Guard Band-Assisted One-Shot Tone Reservation Using Circular 1D-ResNet for 6G OFDM Systems

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6G OFDM 시스템을 위한 가드 밴드 Circular 1D-ResNet 기반 원샷 톤 예약 기법

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Abstract

This paper proposes a novel One-Shot Tone Reservation (TR) scheme based on a circular Convolutional Neural Network (CNN) to address the high Peak-to-Average Power Ratio (PAPR) in 6G OFDM systems. Unlike conventional methods that sacrifice data rate for reserved tones, the proposed method utilizes the inherent guard bands required for interference prevention, thereby eliminating spectral efficiency loss. Furthermore, the proposed circular 1D-ResNet architecture generates the peak-canceling signal in a single inference step, replacing the latency-heavy iterative processes of traditional TR. Simulation results demonstrate that the proposed method achieves significant PAPR reduction.

Ⅰ. Introduction

As the era of 6G communication approaches, the demand for ultra-high data rates has led to exploration of higher frequency bands, such as mmWave and Terahertz (THz) spectra, to secure wider bandwidths. While these high-frequency bands offer substantial capacity gains, they introduce severe hardware challenges. Key impairments include phase noise derived from local oscillator (LO) instability, Carrier Frequency Offset (CFO) due to oscillator mismatch, and most critically, the nonlinearity of the Power Amplifier (PA) at the end of the transmitter system.

In Orthogonal Frequency Division Multiplexing (OFDM) systems, these impairments can destroy orthogonality, cause Inter-Carrier Interference (ICI) and degrade overall system performance. While signal processing algorithms effectively mitigate CFO and phase noise at the receiver [1, 2], the high Peak-to-Average Power Ratio (PAPR) inherent to OFDM remains a bottleneck at the transmitter. High PAPR signals frequently drive PAs into their saturation region, causing spectral regrowth and in-band distortion. This issue is exacerbated in high-frequency bands when PAs often have limited linear operating ranges.

Tone Reservation (TR) is a well-known distortionless technique. TR reserves a subset of subcarriers (tones) to carry peak-canceling signals rather than data. Conventional TR algorithms iteratively optimize these tones to minimize PAPR. However, this approach has two major drawbacks: 1) it inevitably reduces spectral efficiency (throughput) due to the overhead of reserved tones, and 2) the iterative optimization introduces significant processing latency, making it unsuitable for ultra-low latency 6G applications.

In practical multi-user systems employing adjacent frequency bands, "Guard Bands" are mandatory to prevent Inter-Symbol Interference (ISI) and spectral leakage between users. These Guard Bands consist of null subcarriers that are typically wasted resources. In this paper, we propose a novel Circular CNN-based One-Shot Tone Reservation scheme. We utilize the otherwise wasted Guard Bands as reserved tones to eliminate overhead. Furthermore, we employ a lightweight 1D-ResNet model to generate optimal peak-canceling signals in a single "one-shot" inference, ensuring real-time performance with low computational complexity.

Ⅱ. Method

The proposed scheme introduces two key innovations: 1) utilizing Guard Bands as reserved resources, and 2) employing a circular CNN for one-shot signal generation.

In standard OFDM systems with $\boldsymbol{N}$ subcarriers, a subset $\boldsymbol{R}$ is reserved for peak reduction. In our proposal, we designate the Guard Band indices as the set $\boldsymbol{R}$. Let $\mathbf{X} \in \mathbb{C}^N$ be the frequency domain symbol vector. The time-domain signal $\mathbf{x}$ is obtained via IFFT. To reduce PAPR, we add a peak-canceling signal $\mathbf{c}$ generated from the reserved tones:

$$\hat{\mathbf{x}} = \mathbf{x} + \mathbf{c}$$

Here, $\mathbf{c}$ is constructed solely from the Guard Band subcarriers, ensuring no interference with data subcarriers. This approach effectively converts the spectral waste of Guard Bands into a utility for PAPR reduction.

To bypass the latency of iterative algorithms, we design a deep learning model that maps the input signal $\mathbf{x}$ to the optimal canceling signal $\mathbf{c}$ in a single forward pass. We employ a 1D Residual Network (ResNet) structure tailored for OFDM signals. A key feature is the use of Circular Padding in the convolutional layers. Since OFDM signals are cyclically extended (Cyclic Prefix), the features at the end of the symbol are correlated with the beginning. Circular padding preserves this physical property, preventing edge artifacts and improving inference accuracy.

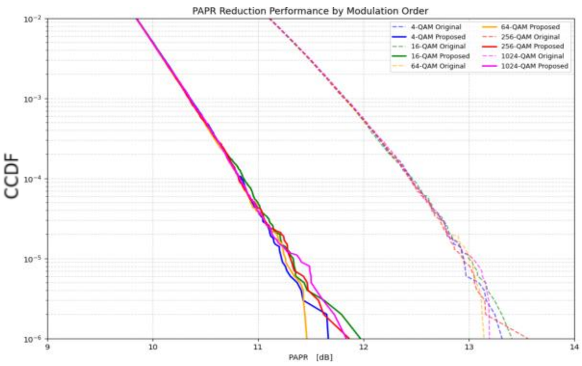
The most significant advantage of the proposed method lies in its processing flow. Traditional algorithms detect peaks, generate a canceling pulse, and re-evaluate the signal until the signal reaches to the PAPR threshold. This process must be repeated K times to handle "peak regrowth", where reducing one peak creates another. Since $i-th$ step depends on $(i-1)-th$ step, the total latency accumulates linearly with the number of iterations which cannot be predefined ($T_{total} \simeq K \times T_{step}$).

The proposed CNN observes the entire signal structure and predicts the optimal canceling signal $\mathbf{c} = \mathbf{Model}(\mathbf{x})$ in a single step. By leveraging the parallel processing capabilities of modern hardware (e.g., GPU or AI accelerators), all layers are computed in a pipelined manner without logical loops. This ensures a deterministic and minimal latency regardless of the signal's peak complexity.

The network is trained to minimize the PAPR of the output signal $\hat{\mathbf{x}}$ while adhering to power constraints. The loss function is defined as: $\boldsymbol{\mathcal{L}} = \mathbf{PAPR}(\mathbf{x}+\mathbf{c}) + \boldsymbol{\lambda}||\mathbf{c}||^{\mathbf{2}}$, where the first term minimizes peak power, and the second term regularizes the power of the canceling signal to maintain power efficiency.

III. Simulation Results

To validate the proposed One-Shot TR scheme, we conducted simulations using 5,000,000 OFDM symbols across various modulation orders ranging from 4-QAM to 1024-QAM each.



[Fig. 1] PAPR reduction performance

Fig. 1 illustrates the Complementary Cumulative Distribution Function (CCDF) of PAPR. The proposed method consistently reduces the PAPR across all tested modulation schemes. This robustness stems from the fact that the CNN operates directly on time-domain signals, making it inherently agnostic to specific frequency-domain modulation constellations.

Table 1 summarizes the overall performance. The proposed method achieves a PAPR reduction gain and especially, notably suppresses the maximum peak PAPR by 1.71 dB. These results confirm that the proposed circular 1D-ResNet successfully mitigates high PAPR in a single inference step without iterative latency.

[Table 1] PAPR reduction by proposed algorithm

Prob (%)	Original	Reduced	PAPR gain
1.0	11.10 dB	9.84 dB	1.26 dB
0.1	11.82 dB	10.34 dB	1.48 dB
0.01	12.44 dB	10.82 dB	1.63 dB
Max (0)	13.71 dB	12.00 dB	1.71 dB

IV. Conclusion

In this paper, we presented a practical PAPR reduction solution for 6G OFDM systems. The key contribution of this work is the transition from serial iterative processing to One-Shot inference. While conventional TR methods suffer from latency bottlenecks due to their serial nature and spectral loss due to reserved tones, our proposed method resolves both issues.

By repurposing Guard Bands, we eliminated spectral overhead. By employing a circular CNN architecture, we replaced the time-consuming iterative loop with a single feed-forward operation. This structural shift guarantees deterministic low latency, making the proposed scheme a highly promising candidate for real-time implementation in future high-frequency wireless systems.

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