off between peak suppression and signal distortion.

The use of SNR_{ref} rather than the conventional average-power-based SNR is deliberate. In a practical transmitter, the HPA must be designed to accommodate the maximum signal excursion, not the average signal level. When no clipping is applied (or when clipping is conservative, corresponding to a high IBO), large-amplitude peaks force the amplifier to operate with substantial back-off. Consequently, for a fixed HPA saturation power, the average transmitted power is low compared to the peak,

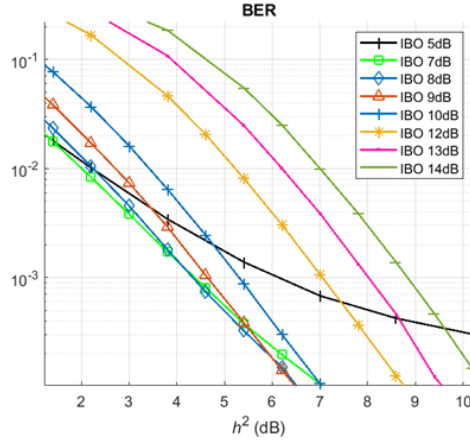


Fig. 2. BER performance for clipped OFDM without TR for different IBO value

and the additive white Gaussian noise (AWGN) floor at the receiver dominates. As clipping becomes more aggressive (lower IBO), these peaks are suppressed, allowing a higher average power to be transmitted within the same peak power constraint – which, in turn, improves the effective SNR at the receiver.

Fig. 2 presents the BER of the clipping only configuration as a function of SNR_{ref} for several candidate IBO values.

The resulting curves reflect two competing mechanisms:

1) High IBO regime (e.g., IBO = 10 dB and above): clipping is conservative. Large signal peaks remain largely unsuppressed, forcing the HPA to operate with a high back-off. For a given peak power constraint P_{max} , the average transmitted power is low, and the resulting SNR_{ref} yields a degraded BER. In this regime, the dominant impairment is not clipping distortion, but poor power efficiency: the HPA operates far from saturation, the low average transmitted power yields a reduced SNR at the receiver, thereby elevating the BER.

2) Low IBO regime (e.g., IBO = 5 dB): Clipping is aggressive. Signal peaks are effectively suppressed, enabling the HPA to operate closer to saturation and deliver higher average power for the same P_{max} . However, the severe amplitude truncation introduces substantial in-band distortion, which manifests as an elevated irreducible error floor at high SNR_{ref} .

The optimal IBO is the value that balances these two effects. In the present simulations, the curve corresponding to IBO = 8 dB achieves the lowest BER across the measured SNR_{ref} range. At this operating point, the peak suppression is sufficient to allow efficient HPA utilization, while the clipping-induced distortion remains within acceptable limits.

Based on this result, IBO = 8 dB is selected as the operating point for all subsequent simulations involving clipping.

Fig. 3 presents the BER vs SNR_{ref} curves for the four PAPR reduction configurations, evaluated with IBO = 8 dB at the HPA. The required SNR_{ref} values to achieve the target BER of 10^{-3} are extracted from the curves and summarized in Table 2.

First, the adaptive TR only configuration (Case 3) achieves a substantial 2.8 dB SNR gain over the baseline. This result confirms that SINR-based adaptive tone allocation, originally proposed for BER improvement in [4], is effective as a standalone PAPR reduction technique. By repurposing low-SINR subcarriers for peak cancellation, the scheme reduces the PAPR without introducing any in-band distortion, and this distortionless nature translates directly into an improved BER.

Second, the joint adaptive TR and clipping configuration (Case 4) yields an additional improvement, achieving a total SNR gain of 4.6 dB over the baseline. Compared to clipping only (Case 2),

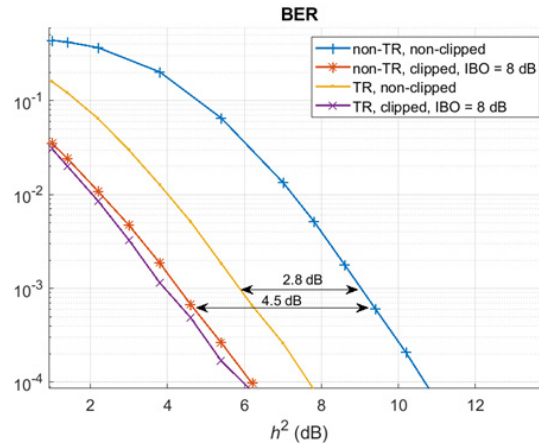


Fig. 3. BER performance for OFDM system with and without clipping and adaptive TR

Table 2

Communication system parameters

System configuration	Required $P_{\max}/N_0$ (dB)	SNR Gain vs Baseline (dB)
(1) non-TR, non-clipped (Baseline)	10.6	—
(2) non-TR, clipping only	6.1	4.5
(3) adaptive TR, non-clipped	7.8	2.8
(4) joint (adaptive TR and clipping)	6.0	4.6

the joint scheme delivers a modest 0.1 dB SNR gain. This incremental improvement is consistent with the physical mechanism: the TR preconditioning stage reduces the dynamic range of the signal prior to clipping, thereby lowering the frequency of clipping events and the associated distortion. While the BER gain over pure clipping is small, the true benefit of the joint scheme becomes apparent when spectral containment is examined, as discussed in the following subsection.

Fig. 4 presents the PSD of the transmitted signal for the four configurations, measured at the HPA output. The PSD curves reveal the spectral containment properties of each scheme.

The following observations are drawn from Fig. 4.

Clipping increases OOB radiation: The clipping only curve exhibits a pronounced spectral broadening, with the OOB emission level rising significantly above the baseline. This behavior is an inherent consequence of the clipping non-linearity: the abrupt amplitude truncation at the threshold A introduces high-frequency components into the signal, which manifest as spectral regrowth in the adjacent bands.

TR mitigates clipping-induced OOB radiation: a comparison of the joint scheme (Case 4) with clipping only (Case 2) reveals a measurable 3.5 dB reduction in OOB emission when the adaptive TR preconditioner is active. The physical explanation follows directly from the cascaded architecture: the TR stage reduces the number of signal samples that exceed the clipping threshold, thereby decreasing the frequency of clipping events. Quantitatively, the occupied bandwidth — measured as the frequency interval containing 99.5% of the total radiated power — is reduced by approximately 40% in the joint scheme compared to clipping only.

In summary, the spectral analysis demonstrates that the joint scheme offers a dual benefit: it retains the aggressive PAPR suppression of clipping while meaningfully mitigating its principal drawback OOB spectral regrowth.

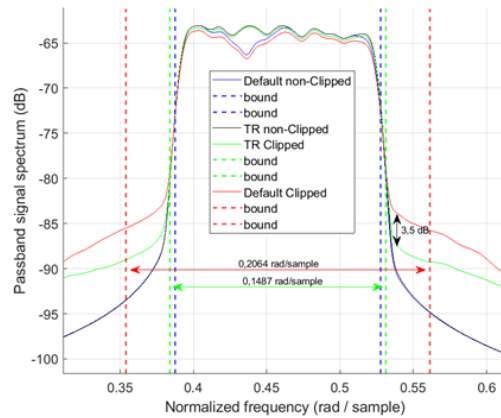


Fig. 4. Transmitted signal spectrums

Conclusion

This paper investigated the joint application of adaptive TR and clipping for PAPR reduction in OFDM systems operating over frequency-selective fading channels, with a particular focus on the UWA propagation environment. Motivated by the SINR-based TR allocation strategy proposed in prior works [7, 9], the study extended the analysis to evaluate the combined effect of this adaptive technique with conventional amplitude clipping. Four transmission configurations were benchmarked in terms of BER performance and spectral containment.

The simulation results confirm the efficacy of adaptive TR as a standalone PAPR reduction technique. By dynamically allocating reserved tones to subcarriers with low SINR — as determined by a greedy bit-loading algorithm — adaptive TR alone achieves a 2.8 dB SNR gain at a target BER of 10^{-3} compared to the non-reduced baseline, without introducing any in-band distortion.

The proposed joint adaptive TR and clipping scheme achieves the best overall performance, yielding a total SNR gain of 4.6 dB over the baseline. While the incremental BER improvement over clipping only is modest (0.1 dB), the joint scheme offers significant practical advantages in the spectral domain. Specifically, the TR preconditioning stage reduces the frequency of clipping events, leading to a 3.5 dB reduction in peak OOB emission and a 40% reduction in the 99.5% occupied bandwidth compared to clipping only. This enhanced spectral containment is of particular value in systems governed by stringent spectral mask regulations.

The results obtained for the UWA channel validate the proposed approach in a realistic propagation scenario where the adaptive allocation of reserved tones is both feasible and beneficial. The availability of perfect CSI at the transmitter, assumed in this study, is consistent with practical UWA communication systems that employ channel estimation during the preamble phase of each transmission packet.

Future work will extend the analysis to channels with mobility-induced Doppler spread, where the coherence time of the channel limits the validity period of the reserved tone assignment, and to scenarios with imperfect CSI, where channel estimation errors may degrade the performance of the SINR-based allocation strategy.

ABBREVIATIONS:

- ACLR — adjacent channel leakage ratio;
- AWGN — additive white Gaussian noise;
- BER — bit error rate;

- CR – clipping ratio;
- CSI – channel state information;
- HPA – high-power amplifier;
- IBO – input back-off;
- OFDM – orthogonal frequency-division multiplexing;
- OOB – out-of-band;
- PAPR – high peak-to-average power ratio;
- PCG – projected conjugate gradient;
- PSD – power spectral density;
- RMS – root mean square;
- SINR – signal-to-interference-plus-noise ratio;
- SNR – signal-to-noise ratio;
- TR – tone reservation;
- UWA – underwater acoustic.

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