Postprint of Improved Iterative Clipping and Filtering TDCS PAPR Suppression Algorithm

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Date: 2018-10-11T00:00:00+00:00

Abstract

To address the issues of high peak-to-average power ratio (PAPR) in existing transform domain communication systems and the slow convergence of conventional iterative clipping and filtering algorithms, an improved iterative clipping and filtering algorithm for PAPR suppression of transform domain communication signals is proposed. By introducing clipping noise and filtering it, the algorithm reduces PAPR regrowth while effectively eliminating out-of-band spectral spreading, thereby achieving better PAPR suppression performance throughout the iterative process. Simulation results demonstrate that, on the one hand, the algorithm achieves superior PAPR suppression performance, obtaining approximately 1 dB performance gain with a single iteration compared to the conventional algorithm, and three iterations outperform four iterations of the conventional algorithm; on the other hand, it improves out-of-band spectral performance, reducing out-of-band spectral power by approximately 5 dB after filtering. Comparison results of bit error rate show that the system transmission performance loss incurred by the improved algorithm is very low.

Full Text

Improved Iterative Clipping and Filtering Method for TDCS PAPR Reduction

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Abstract

Transform domain communication systems (TDCS) suffer from high peak-to-average power ratio (PAPR), and traditional iterative clipping and filtering algorithms exhibit slow PAPR convergence. To address these issues, this paper proposes an improved iterative clipping and filtering algorithm for TDCS signal PAPR reduction. The algorithm introduces clipping noise, filters it to reduce PAPR regrowth while effectively eliminating out-of-band spectral spread, thereby achieving superior PAPR suppression during iteration. Simulation results demonstrate that the proposed method offers better PAPR suppression: a single iteration provides approximately 1 dB performance gain over the conventional method, while three iterations outperform four iterations of the traditional approach. Additionally, the algorithm improves out-of-band spectral performance, reducing out-of-band spectral power by about 5 dB after filtering. Bit error rate comparisons reveal that the system transmission performance loss incurred by the improved algorithm is minimal.

Keywords: transform domain communication system; peak-to-average power ratio; improved iterative clipping and filtering

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0 Introduction

Transform domain communication systems (TDCS) represent a cognitive radio architecture that actively avoids interference through spectrum sensing [1-4]. TDCS signals exhibit orthogonality with interference in the frequency domain and noise-like characteristics in the time domain, endowing them with strong anti-jamming and anti-interception capabilities [5]. However, as a multicarrier system, TDCS suffers from high peak-to-average power ratio (PAPR) due to the superposition of multiple carriers at the transmitter [6]. When signal peaks exceed the linear range of power amplifiers, severe in-band amplitude distortion and out-of-band noise occur, degrading system bit error rate performance. Moreover, excessive amplitude peaks cause disproportionate power allocation, resulting in energy waste. Therefore, PAPR suppression is crucial for practical TDCS implementation.

Clipping is a common PAPR reduction technique for multicarrier systems, but it introduces in-band distortion and out-of-band spectral spread [7-10], necessitating filtering to improve spectral performance. However, filtering causes PAPR regrowth, requiring multiple iterations to achieve desired PAPR levels [10-12]. Traditional iterative clipping and filtering algorithms suffer from slow convergence and high computational complexity. This paper proposes an improved iterative clipping and filtering algorithm for TDCS that introduces clipping noise, filters it, and combines signals in the frequency domain to enhance PAPR suppression while controlling out-of-band spectral spread. The following sections elaborate on the fundamental clipping and filtering method, present the improved algorithm' s principles and procedures, provide theoretical analysis, and validate the algorithm through simulations of PAPR suppression and bit error rate performance.

1 TDCS System

A TDCS communication system comprises a transmitter and receiver. [Figure 1: see original paper] illustrates the TDCS transmitter architecture employing cyclic code shift keying (CCSK) modulation. The transmitter samples the electromagnetic spectrum environment using spectrum estimation techniques, identifies interference locations, and generates a spectral estimation result. By comparing this with a predefined interference threshold, the system sets interfered frequency bands to zero and available bands to one, yielding an amplitude spectrum vector. A pseudo-random sequence generated through a cyclic shift register undergoes phase mapping to produce random phases, which are multiplied with the amplitude spectrum vector to obtain the basis function' s frequency-domain representation. After energy adjustment, the basis function is transformed to the time domain via IDFT, and data is modulated onto the time-domain basis function for transmission.

The TDCS receiver structure is shown in [Figure 2: see original paper]. The receiver generates a local basis function through environmental spectrum sensing, takes its conjugate, correlates it with the received signal, and demodulates the transmitted data.

2 TDCS PAPR Analysis

From the TDCS signal expression, the signal comprises multiple subcarriers at different frequencies in the frequency domain. When the number of subcarriers is large, the TDCS signal envelope follows a Rayleigh distribution [13]. The peak-to-average power ratio (PAPR) is commonly used to characterize signal amplitude variations, defined for TDCS signals as [14]:

$$\text{PAPR} = \frac{\max_{n\in[1,N]} |s_i(n)|^2}{E\{|s_i(n)|^2\}}$$

where $s_i(n)$ represents the i-th TDCS modulated signal and N is the number of basis function samples. The PAPR varies with the basis function amplitude and random phase. This paper employs the complementary cumulative distribution function (CCDF) to evaluate PAPR suppression performance, representing the probability that PAPR exceeds a predetermined threshold [15]:

$$\text{CCDF} = \Pr\{\text{PAPR} > \text{PAPR}_0\}$$

where PAPR_0 denotes a constant PAPR value. According to the central limit theorem, the real and imaginary parts of TDCS signals follow Gaussian distributions with zero mean and variance σ^2, and the instantaneous power follows a χ^2 distribution. The CCDF can be expressed as:

$$\Pr\{\text{PAPR} > \text{PAPR}_0\} = 1 - (1 - e^{-\text{PAPR}_0})^N$$

Clipping applies a preset threshold γ to limit signal amplitudes exceeding the threshold while preserving phase information. The clipped TDCS transmitted signal can be expressed as [16]:

$$\tilde{s}_i(n) = \begin{cases} s_i(n), & |s_i(n)| \le \gamma \\ \gamma e^{j\theta_n}, & |s_i(n)| > \gamma \end{cases}$$

where γ is the clipping threshold, $s_i(n)$ is the TDCS transmitted signal, and $|s_i(n)|$ and θ_n represent the amplitude and phase of the transmitted signal, respectively. To enable clipping for different signals, the clipping ratio (CR) is typically used to calculate the threshold:

$$\mathrm{CR} = \frac{\gamma}{\sqrt{E\{|s_i(n)|^2\}}}$$

The theoretical PAPR value of the clipped TDCS signal can be expressed as:

$$\mathrm{PAPR} = 20\log_{10}(\mathrm{CR})\ \mathrm{dB}$$

However, clipping is a nonlinear process that causes in-band distortion and out-of-band spectral spread in the frequency domain, affecting the anti-jamming performance of TDCS basis functions. System performance degrades significantly when the clipping threshold is set too low.

3 Improved Iterative Clipping and Filtering Algorithm

To address out-of-band spectral spread caused by clipping, filtering is employed. Since TDCS operates in the Fourier transform domain, frequency-domain filtering is used. The clipping and filtering procedure for TDCS signals involves:

a) Performing an N-point FFT on the i-th TDCS modulated signal $s_i(n)$ to obtain its frequency-domain representation $S_{k,i}$, followed by zero-insertion:

$$S'_{k,i} = [S_{-N/2,i}, \dots, S_{-1,i}, \underbrace{0, 0, \dots, 0}_{(J-1)N \text{ zeros}}, S_{0,i}, \dots, S_{N/2-1,i}]$$

b) Transforming the zero-inserted signal $S'_{k,i}$ to the time domain via JN-point IFFT:

$$s'_i(n) = \mathrm{IFFT}_{JN}\{S'_{k,i}\}$$

c) Clipping the time-domain signal $s'_i(n)$ to obtain $\tilde{s}'_i(n)$, then transforming it back to the frequency domain via JN-point FFT:

$$S''_{k,i} = \mathrm{FFT}_{JN}\{\tilde{s}'_i(n)\}$$

d) Filtering the frequency-domain signal $S''_{k,i}$ by zeroing out non-data subcarrier positions:

$$\hat{S}_{k,i} = [\,\underbrace{0,\dots,0}_{N/2\text{ zeros}}, S''_{-N/2,i},\dots,S''_{N/2-1,i},\ \underbrace{0,\dots,0}_{(J-1)N\text{ zeros}}\,]$$

e) Removing zeroed data and performing a final N-point IFFT on the filtered frequency-domain signal to obtain the processed TDCS modulated signal.

While filtering suppresses out-of-band spectral spread, it causes PAPR regrowth. Combining clipping and filtering through iteration is necessary to achieve desired PAPR levels while controlling spectral spread. The optimal number of iterations depends on the TDCS modulation scheme and selected CR.

Traditional iterative clipping and filtering algorithms exhibit slow convergence toward the theoretical PAPR value, requiring numerous iterations with multiple FFT and IFFT operations, resulting in high computational complexity [17]. This paper proposes an improved iterative clipping and filtering algorithm that achieves superior suppression with fewer iterations.

Traditional filtering methods directly filter the clipped signal, causing significant PAPR regrowth. The proposed improvement introduces clipping noise $d_i(n) = \tilde{s}'_i(n) - s'_i(n)$ for the i-th TDCS modulated signal and filters this noise instead of the signal directly, reducing PAPR regrowth. The improved algorithm block diagram is shown in [Figure 3: see original paper].

The improved algorithm proceeds as follows:

a) Transform $s_i(n)$ to the frequency domain and perform zero-insertion to obtain $S'_{k,i}$.

b) Transform the zero-inserted frequency-domain signal to the time domain for clipping to obtain $\tilde{s}'_i(n)$, and calculate the clipping noise:

$$d_i(n) = \tilde{s}'_i(n) - s'_i(n)$$

c) Transform the clipping noise $d_i(n)$ to the frequency domain to obtain $D_{k,i}$, filter it by zeroing symbols at non-data subcarrier positions to obtain $\hat{D}_{k,i}$.

d) Synthesize the filtered noise with the original frequency-domain signal:

$$\hat{S}'_{k,i} = S'_{k,i} - \hat{D}_{k,i}$$

e) Transform $\hat{S}'_{k,i}$ to the time domain to obtain the processed TDCS modulated signal.

Steps (a)-(e) are repeated iteratively. The PAPR of the processed signal is checked after each iteration, and the process terminates when the desired value is reached.

Theoretical analysis shows that the PAPR regrowth is inversely proportional to the number of subcarriers and directly proportional to signal power. Traditional clipping and filtering clips the zero-inserted signal, then zeros and removes data at the inserted positions, effectively reducing the subcarrier number N and causing increased PAPR regrowth. The proposed algorithm filters the relatively low-power clipping noise $d_i(n)$, reducing power loss under the same subcarrier reduction condition and achieving better PAPR suppression.

4 Simulation Analysis

Simulations were conducted to validate the improved algorithm' s effectiveness in PAPR suppression, filtering performance, and system bit error rate. The experimental parameters included: sampling rate $f_s = 512$ MHz, $N = 512$ subcarriers, CCSK modulation, 10% narrowband interference in the electromagnetic spectrum environment, Burg method for power spectrum estimation with interference-to-signal ratio of 4 dB, AWGN transmission channel, and clipping ratio CR = 1.6. The probability distribution of PAPR was statistically analyzed for 1000 TDCS modulated signals.

[Figure 5: see original paper] compares the PAPR suppression performance between the improved and traditional iterative clipping and filtering algorithms. With CR = 1.6, the theoretical PAPR value is approximately 4 dB. The results show that after the first iteration, the improved algorithm controls PAPR around 6 dB at CCDF = 0.01, providing about 1 dB improvement over the traditional method. After three iterations, the improved algorithm achieves better suppression than four iterations of the traditional method, demonstrating faster convergence toward the 4 dB theoretical value.

The effectiveness of filtering for out-of-band spectral suppression is verified in [Figure 6: see original paper]. Subfigure (a) shows the power spectrum of an unprocessed TDCS modulated signal under 10% narrowband interference. Subfigure (b) reveals spectral spread into non-transmission bands after clipping, which degrades TDCS system performance. Subfigure (c) demonstrates that filtering the clipping noise reduces out-of-band radiation power by approximately 5 dB at 180 MHz compared to clipping without filtering.

Bit error rate performance was evaluated using 10,000 symbols, as shown in [Figure 7: see original paper]. The improved algorithm exhibits similar BER to the traditional method at $E_b/N_0 < 8$ dB, with a slight increase at $E_b/N_0 > 8$ dB. Since the improved algorithm enhances PAPR suppression, it introduces slightly more clipping noise, causing marginal BER degradation. However, the performance loss remains very low, confirming the algorithm' s suitability for TDCS systems.

5 Conclusion

This paper addresses the high PAPR of TDCS signals, PAPR regrowth from clipping and filtering, and the high computational complexity and poor suppression performance of traditional methods by proposing an improved iterative clipping and filtering scheme. Simulation results demonstrate that the proposed scheme enhances PAPR suppression while effectively reducing out-of-band spectral spread, achieving superior performance with fewer iterations. The algorithm holds practical significance for improving TDCS system transmission performance.

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Note: Figure translations are in progress. See original paper for figures.