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A PAPR Joint Optimization Algorithm in AF Cooperative Multicarrier System

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Abstract

In this paper, to reduce PAPR (Peak-to-Average Power Ratio) in AF (Amplify and Forward) cooperative multicarrier system, an SLM-TR (Selective Mapping-Tone Reservation) joint optimization algorithm based on CAZAC (Constant Amplitude Zero Auto-Correlation) sequence is proposed. In our proposed method, several carriers are reserved for tone candidates, and then SLM (Selective Mapping) algorithm is utilized for the remaining data carriers. In SLM procedure, CAZAC sequences are utilized as the initial phase vector candidates and phase vector optimization is further processed by using feedback phase rotation algorithm for data carriers. After that, in continued TR (Tone Reservation) operation, random sequence is considered as the initial tone sequence and further optimized and subtracted from the modified data signal for peak cancelling using cyclic transposition searching algorithm to further reduce PAPR. Finally, the signal with the lowest PAPR is transmitted. By doing so, not only exhausting searching for optimal phase vectors is avoided efficiently, but also additional PAPR reduction is achieved by tone sequence modification. Simulation results show that the proposed method can reduce PAPR considerably and improve BER (Bit Error Rate) performance effectively, with insurance of high spectrum efficiency, low complexity and low loss in power efficiency. The influences of several conditions such as HPA (High power Amplifier) type, initial phase vector number, tone carrier number and sequence type are discussed to improve system QoS(Quality of Service).

***Keywords**: PAPR, SLM, TR, CAZAC Sequence*

1. Introduction

Cooperative diversity is a new technique for wireless communication which has gained wide attention. Cooperative communication exploits spatial cooperative diversity gain, and simultaneously provides reliability to the previous communication system without additional antenna.

OFDM (Orthogonal frequency division multiplexing) is one of the promising techniques for high data rate transmission for future wireless communication as in [1]. It shows high speed transmission rate, good spectrum efficiency, and robustness to frequency selective fading and narrowband interference. So, OFDM has been adopted as the standard for Europe DAB/DVB (Digital Audio and Video Broadcasting) system, the high-rate WLAN (Wireless Local Area Networks) such as IEEE802.11x, HIPERLAN II, MMAC(Multimedia Mobile Access Communications), terrestrial DMB(Digital

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Multimedia Broadcasting) system, WiMAX (World interoperability for Microwave access), and 4G system. [1]

However, there are some drawbacks due to the inherent multicarrier nature of OFDM, one of which is the high PAPR (Peak-to-Average Power Ratio). When high PAPR signal which is caused by the summation of multicarrier signals with same phase exceeds the linear operation region of nonlinear HPA(High Power Amplifier), some portions of the transmitted signal will be clipped which results in considerable signal distortion. Signal distortion further induces unwanted out-of-band radiation and decreases system performance.

Currently, there are several PAPR reduction methods, such as, signal pre-distortion technique, coding technique and non-distortion scrambling technique as in [2]. Signal pre-distortion technique is simple and has small system complexity, but can cause signal distortion and out-band regrowth. Where, clipping and filtering can be considered as the procedure of adding one extra signal to the original signal as in [3].

Coding technique can achieve significant PAPR reduction performance accompanying with a little data rate loss. It doesn't bring interference to the original signal, but induces low coding rate and spectrum efficiency loss, so it is not appropriate to the systems with large subcarriers. Golay complementary code and Reed-Muller code are considered to reduce PAPR as in [4].

The main idea of non-distortion scrambling method is to reduce the occurrence of high PAPR signal in which PAPR exceeds a predefined threshold. Scrambling method involves PTS (Partial Transmit Sequence), TR (Tone Reservation), and SLM (Selective Mapping) method as in [5-7]. A new low complexity PTS method was introduced as in [5], where, 2^n-point IFFT (Inverse Fast Fourier Transform) was divided into two parts. Multi-stage TR scheme for PAPR reduction was introduced as in [6], where, several PRTs (Peak Reduction Tone) were adaptively selected according to the PAPR of OFDM signal. A low complexity SLM method was introduced as in [7], where only two IFFT operations were required. Scrambling method can significantly reduce PAPR in the multi-carrier system without any signal distortion. However, one shortcoming is that, in the scrambling method, additional side information should be transmitted to the receiver for signal recovery, so it may result in transmission efficiency loss, high implementation complexity, and further error rate diffusion.

Until now, a few studies have been made about PAPR problem in the cooperative communication scenario. In this paper, a new SLM-TR (Selective Mapping-Tone Reservation) joint optimization algorithm based on CAZAC (Constant Amplitude Zero Auto-Correlation) sequence is proposed in the cooperative communication system. Simulation results show that, by applying proposed method, PAPR can be reduced significantly, further insuring the high spectrum efficiency and relatively low complexity.

2. System Description

2.1. Cooperative Diversity

Cooperative communication can avoid the limitation of one antenna mobile terminal which cannot realize space diversity. It exploits spatial cooperative diversity gain, increase system capacity, increase communication coverage, and provide reliability to the previous communication system without additional antenna as in [8].

Usually, half-duplex transmission mode is considered in the communication process which is divided into two phases, where data can be transmitted and received through different time slot or frequency slot, but cannot be transmitted and received simultaneously in one phase.

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Suppose this is the TDD (Time Division Duplex) mode cooperative system, the two phases are divided in time domain. in the first phase, S(Source) transmits information data to R(Relay) and D(Destination) through broadcast mode; if there is S-D direct link, R and D can receives data, if not, only R receives data. In the second phase, R forwards the data to the D according to certain protocols. Finally, at the D, the received signals from S and R are combined together to make correct decision.

In the LTE-Advanced system, S means eNode B, R means RN, D means UE. Figure. 1 and Figure. 2 describe the system model and time slot structure which is applied in this paper.

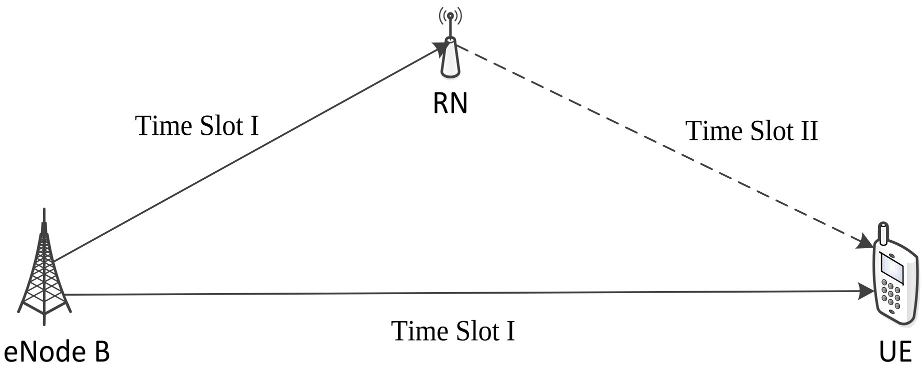

Figure 1. Cooperative System Model

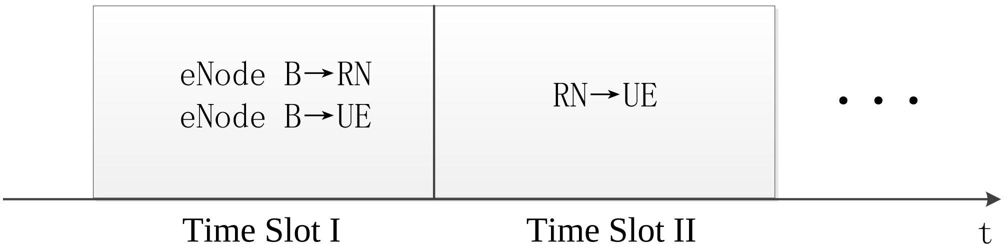

Figure 2. Time Slot Structure Diagram

Suppose using AF (Amplify and Forward) mode, R only amplifies information data from S and then forwards it to D, while S does not transmit. During this process, noise and interference received by R are also amplified and transmitted to the D. So, two different fading signals from S and R are received by D, then, combined using SIC (Soft Information Combination) or MRC (Maximal Ratio Combining) criterion for correct decision.

2.2. OFDM (Orthogonal Frequency Division Multiplexing)

The process of a typical OFDM system is as follows. The incoming serial data is first converted from serial to parallel and grouped into X bits each to form a complex number. The complex numbers are modulated by the IFFT in a baseband mode, and converted back to serial data for transmission. A guard interval is inserted between symbols to avoid ISI (Inter Symbol Interference) caused by multipath distortion. The discrete symbols are converted to analog for RF (Radio Frequency) up-conversion. The receiver performs the inverse process of the transmitter as in [9].

Suppose $X=\left[X_0, X_1,\ldots, X_{N-1}\right]^T$ denotes input data after serial to parallel converter (S/P), the complex base-band OFDM signal in time domain is given by

$$x(t) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k \exp(j2\pi k \Delta f t), \quad 0 < t < NT \tag{1}$$

where j= $\sqrt{-1}$, N is the total number of sub-carriers, T is the data period, NT is OFDM symbol duration and $\Delta f = \frac{1}{NT}$ is the sub-carrier spacing, X_k is the data modulated on k-th subcarrier. An OFDM symbol is actually extended by the cyclic prefix in order to cope with multi-path delay spread in the wireless communication environment.

2.3. PAPR (Peak-to-Average Power Ratio)

In order to evaluate the variation of envelope of OFDM signal, PAPR is defined as the ratio of peak power to average power of OFDM signal. The PAPR can be expressed as follows [1, 9]:

$$PAPR \equiv \max_{0 \le t < T} \frac{|x(t)|^2}{E\left[|x(t)|^2\right]_{av}} \tag{2}$$

where, $E[\bullet]$ means the expectation operation.

A multicarrier signal is the sum of many independent signals modulated onto each sub-channel. When the phases of each sub-carrier sample are the same, the peak power of the signal is N times of the average power, so the maximum PAPR of the OFDM baseband signal can be $10\lg N$. It is necessary to evaluate the statistical property of PAPR.

According to central limit theory, when carrier number N is sufficiently large, real part and imaginary part of OFDM signal $x(t)$ will respectively be Gaussian distributed with mean 0 and variance 0.5. According to statistical theory, the amplitude r of OFDM signals abbeys Rayleigh distribution, PDF (probability density function) of amplitude can be expressed as $p_r(t) = 2re^{-r^2}$. PDF of power satisfies central Gamma distribution with two freedoms, mean 0 and variation 1, which can be expressed as $p_{power}(y) = e^{-y}$.

So, the CDF (cumulative density function) can be expressed as:

$$F_{Pow}(z) = \mathrm{P}\{Power \le z\} = \int_0^z e^{-y} dy = 1 - e^{-z} \tag{3}$$

In OFDM duration, suppose samples are uncorrelated each other, probability of PAPR bellows a certain level z is:

$$F_{Pow}^N(z) = \mathrm{P}^N\{Power \le z\} = (1 - e^{-z})^N \tag{4}$$

Normally, we consider the probability of PAPR exceeding a certain level z. This probability is called as CCDF (complementary cumulative density function),

$$\begin{aligned} \mathrm{P\{PAPR>Z\}=P}^N &\{Power > z\} \\ &= 1 - \mathrm{P}^N\{Power \le z\} = 1 - (1 - e^{-z})^N \end{aligned} \tag{5}$$

It is difficult to find the accurate PAPR because the true peak of continuous-time OFDM signal may be missed in the Nyquist sampling. So, here, 4 times over-sampling is considered for PAPR computation.

2.4. CAZAC (Constant Amplitude Zero Auto-Correlation) Sequence

In SLM procedure, in order to shorten searching time of optimal phase vector with suboptimal PAPR, CAZAC sequences are utilized as the initial phase vector candidates instead of randomly generated phase vectors.

CAZAC sequence, which is a constant envelope zero autocorrelation sequence, mainly includes ZC (Zadoff-Chu) sequence, Frank sequence, Golomb polyphone sequence and GCL (Generalized Chrip-Like) sequence.

ZC sequence is selected as the initial phase vector candidate. It is mathematically expressed as [10]:

$$p_k{}^M = \exp\left[j2\pi \frac{M}{N}\left(\frac{k(k+1)}{2} + qk \right)\right] \tag{6}$$

where $k = 0,1,...,N-1$, k is odd, and

$$p_k{}^M = \exp\left[j2\pi \frac{M}{N}\left(\frac{k^2}{2} + qk \right)\right] \tag{7}$$

where $k = 0,1,...,N-1$, k is even.

N is the length of ZC sequence, *M* is arbitrary integer and prime with *N*, *q* is also an arbitrary integer. Different ZC sequences may be produced when *M* changes.

ZC sequence possesses following features.

1) ZC sequence has constant amplitude. That is, ZC sequence is a kind of CAZAC sequence, which still keeps constant amplitude after DFT processing. Constant amplitude character can restrict PAPR and limit interference to other users.

2) ZC sequence possesses periodic auto-correlation characteristic. That is, ZC sequences with different length have an ideal cycling auto-correlation.

3) Cross-correlation characteristic of ZC sequence is very excellent and cross-correlation and partial correlation values are close to zero.

3. Conventional SLM Method and TR Method

3.1. Conventional SLM (Selected Mapping) Method

In the conventional SLM approach, suppose transmission data is $X = [X_0, X_1, ..., X_{N-1}]$, U different phase rotation sequences of length N are $P^u = [P_0^u, P_1^u, ..., P_{N-1}^u]$, where $P_n^u = e^{j\varphi(u,n)}$, $u \in [1,U]$, $n \in [0, N-1]$, $\varphi(u,n) = [0, 2\pi)$, N is the number of sub-carriers. First, original data symbol $X = [X_0, X_1, ..., X_{N-1}]$ is multiplied by above individual phase rotation sequence $P^u = [P_0^u, P_1^u, ..., P_{N-1}^u]$. Each candidate signal is achieved through IFFT. Then one modified OFDM signal with lowest PAPR is selected for transmission from a set of sufficiently different candidate signals. To detect the OFDM signal at receiver side, appropriate side information indicating how transmitter generates transmission signal is embedded and transmitted together after encoded by error control code.

3.2. Conventional TR (Tone Reservation) Method

The main idea of TR method is as follows. At transmitter side, several subcarriers are reserved to generate peak-canceling tone signals. Generated tone signal is added to the original information signal, which means, one irrelevant signal is added to the original parallel information signal in order to suppress peak power. The independent time-domain tone signal should be easy to calculate, add and remove.

The main problem of TR method is to find the optimum time-domain tone signal.

Assume the data symbol set is $\boldsymbol{X}$, the peak-canceling tone set is $\boldsymbol{C}$, $\boldsymbol{C} = [C_0, C_1, ..., C_{N-1}]^T$, and newly generated time-domain peak-reduced signal is expressed as:

$$\begin{aligned}\bar{x}(n) &= x(n)+c(n)=IDFT\{X_k+C_k\}\\ &=\frac{1}{\sqrt{N}}\sum_{k=0}^{N-1}(X_k+C_k)e^{j2\pi kn/N}\end{aligned} \tag{8}$$

In TR method, the reserved tone subcarriers are used for PAR reduction and the other remained subcarriers are used for data transmission. So, $\boldsymbol{X}$ and $\boldsymbol{C}$ are not allowed to be nonzero on the same subcarriers as shown in the following equation.

$$X_k+C_k=\begin{cases}X_k, k\in u^c\\ C_k, k\in u\end{cases} \tag{9}$$

where u^c denotes the subcarrier set of information data, u denotes tone subcarrier set for peak-canceling tone signal. Since subcarriers are orthogonal to each other, the added tone signal causes no interference to the data signal.

The goal of the TR method is to find the optimal value of $\boldsymbol{C}^*$, such that PAPR of the transmitted time-domain signal is minimized. So, $\boldsymbol{C}$ must be chosen to minimize the maximum of the time-domain signal, *i.e.*

$$\boldsymbol{C}^* = \arg\min_{c}\max_{0\le n\le N}\left|\frac{1}{\sqrt{N}}\sum_{k=0}^{N-1}(X_k+C_k)e^{j2\pi kn/N}\right|^2 \tag{10}$$

This problem can also be reformulated as a quadratically constrained quadratic program (QCQP) [6, 11] as follows:

$$\min_{c} E \text{ s.t.}: \left|x_n+q_n\boldsymbol{C}\right|^2\le E \text{ for all } n=0,1,\cdots,N-1 \tag{11}$$

Where q_n is the n-th row of an IFFT matrix.

Usually, high computational cost is needed for the optimal solution of QCQP problem, so sub-optimal solutions can be employed to reduce complexity.

4. A New SLM-TR Joint Optimization Algorithm Based on CAZAC Sequence

In this paper, to reduce PAPR in AF cooperative multicarrier system, a SLM-TR joint optimization algorithm based on CAZAC sequence is proposed.
The main idea is as follows:

1) Several carriers are reserved for tone candidates like TR algorithm.

2) SLM algorithm is utilized for the remained data carriers.

3) To decrease phase vector searching complexity of SLM procedure, CAZAC sequences are utilized as the initial phase vector candidates.

4) Phase vector optimization is further processed by using feedback phase rotation algorithm for data carriers. To reduce searching time and remain excellent PAPR reduction performance, fixed phase rotation method is applied for the phase optimization. In the searching process, phase of CAZAC sequence is sequentially rotated bit by bit to find minimum PAPR value, where, three fixed phase rotation values such as $(\exp(j\pi/2), \exp(j\pi), \exp(j(3\pi/2)))$, are considered.

5) In TR procedure, tone sequence is optimized and added using cyclic transposition searching algorithm to further reduce PAPR. By doing so, the exhausting search for optimal tone signal is avoided efficiently. Besides, because only small numbers of subcarriers are reserved for tone signal, the power of tone signal is relatively low compared with information signal, the short-term average power of one OFDM frame varies slowly; it reduces loss in power efficiency compared with conventional TR method.
The algorithm of the proposed BSLM-TR joint optimization algorithm can be summarized as follows:

Step1: N_{TR} tone carriers and $N-N_{TR}$ data carriers are divided first. Tone carriers are reserved for tone candidates, data carriers are prepared for data transmission. n_{cazac} CAZAC sequences with length $N-N_{TR}$ are generated and stored in the memory, ready for use as the initial phase vector candidates of SLM procedure;

Step2: Select one CAZAC sequence as the initial phase vector candidate, multiply (point-wise multiplication) the data sequence with the first phase vector $P^{(0)}$ (selected CAZAC sequence), perform IFFT and then compute PAPR. Set this PAPR to $\text{PAPR}_{\min}$;

Step3: Multiply the first element of phase vector ($P_n^{(0)}$, n=0), with three phase rotation factors $\left(\exp(j\pi/2), \exp(j\pi), \exp(j(3\pi/2))\right)$, multiply the data sequence with these modified phase rotation factors respectively, perform IFFT and compute PAPR, name them as PAPR2, PAPR3, PAPR4;

Step4: Compare $\text{PAPR}_{\min}$ with PAPR2, PAPR3, and PAPR4 computed in step3. If $\text{PAPR}_{\min}$ is still the smallest, store the $\text{PAPR}_{\min}$ and corresponding phase vector, If PAPR2 is the smallest, let $\text{PAPR}_{\min}$=PAPR2, and store corresponding $\text{PAPR}_{\min}$ and phase vector, If PAPR3 is the smallest, let $\text{PAPR}_{\min}$=PAPR3, and store corresponding $\text{PAPR}_{\min}$ and phase vector, If PAPR4 is the smallest, let $\text{PAPR}_{\min}$=PAPR4, and store corresponding $\text{PAPR}_{\min}$ and phase vector;

Step5: Repeat the same procedure from step3 to step4 for the remaining elements of the first phase vector $P^{(0)}$;

Step6: Change the phase vector to $P^{(1)}$ and compute PAPR, compare $\text{PAPR}_{\min}$ with the PAPR in step6, if PAPR>$\text{PAPR}_{\min}$, then maintain $\text{PAPR}_{\min}$; If PAPR<$\text{PAPR}_{\min}$, update $\text{PAPR}_{\min}$ as the PAPR computed in step6;

Step7: Repeat the procedure from step3 to step5 for the phase vector $P^{(1)}$;

Step8: Change the phase vector from $P^{(2)}$ to $P^{(D-1)}$ one by one, repeat step6, and then continually repeat the procedure from step3 to step5. Finally, select the modified time domain data signal with final minimum PAPR, and select final achieved phase vector $P_{selceted}$ as side information. The modified time domain data signal is considered as the initial transmission signal;

Step9: In TR procedure, randomly generate tone sequence of length N satisfying following formula, $P(m)=\begin{cases}1, & 0\le m\le N_{TR}-1\\ 0, & N_{TR}\le m\le N-1\end{cases}$, and achieve corresponding time domain tone signal through IFFT;

Step10: Find max value $x_{\max}$ and its position $m_{\max}$ of initial transmission signal, find corresponding phase and amplitude information, name it as amplitude and phase factor α , $\alpha = x_{\max}\cdot\exp(j\cdot phase(x_{\max}))$;

Step11: Time domain tone signal is optimized using cyclic transposition algorithm, that is, the max value position of time domain tone signal is cyclic trans posited to the position $m_{\max}$, then multiplied with corresponding amplitude and phase factor α computed in step10, generated signal is named as modified time domain peak-cancelling tone signal;

Step12: The above modified time domain peak-cancelling tone signal in step11 is subtracted from the initial transmission signal, residual signal is considered as the modified initial transmission signal;

Step13: Repeat the procedure k_{loop} (small value of k_{loop} is considered to reduce complexity) times from step9 to step12, update initial transmission signal, compute PAPR, finally achieve optimized transmission signal with lowest PAPR, transmit final optimized transmission signal, and simultaneously transmit phase vector $P_{selceted}$ for side information.

5. Performance Results

In this paper, in order to evaluate the performance of the proposed SLM-TR joint optimization algorithm, CCDF of PAPR and BER (bit error rate) are discussed in AF cooperative communication system.

Simulation parameters are as following Table 1.

Table 1. Simulation Parameters

Parameter	Value	Parameter	Value
Carrier number	128	HPA back off (dB)	4
Modulation format	QPSK	Tone carrier number	4, 8
OFDM symbol rate （symbol/s）	250	CAZAC sequence number	2, 4, 8
oversampling	4	HPA	SSPA, TWTA
Cooperative mode	AF	k_{loop}	10

Figure. 3 and Figure. 4 show the PAPR and BER performances when different algorithms are applied. Where, the number of CAZAC sequences used for initial phase vectors is 4, the number of reserved tone carriers is 8, and SSPA with 0dB backoff is used. As shown in the figures, our proposed method has considerable performance improvement compared with conventional SLM method, conventional TR method and original system without any PAPR reduction method.

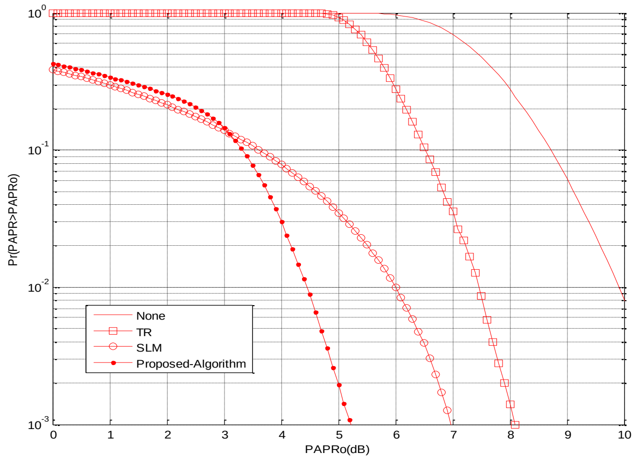

Figure 3. CCDFs of PAPR of Different Algorithms

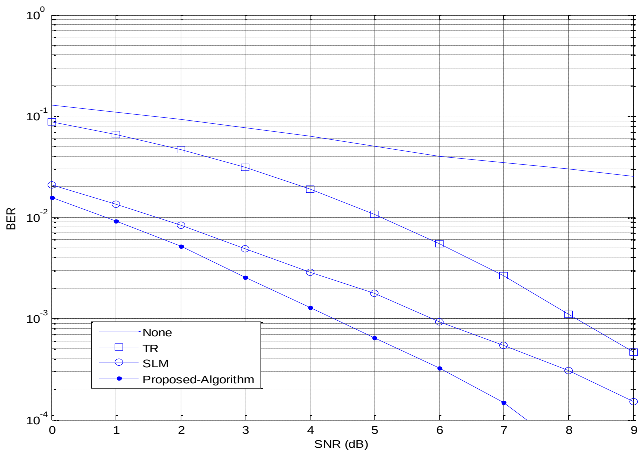

Figure 4. BER Performances of Different Algorithms

Figure. 5 shows the BER performance comparison when S and R utilizes different types of HPA. Where, HPA backoff is all supposed to be 0dB, the number of initial phase vectors is 4, and the number of reserved tone carriers is 8. As shown in the figure, best BER performance can be achieved when SSPA is used for both S and R.

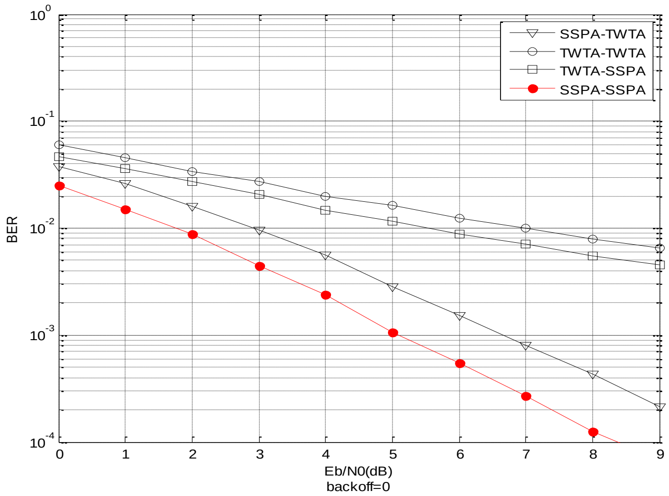

Figure 5. BER Performances of Different HPAs

Figure. 6 and Figure. 7 show the CCDFs of PAPR and BER performances when different numbers of initial phase vector are supposed. Where, SSPA with 0dB backoff is used and the number of reserved tone carriers is 8. As shown in the figure below, CCDF and BER performances can be improved when more initial phase vectors are used.

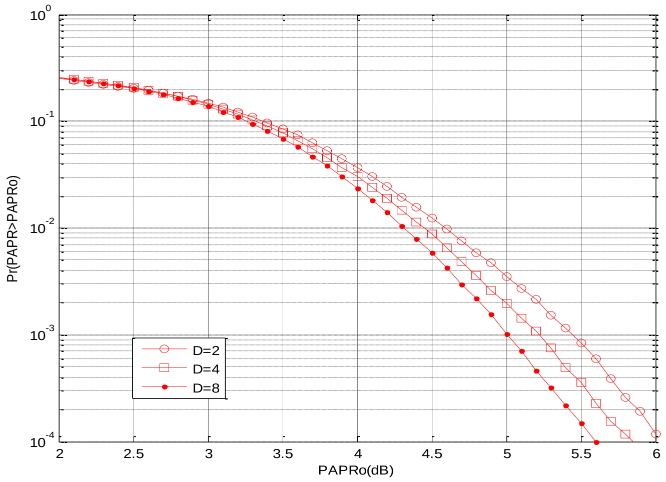

Figure 6. CCDFs of PAPR Using Different Numbers of CAZAC Sequence

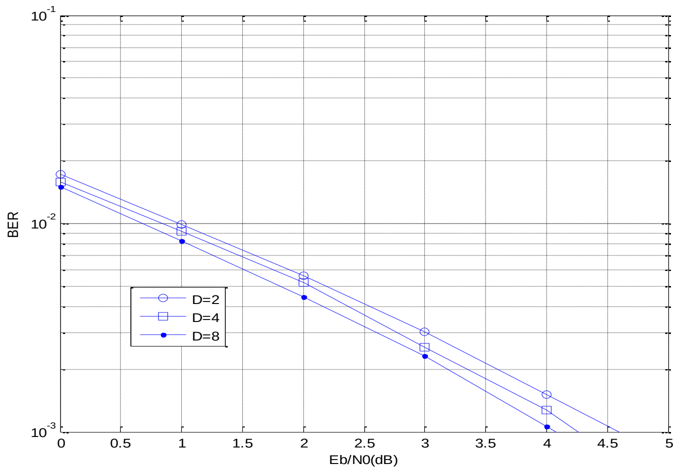

Figure 7. BER Performances Using Different Numbers of CAZAC Sequence

Figure. 8 and Figure. 9 shows CCDFs of PAPR and BER performances when different numbers of tone carrier are considered, where, 4 initial phase vectors are used and SSPAs with 0dB backoff are used for both S and R. As shown in the figures below, the more tone carriers are reserved, the better PAPR and BER performances can be achieved.

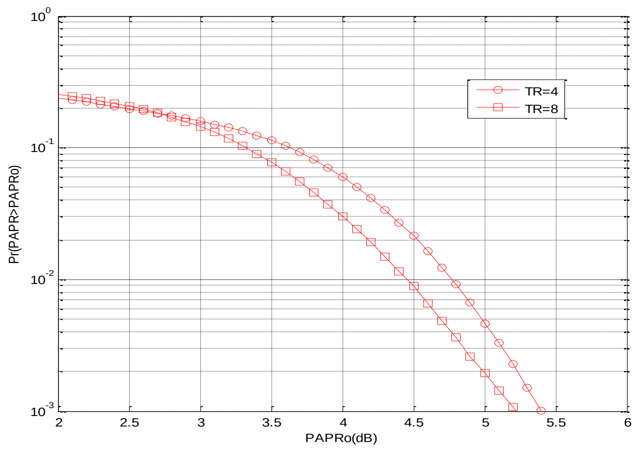

Figure 8. CCDFs of PAPR with Different Numbers of Tone

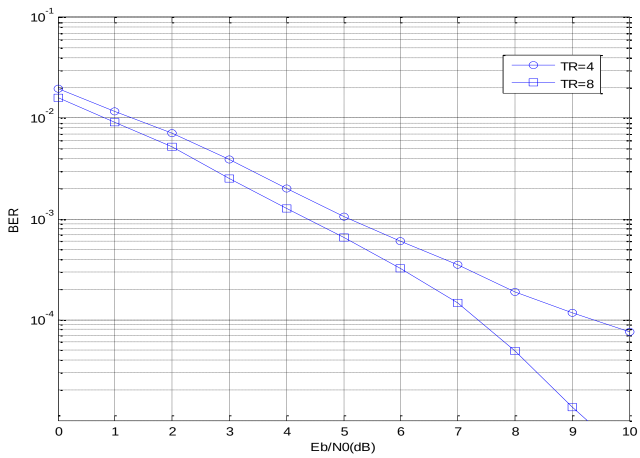

Figure 9. BER Performances with Different Numbers of Tone

Figure. 10 and Figure. 11 shows CCDFs of PAPR and BER performances when different types of sequence are used as initial phase vector. Where, number of initial sequences is 4, and SSPAs with 0dB backoff are used for S and R. Besides, Gold sequence, Walsh sequence, random sequence and CAZAC sequence are considered for performance comparison, where random sequence is randomly generated by computer. As shown in the figure, best PAPR and BER performance can be achieved when CAZAC sequence is used for initial phase vector.

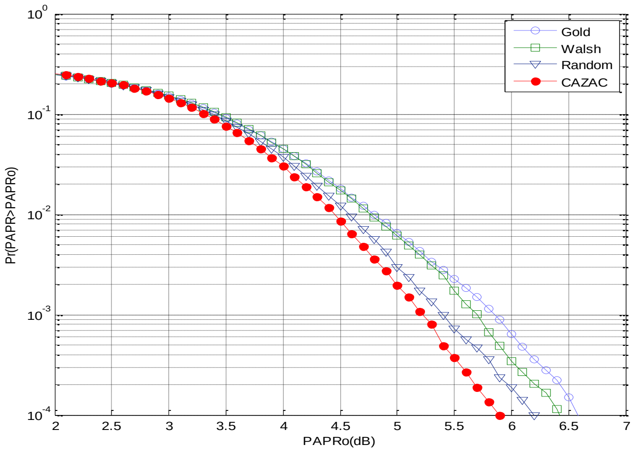

Figure 10. CCDFs of PAPR with Different Codes

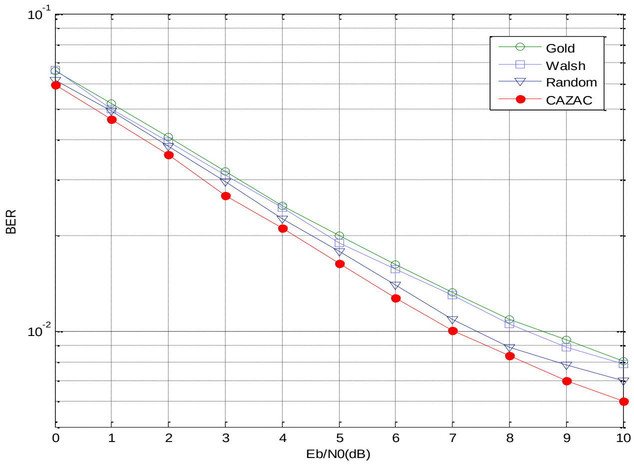

Figure 11. BER Performances with Different Codes

6. Conclusions

In this paper, a new SLM-TR joint optimization algorithm based on CAZAC sequence is proposed to reduce PAPR in AF cooperative multicarrier system.

In our proposed method, several carriers are reserved for tone candidates at first, and then SLM algorithm is utilized for the remained data carriers. In SLM procedure, CAZAC sequences are utilized as the initial phase vector candidates and phase vector optimization is further processed by using feedback phase rotation algorithm for data carriers. After that, in TR procedure, random sequence is considered as the initial tone sequence and further optimized and subtracted from the updated data signal for peak cancelling using cyclic transposition searching algorithm to further reduce PAPR. Finally, the signal with lowest PAPR is transmitted.

By doing so, not only exhausting search of optimal phase vectors is avoided efficiently, but also additional PAPR reduction is achieved by tone sequence modification.

Simulation results show that the proposed method can reduce PAPR considerably and improve BER performance effectively, with insurance of high spectrum efficiency, low complexity and low loss in power efficiency. Further discussion proves that, with the increase of initial phase vector number and tone carrier number, PAPR and BER performances can be improved, but it is not appropriate to increase number too much for the reason of system complexity and spectrum efficiency, about 2 or 4 is enough. Additionally, further studies must be continued to find optimum sequences as CAZAC sequence to improve system QoS.

Therefore, the proposed method could be used for the cooperative multicarrier system which requires low PAPR and low complexity, such as future mobile communication system.

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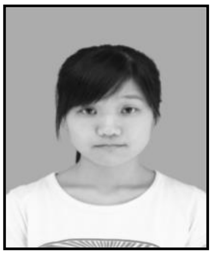

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