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Complexity-Reduced Adaptive PAPR Reduction Method Using Null Space in MIMO Channel for MIMO-OFDM Signals*

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SUMMARY This paper proposes a computational complexity-reduced algorithm for an adaptive peak-to-average power ratio (PAPR) reduction method previously developed by members of our research group that uses the null space in a multiple-input multiple-output (MIMO) channel for MIMO-orthogonal frequency division multiplexing (OFDM) signals. The proposed algorithm is an extension of the peak cancellation (PC) signal-based method that has been mainly investigated for per-antenna PAPR reduction. This method adds the PC signal, which is designed so that the out-of-band radiation is removed/reduced, directly to the time-domain transmission signal at each antenna. The proposed method, referred to as PC-CNC (PC with channel-null constraint), performs vector-level signal processing in the PC signal generation so that the PC signal is transmitted only to the null space in the MIMO channel. We investigate three methods to control the beamforming (BF) vector in the PC signal, which is a key factor in determining the achievable PAPR performance of the algorithm. Computer simulation results show that the proposed PCCNC achieves approximately the same throughput-vs.-PAPR performance as the previous method while dramatically reducing the required computational cost.

key words: OFDM, PAPR, MIMO, beamforming, clipping and filtering, peak cancellation, computational complexity reduction

1. Introduction

Massive multiple-input multiple-output (MIMO) or large-scale MIMO [1], [2], in which a base station transmitter employs a very large number of antennas, along with beamforming (BF) is considered to be a promising basic technique for future radio access such as 5G. Orthogonal frequency division multiplexing (OFDM) is known to be robust against multipath interference due to its low symbol rate and the use of a cyclic prefix. Therefore, the combination of massive MIMO using BF and OFDM signals offers broadband high-speed data transmission with wide coverage through high power gain. In massive MIMO, the high peak-to-average power ratio (PAPR) of the OFDM signals may be further enhanced due to the variation in the transmission power levels among the transmitter antennas caused by the

BF process. The PAPR reduction is considered an important issue facing massive MIMO-OFDM transmission with BF.

A number of PAPR reduction techniques have been proposed [3]. The clipping and filtering (CF) method [4]–[6] limits the peak envelope of the input signal in the time domain to a predetermined value by clipping operation. However, the distortion caused by the amplitude clipping is viewed as another source of noise. The CF method does not reduce the frequency efficiency, but causes in-band interference due to the PAPR reduction signal. There are several modified CF methods, e.g., active constellation extension (ACE) in [7], that restrict the allowable PAPR reduction signal so that the degradation in the error rate at the receiver is reduced. Meanwhile, the tone reservation (TR) method [8] separates the total number of subcarriers into two parts: the subcarriers for data transmission and those for PAPR reduction signal transmission. The TR method does not interfere with the data symbols, but reduces the frequency efficiency since a part of the transmission bandwidth cannot be used for data transmission. Among these techniques, the CF-based method is very powerful from the viewpoint of the tradeoff between the PAPR reduction and error rate [9].

The PAPR reduction problems in MIMO-OFDM signaling have also been discussed extensively in literature. References [10] and [11] assume the case of no BF. Reference [12] assumes eigenmode MIMO-based BF and applies the selected mapping (SLM) [13] and partial transmit sequence (PTS) [14] method. The use of SLM or PTS degrades the achievable error rate or throughput of the MIMO-OFDM signal due to a reduced channel coding gain. In a massive MIMO downlink scenario, the number of base station transmitter antennas is in general much larger than that of user terminal receiver antennas. Under this assumption, joint optimization of BF, OFDM modulation, and PAPR reduction is investigated in [15]. Reference [16] proposes a PAPR reduction method in which some of the transmitter antennas are exclusively used for PAPR reduction in order to remove the in-band interference due to the PAPR reduction signal on the receiver side. However, the method in [16] reduces the BF gain of the data streams since the number of transmitter antennas used for the transmission of data streams is reduced.

Members of our research group reported on an adaptive PAPR reduction method using the null space in a channel for MIMO-OFDM signals [17]–[19]. This method restricts the peak reduction signal transmitted to only the null space in

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the given MIMO channel to suppress the degradation in the transmission quality of the data streams due to the interference from the in-band peak reduction signal. Since all the transmitter antennas are fully utilized for the transmission of the data streams, the achievable BF gain of the reported method is higher than the method in [16]. It is expected that the effect of the adaptive PAPR reduction method using the null space in the MIMO channel will increase in a massive MIMO scenario, since the dimensions of the null space increase. Members of our research group also investigated the performance of this method in a massive MIMO transmission scenario [20], [21]. We note that [22] investigates the unused beam reservation-based PAPR reduction method, which is similar to the use of null space in a MIMO channel as originally reported in [17]–[19].

In our previous investigations in [17]–[19], the adaptive PAPR reduction method using the null space in a MIMO channel is actualized by using an iterative algorithm. CF and the projection of the peak reduction signal generated by CF onto the null space in a MIMO channel are applied at each iteration. However, since the fast Fourier transform (FFT) and inverse fast Fourier transform (IFFT) operations are required at each iteration and peak regrowth occurs due to the filtering of out-of-band radiation and the channel null constraint in the peak reduction signal, the required computational complexity of this iterative algorithm is relatively high. Therefore, this paper investigates a computationally efficient algorithm for the adaptive PAPR reduction method using the null space in the MIMO channel. More specifically, we propose a complexity-reduced algorithm by extending the idea of the peak cancellation (PC) signal method proposed in [23] and [24]. The PC signal-based method achieves approximately the same PAPR reduction performance while reducing the required computational cost compared to that for CF. The point of the PC signal-based method is to define the PC signal that satisfies the requirement for out-of-band radiation. This paper focuses on baseband signaling, and specifies that the requirements for the out-of-band radiation are zero for the sake of simplicity. Furthermore, by directly adding the PC signal to the time-domain transmission signal at the transmitter antenna, the PAPR reduction equivalent to the CF method is achieved. In [23] and [24], the PAPR reduction using the PC signal is performed independently at each transmitter antenna. In this case, the data streams suffer from interference from the in-band PC signal.

The proposed algorithm performs PC signal-based PAPR reduction jointly considering all the transmission signals for all antennas. Thus, the PC signal is constructed in vector form. By setting the BF vector of the PC signal orthogonal to the MIMO channel, i.e., the BF vector is restricted within the null space in the MIMO channel, the interference to the data streams can be eliminated on the receiver side. The construction method for the BF vector in the PC signal is a key factor in determining the achievable PAPR performance of the proposed algorithm. Therefore, we investigate three methods to control the BF vector in

the PC signal and compare them based on computer simulations. We show that the proposed algorithm achieves computationally efficient PAPR reduction using the null space in the MIMO channel and that the achievable throughput-vs.-PAPR performance is quite comparable to the CF-based iterative algorithm assumed in [17]–[19]. We note that our initial investigations on the PC signal-based algorithm for the adaptive PAPR reduction method using the null space in the MIMO channel are presented in [25] and [26]. This paper is a compilation of [25] and [26], with enhanced evaluation and discussions.

The remainder of the paper is organized as follows. First, Sect. 2 briefly describes the principle of the adaptive PAPR reduction method using the null space in the MIMO channel and conventional CF-based implementation. Section 3 describes the conventional PC signal-based PAPR reduction method. Section 4 describes the proposed method including three methods to control the BF vector in the PC signal. Section 5 presents numerical results based on computer simulations. Finally, Sect. 6 concludes the paper.

2. Principle of Adaptive PAPR Reduction Method Using Null Space in MIMO Channel and Conventional Implementation Algorithm

2.1 Principle of Adaptive PAPR Reduction Method

Here, we briefly explain the principle behind the adaptive PAPR reduction method using the null space in a MIMO channel [17]–[19]. The numbers of transmitter and receiver antennas are denoted as N and M , respectively. We assume $N > M$. Therefore, the number of data streams spatially multiplexed is M . In this paper, we assume that the MIMO channel is not frequency selective for simplicity. The $M \times N$ -dimensional channel matrix is denoted as $\mathbf{H}$. Matrix $\mathbf{B}_{\text{data}}$ is the $N \times M$ -dimensional BF matrix where $\mathbf{B}_{\text{data}} = [\mathbf{b}_1 \dots \mathbf{b}_M]$ and $\mathbf{b}_m$ ($m = 1, \dots, M$) corresponds to the BF vector for data stream m . The number of subcarriers in the OFDM signal is denoted as K .

In general, when PAPR reduction is applied to each transmitter antenna independently, the interference component of the peak reduction signal appears in the transmission frequency band. The adaptive PAPR reduction method using the null space in the MIMO channel limits the transmission of the interference component for PAPR reduction purposes to only the null space in the MIMO channel. This results in mitigating the throughput reduction due to the interference for PAPR reduction.

Since N is greater than M , we have N -dimensional $N - M$ vectors, $\mathbf{v}_1, \dots, \mathbf{v}_{N-M}$, that are orthogonal to $\mathbf{H}$ (thus, $\mathbf{H}\mathbf{v}_l = \mathbf{0}$, $l = 1, \dots, N - M$) and orthogonal to each other (thus, $\mathbf{v}_i^H \mathbf{v}_j = 0$ for $j \neq i$). We assume $\|\mathbf{v}_l\| = 1$, $l = 1, \dots, N - M$. The $N \times (N - M)$ -dimensional matrix $\mathbf{V} = [\mathbf{v}_1 \dots \mathbf{v}_{N-M}]$ corresponds to the null space in MIMO channel $\mathbf{H}$. The $N \times N$ -dimensional BF matrix including $\mathbf{V}$ is denoted as $\mathbf{B} = [\mathbf{B}_{\text{data}} \mathbf{V}]$. The M -dimensional effective data transmission signal vector at subcarrier k ($k = 1, \dots,$

K) before BF is denoted as $\mathbf{s}_{\text{data},k}$. The frequency-domain N -dimensional transmission signal vector at subcarrier k after BF and PAPR reduction are applied can be denoted as $\mathbf{x}_{\text{freq},k} = \mathbf{B}_{\text{data}}\mathbf{s}_{\text{data},k} + \Delta_k$. Here, Δ_k is the interference component added by PAPR-reduction operation. This means that the N -dimensional transmission signal vector before BF is equivalently converted as

$$\begin{aligned} \mathbf{B}^{-1}\mathbf{x}_{\text{freq},k} &= \mathbf{B}^{-1}(\mathbf{B}_{\text{data}}\mathbf{s}_{\text{data},k} + \Delta_k) \\ &= \mathbf{B}^{-1}\left(\mathbf{B}\begin{bmatrix} \mathbf{s}_{\text{data},k} \\ \mathbf{0} \end{bmatrix} + \Delta_k\right) = \begin{bmatrix} \mathbf{s}_{\text{data},k} \\ \mathbf{0} \end{bmatrix} + \mathbf{B}^{-1}\Delta_k = \begin{bmatrix} \mathbf{s}_{\text{data},k} + \mathbf{e}_{\text{data},k} \\ \mathbf{e}_{\text{null},k} \end{bmatrix}, \end{aligned} \quad (1)$$

where $\mathbf{e}_{\text{data},k}$ is the interference given to effective data stream $\mathbf{s}_{\text{data},k}$, which degrades the throughput. In the adaptive PAPR reduction method using the null space in the MIMO channel, by limiting the interference, the N -dimensional transmission signal vector before BF at subcarrier k , $\mathbf{s}_k$, is controlled in order to minimize $\mathbf{e}_{\text{data},k}$, i.e.,

$$\mathbf{s}_k = \mathbf{B}^{-1}\mathbf{x}_{\text{freq},k} = \mathbf{B}^{-1}(\mathbf{B}_{\text{data}}\mathbf{s}_{\text{data},k} + \Delta_k) \approx \begin{bmatrix} \mathbf{s}_{\text{data},k} \\ \mathbf{e}_{\text{null},k} \end{bmatrix}. \quad (2)$$

The peak reduction signal, $\mathbf{e}_{\text{null},k}$, suppresses the PAPR and is then transmitted only to the null space in the MIMO channel. Thus, since $\mathbf{e}_{\text{null},k}$ for the PAPR reduction is not observed on the receiver side of M antennas as $\mathbf{H}\mathbf{V}\mathbf{e}_{\text{null},k} = \mathbf{0}$, PAPR reduction is achieved while the throughput degradation is alleviated.

2.2 Conventional CF-Based Implementation Algorithm (CFCNC)

Next, the conventional implementation algorithm in [17]–[19] is described. This iterative algorithm alternately repeats the PAPR reduction process using the CF operation and restores the restrictions on the peak reduction signal components as in (2). In the following, this algorithm is referred to as CF followed by the channel-null constraint (CFCNC). Figure 1 shows the block diagram of CFCNC.

The number of iterations is denoted as J . The $\mathbf{e}_{\text{null},k}$ vector generated at the j -th iteration ($j = 1, \dots, J$) is denoted as $\mathbf{e}_{\text{null},k}^{(j)}$. As the initial setting, $\mathbf{e}_{\text{null},k}^{(0)}$ is set to $\mathbf{0}$. The frequency-domain transmission signal vector after BF at subcarrier k , $\mathbf{x}_{\text{freq},k}^{(j)}$, is obtained as

$$\mathbf{x}_{\text{freq},k}^{(j)} = \mathbf{B}_{\text{data}}\mathbf{s}_{\text{data},k} + \mathbf{V}\mathbf{e}_{\text{null},k}^{(j-1)}. \quad (3)$$

The IFFT is applied to the frequency-domain transmission signal sequence, in which the components of $\mathbf{x}_{\text{freq},k}^{(j)}$

for all subcarriers are collected, at each transmitter antenna and the corresponding time-domain transmission signal sequence for each transmitter antenna is obtained.

Clipping is applied to the time-domain transmission signal sequence based on a predetermined threshold. Then, filtering is performed on the clipped signal. In this paper, we assume that filtering to remove the out-of-band radiation caused by the clipping is performed by setting the signal strength of the frequency component corresponding to the out-of-band radiation to zero in the frequency domain by applying the FFT to the clipped time-domain signal. After the above CF, the frequency-domain transmission signal vector after BF, $\mathbf{x}_{\text{freq},k}^{(j)}$, is assumed to be converted as $\tilde{\mathbf{x}}_{\text{freq},k}^{(j)} = \mathbf{B}_{\text{data}}\mathbf{s}_{\text{data},k} + \Delta_k^{(j)}$.

The last step of the process at the j -th iteration of CFCNC is to restore the restriction that the peak reduction signal is transmitted only to the null space in the MIMO channel. To achieve this, $\mathbf{e}_{\text{null},k}^{(j)}$ is updated as

$$\mathbf{e}_{\text{null},k}^{(j)} = \mathbf{V}^H \tilde{\mathbf{x}}_{\text{freq},k}^{(j)} = \mathbf{V}^H \Delta_k^{(j)}. \quad (4)$$

This is the projection of the peak reduction signal to the null space in the MIMO channel.

Then, iteration index j is updated as $j+1$ and the above process is repeated until j reaches J . At the last iteration, $\tilde{\mathbf{x}}_{\text{freq},k}^{(J)}$ is transmitted.

3. Conventional Per-Antenna PC Signal-Based PAPR Reduction Method (PAPC)

This section describes the conventional PC signal-based PAPR reduction method in [23] and [24]. The point of the PC signal-based method is to define the PC signal that satisfies the requirement for the out-of-band radiation. By directly adding the PC signal to the time-domain transmission signal at the transmitter antenna, the PAPR reduction equivalent to the CF operation is achieved, while the required computational cost of the PC signal-based method is significantly reduced compared to that for the CF method.

The basic time-domain signal, $g[t]$, which is used to generate the PC signal, is given as

$$g[t] = \frac{1}{K} \sum_{k=-K/2}^{K/2+1} h[t]e^{j\omega_k t}. \quad (5)$$

Term t represents the discrete time index and $t = 0, \dots, F-1$, where F is the number of FFT/IFFT points. Term $h[t]$ is the impulse response of the transmitter low-pass filter and ω_k represents the angular frequency at subcarrier k . We assume $h[t] = 1$, $t = 0, \dots, F-1$ in the paper so that its frequency transfer function becomes an ideal rectangular function. Thus, $g[t]$ is a sinc function that has its peak amplitude of 1.0 at $t = 0$ and satisfies the requirement for the out-of-band radiation to be zero at the baseband transmission signal.

The time-domain transmission signal before PAPR reduction at transmitter antenna n at t is denoted as $x_n[t]$. The

Fig. 1 Block diagram of CFCNC.

PAPR reduction method using the PC signal in [23] and [24] is applied independently at each transmitter antenna. In the following, this method is referred to as the per-antenna PC (PAPC). Hereafter, the PAPC is briefly described.

The time-domain transmission signal of transmitter antenna n at the j -th iteration of PAPC is denoted as $x_n^{(j)}[t]$. As the initial setting, $x_n^{(1)}[t]$ is set to $x_n[t]$. The time index, where $x_n^{(j)}[t]$ for a given n has the maximum amplitude that exceeds the predetermined amplitude threshold, A_{th} , is denoted as $\tau_n^{(j)}$. PAPC adds the following PC signal, $p_n^{(j)}[t]$, to $x_n^{(j)}[t]$ to reduce the peak power.

$$p_n^{(j)}[t] = -\left(x_n^{(j)}[\tau_n^{(j)}] - A_{th}\right) e^{j\theta_n^{(j)}} g[t - \tau_n^{(j)}]. \quad (6)$$

$$x_n^{(j+1)}[t] = x_n^{(j)}[t] + p_n^{(j)}[t]. \quad (7)$$

Here, $\theta_n^{(j)}$ represents the phase of $x_n^{(j)}[\tau_n^{(j)}]$. Since basic signal $g[t]$ has its peak amplitude of 1.0 at $t = 0$ and satisfies the requirement for the out-of-band radiation, by adding $p_n^{(j)}[t]$ to $x_n^{(j)}[t]$, the peak power observed at $t = \tau_n^{(j)}$ at antenna n is suppressed to the threshold value, A_{th} , while the impact of adding the PC signal to the other timing is mitigated. PAPC repeats the above process J times at each transmitter antenna n independently.

PAPC achieves approximately the same PAPR reduction performance as that for the PAPR reduction method where CF is applied independently at each transmitter antenna (hereafter this method is referred to as the per-antenna CF (PACF)). Meanwhile, the computational complexity of PAPC is lower than that of PACF since the FFT and IFFT operations are not required at each iteration to filter the out-of-band radiation. However, the data streams suffer from interference from the in-band PC signal since a part of the PC signal is transmitted to the effective MIMO channel.

4. Proposed PC Signal-Based Method

4.1 Proposed Complexity-Reduced Algorithm for Adaptive PAPR Reduction Method Using Null Space in MIMO Channel (PCCNC)

The proposed complexity-reduced implementation algorithm for adaptive PAPR reduction method using the null space in a MIMO channel performs PC signal-based PAPR reduction jointly considering all the transmission signals for all antennas. Thus, the PC signal is constructed in vector form. By setting the BF vector of the PC signal orthogonal to the MIMO channel, i.e., the BF vector is restricted within the null space in the MIMO channel, the interference to the data streams can be eliminated on the receiver side. Hereafter, the proposed algorithm is referred to as the PC with channel-null constraint (PCCNC).

Here, PCCNC is described in detail. The N -dimensional time-domain transmission signal vector before PAPR reduction at time t is denoted as $\mathbf{x}[t]$, whose n -th element is $x_n[t]$.

$$\mathbf{x}[t] = [x_1[t] \ \cdots \ x_N[t]]^T. \quad (8)$$

Fig. 2 Block diagram of proposed PCCNC.

The time-domain transmission signal vector at the j -th iteration of PCCNC is denoted as $\mathbf{x}^{(j)}[t] = [x_1^{(j)}[t] \ \cdots \ x_N^{(j)}[t]]^T$. We assume $\mathbf{x}^{(1)}[t] = \mathbf{x}[t]$. In the j -th iteration of PCCNC, the PC signal vector, $\mathbf{p}^{(j)}[t]$, which is represented in the form of (9), is added to $\mathbf{x}^{(j)}[t]$ to reduce the peak power.

$$\mathbf{p}^{(j)}[t] = -\mathbf{w}^{(j)} g[t - \tau^{(j)}]. \quad (9)$$

$$\mathbf{x}^{(j+1)}[t] = \mathbf{x}^{(j)}[t] + \mathbf{p}^{(j)}[t]. \quad (10)$$

Here, $\tau^{(j)}$ is the time index where $x_n^{(j)}[t]$ for all $n = 1, \dots, N$ and $t = 0, \dots, F-1$ has the maximum amplitude that exceeds amplitude threshold A_{th} at the j -th iteration. We assume that at the j -th iteration of PCCNC, the aim of $\mathbf{p}^{(j)}[t]$ is to cancel the peak signal observed in $\mathbf{x}^{(j)}[\tau^{(j)}]$ using the peak signal portion of $g[0]$. An important component of $\mathbf{p}^{(j)}[t]$ is $\mathbf{w}^{(j)}$, which is the BF vector of the PC signal at the j -th iteration. The N -dimensional vector, $\mathbf{w}^{(j)}$, should lie within the null space in the MIMO channel. Thus, in PCCNC, $\mathbf{w}^{(j)}$ is controlled so that it satisfies $\mathbf{H}\mathbf{w}^{(j)} = \mathbf{0}$. PC signal vector $\mathbf{p}^{(j)}[t]$, which is generated by multiplying $\mathbf{w}^{(j)}$ to the $\tau^{(j)}$ -time-shifted version of $g[t]$, satisfies the requirements for the out-of-band radiation and for zero interference to the data streams. This is because the PC signal is transmitted to only the null space in the given MIMO channel and does not appear on the receiver side.

Figure 2 shows a block diagram of PCCNC. PCCNC repeats the above process J times. The PC signal vector added to the transmission signal vector satisfies the requirements for the out-of-band radiation and zero interference to the data streams by using the null space in the MIMO channel. Since the FFT/IFFT operations are not needed and the peak regrowth due to the filtering after clipping is avoided, PCCNC is expected to achieve lower computational complexity than the conventional CFCNC.

4.2 PC Signal Generation Method for PCCNC

How to determine BF vector $\mathbf{w}^{(j)}$ significantly affects the achievable PAPR performance of PCCNC. This is because peak regrowth may occur due to inappropriate PC signal addition to the antennas other than the target antenna, which has the peak signal, depending on how $\mathbf{w}^{(j)}$ is determined. This section describes three generation methods for $\mathbf{w}^{(j)}$. In the following, three methods are presented for generating $\mathbf{w}^{(j)}$ for the given $\mathbf{x}^{(j)}[t]$ and $\tau^{(j)}$.

(1) Method 1

As already mentioned, for given $M \times N$ -dimensional MIMO channel $\mathbf{H}$, we have $N \times (N - M)$ -dimensional matrix

$\mathbf{V} = [\mathbf{v}_1 \dots \mathbf{v}_{N-M}]$ which corresponds to the null space in MIMO channel $\mathbf{H}$ (thus, $\mathbf{H}\mathbf{V} = \mathbf{O}$). We assume that $\mathbf{v}_i^H \mathbf{v}_j = 0$ for $j \neq i$, and $\|\mathbf{v}_l\| = 1$ for all l . Although set $\{\mathbf{v}_1, \dots, \mathbf{v}_{N-M}\}$ can take arbitrary representations, we assume here a specific representation. The n -th ($n = 1, \dots, N$) element of $\mathbf{v}_l$ is denoted as $v_{l,n}$. The amplitude and phase of $v_{l,n}$ are denoted as $r_{l,n}$ and $\varphi_{l,n}$, respectively ($v_{l,n} = r_{l,n}e^{j\varphi_{l,n}}$). We note that in the computer simulation, $\mathbf{V}$ is first generated in a random manner. By applying the Gram-Schmidt orthogonalization to matrix $[\mathbf{H}^H \ \mathbf{V}]$, matrix $\mathbf{V}$ is obtained.

PC signal generation method 1 generates $\mathbf{w}^{(j)}$ by selecting one $\mathbf{v}_l$ from prepared set $\{\mathbf{v}_1, \dots, \mathbf{v}_{N-M}\}$. The main advantageous property of method 1 is its simplicity. First, antenna index n , with which $|x_n^{(j)}[\tau^{(j)}]|$ takes the maximum for given $\tau^{(j)}$, is denoted as $n^{(j)}$.

$$n^{(j)} = \arg \max_n |x_n^{(j)}[\tau^{(j)}]|. \quad (11)$$

Method 1 selects $\mathbf{v}_l$ such that it has the highest $|v_{l,n^{(j)}}|$. Vector $\mathbf{w}^{(j)}$ is generated by multiplying complex coefficient $a^{(j)}$ to the selected $\mathbf{v}_l$. Coefficient $a^{(j)}$ is determined such that the amplitude of peak signal $x_{n^{(j)}}^{(j)}[\tau^{(j)}]$ becomes the threshold value, A_{th} , after adding the PC signal. Thus,

$$l^{(j)} = \arg \max_l |v_{l,n^{(j)}}| = \arg \max_l r_{l,n^{(j)}}, \quad (12)$$

$$\mathbf{w}^{(j)} = a^{(j)} \mathbf{v}_{l^{(j)}}, \quad (13)$$

where

$$a^{(j)} = \frac{|x_{n^{(j)}}^{(j)}[\tau^{(j)}]| - A_{\text{th}}}{r_{l^{(j)},n^{(j)}}} e^{j(\theta_{n^{(j)}}^{(j)}[\tau^{(j)}] - \varphi_{l^{(j)},n^{(j)}})}. \quad (14)$$

$\theta_{n^{(j)}}^{(j)}[\tau^{(j)}]$ is the phase of $x_{n^{(j)}}^{(j)}[\tau^{(j)}]$.

The reason why $\mathbf{v}_l$ with the highest $|v_{l,n^{(j)}}|$ is selected as $\mathbf{w}^{(j)}$ in method 1 is that we can expect that such a $\mathbf{v}_l$ has a relatively small $|v_{l,n}|$ for $n \neq n^{(j)}$ under the condition of $\|\mathbf{v}_l\| = 1$. Therefore, we can further expect that such a $\mathbf{v}_l$ will avoid the peak regrowth caused by the addition of the PC signal at antenna n other than $n^{(j)}$ with high probability. This is because the PC signal added to antenna $n \neq n^{(j)}$ is expected to be small. However, since method 1 does not directly measure and take into account the impact of adding the PC signal on the transmission signal at $n \neq n^{(j)}$ as a cost of simplicity, the achievable PAPR reduction performance may be degraded compared to that in the other methods.

(2) Method 2

PC signal generation method 2 generates $\mathbf{w}^{(j)}$ by selecting one $\mathbf{v}_l$ from prepared set $\{\mathbf{v}_1, \dots, \mathbf{v}_{N-M}\}$, which is similar to method 1. However, method 2 directly measures the impact of the addition of the PC signal on the transmission signal at $n \neq n^{(j)}$ and this is taken into account when generating $\mathbf{w}^{(j)}$.

In method 2, the l -th ($l = 1, \dots, N - M$) candidate vector, $\mathbf{w}^{(j,l)}$, for $\mathbf{w}^{(j)}$ is generated using $\mathbf{v}_l$ in the same way as in PC signal generation method 1.

$$\mathbf{w}^{(j,l)} = a^{(j,l)} \mathbf{v}_l, \quad (15)$$

$$a^{(j,l)} = \frac{|x_{n^{(j)}}^{(j)}[\tau^{(j)}]| - A_{\text{th}}}{r_{l,n^{(j)}}} e^{j(\theta_{n^{(j)}}^{(j)}[\tau^{(j)}] - \varphi_{l,n^{(j)}})}. \quad (16)$$

Next, the transmission signal vector at time $\tau^{(j)}$ after PC signal addition, $\mathbf{x}^{(j+1,l)}[\tau^{(j)}]$, assuming that $\mathbf{w}^{(j,l)}$ is used is calculated based on (9) and (10).

$$\mathbf{x}^{(j+1,l)}[\tau^{(j)}] = \mathbf{x}^{(j)}[\tau^{(j)}] - \mathbf{w}^{(j,l)} g[t - \tau^{(j)}]. \quad (17)$$

Then, the maximum amplitude of the elements in $\mathbf{x}^{(j+1,l)}[\tau^{(j)}]$ other than $n = n^{(j)}$, $a_{\text{max}}^{(j,l)}$, is measured.

$$a_{\text{max}}^{(j,l)} = \max_{n \neq n^{(j)}} |x_n^{(j+1,l)}[\tau^{(j)}]|. \quad (18)$$

Finally, $\mathbf{w}^{(j,l)}$ such that it has the lowest $a_{\text{max}}^{(j,l)}$ is selected as $\mathbf{w}^{(j)}$.

$$\mathbf{w}^{(j)} = \mathbf{w}^{(j,l_{\min})}, \quad \text{where } l_{\min} = \arg \min_l a_{\text{max}}^{(j,l)}. \quad (19)$$

Method 2 achieves more accurate PAPR reduction at each iteration compared to that in method 1 at the cost of increased computational complexity.

(3) Method 3

PC signal generation method 3 aims to generate the most effective $\mathbf{w}^{(j)}$ to reduce the PAPR at the j -th iteration at the cost of increased computational complexity per iteration compared to methods 1 and 2. In PC signal generation method 3, to generate $\mathbf{w}^{(j)}$, vector $\tilde{\mathbf{w}}^{(j)}$ is first calculated as

$$\tilde{\mathbf{w}}^{(j)} = [\tilde{w}_1^{(j)} \dots \tilde{w}_N^{(j)}]^T$$

$$\tilde{w}_n^{(j)} = \begin{cases} x_n^{(j)}[\tau^{(j)}] - A_{\text{th}} e^{j\theta_n^{(j)}[\tau^{(j)}]}, & |x_n^{(j)}[\tau^{(j)}]| > A_{\text{th}} \\ 0, & \text{Otherwise} \end{cases} \quad (20)$$

Here, $\theta_n^{(j)}[\tau^{(j)}]$ is the phase of $x_n^{(j)}[\tau^{(j)}]$. Vector $\tilde{\mathbf{w}}^{(j)}$ is an ideal peak reduction vector in the sense that if vector $\tilde{\mathbf{w}}^{(j)}$ is used as $\mathbf{w}^{(j)}$ in (9), the amplitude levels of the transmission signals for all N antennas at time $\tau^{(j)}$ (thus, $|x_n^{(j)}[\tau^{(j)}]|$ for all n) can simultaneously be set equal to or lower than threshold A_{th} .

However, vector $\tilde{\mathbf{w}}^{(j)}$ has a component that is orthogonal to the null space in the MIMO channel, which causes interference to the data streams. Therefore, $\tilde{\mathbf{w}}^{(j)}$ is projected onto the null space in MIMO channel $\mathbf{V}$ to generate $\mathbf{w}^{(j)}$ in (9).

$$\mathbf{w}^{(j)} = \mathbf{V}\mathbf{V}^H \tilde{\mathbf{w}}^{(j)}. \quad (21)$$

Method 3 generates the most effective PC signal vector among the three investigated methods under the constraint that the PC signal should be transmitted only to the null space in the MIMO channel.

5. Numerical Results

5.1 Simulation Parameters

The number of subcarriers, K , is set to 64. The number

of FFT/IFFT points, F , is set to 256, which corresponds to 4-times oversampling in the time domain in order to measure the PAPR levels accurately [27]. For general evaluation, we assume that the signal constellation of each sub-carrier follows an independent standard complex Gaussian distribution. The number of transmission antennas, N , is parameterized from 8 to 100, while the number of receiver antennas, M , is fixed at 4. Assuming multiuser MIMO, zero-forcing BF is applied. For the channel model, we assume flat Rayleigh fading, which is independent between transmitter antenna branches and between receiver antenna branches. The signal-to-noise ratio (SNR) is set to 20 dB. As for the PAPR reduction method for evaluation, as a per-antenna independent PAPR reduction approach, PACF and PAPC are tested. As the adaptive PAPR reduction approach using the null space in the MIMO channel, the conventional CFCNC and PCCNC with PC signal generation methods 1, 2, and 3 are tested for comparison. For all algorithms, the number of iterations, J , is parameterized.

In the PCCNC algorithm, we assume that after J iterations, PAPC is performed with J_{add} iterations in order to achieve a lower PAPR at the cost of reduced throughput for the purpose of clear comparison with the conventional CFCNC. The J_{add} value is selected from among 10, 20, 40, and 60 depending on the J value. Furthermore, after several iterations in PCCNC with PC signal generation method 3, when the projection of $\tilde{\mathbf{w}}^{(j)}$ onto the null space in the MIMO channel is occasionally close to $\mathbf{0}$, further PAPR reduction is not achieved since subsequent iterations repeat the same process for the same target peak signal. This situation occurs especially when the dimensions of the null space in the MIMO channel are low. To avoid trivial PAPR reduction results using PCCNC due to the above phenomenon, when the same peak is targeted for consecutive βJ iterations, we insert a 1-time PAPC process within the PCCNC processes. We note that β of one means that the insertion of the 1-time PAPC process is not applied. Based on the pre-performed computer simulation results, β is set to 0.01 for PC signal generation methods 1 and 2, while it is set to 0.1 for method 3 when N is 8. When N is 100, β is set to 1.0 for all the PC signal generation methods.

The power threshold, $P_{\text{th}} = (A_{\text{th}})^2$, in PAPR reduction is defined as the signal power threshold normalized by the signal power per antenna averaged over the channel realizations. The PAPR is defined as the ratio of the peak signal power to the average signal power across all the transmitter antennas per OFDM symbol. The sum throughput of M streams (users) is calculated based on the Shannon formula taking into account Bussgang's theorem [28].

5.2 Simulation Results

First, we compare the performance of the three PC signal generation methods in PCCNC. Figures 3 and 4 show the complementary cumulative distribution function (CCDF) of the PAPR and throughput for PCCNC with PC signal generation methods 1, 2 and 3, respectively. Threshold P_{th} and

Fig. 3 CCDF of PAPR for PCCNC with PC signal generation methods 1, 2 and 3.

Fig. 4 CCDF of throughput for PCCNC with PC signal generation methods 1, 2 and 3.

J are set to 7 dB and 100, respectively. J_{add} is 60. Both N of 8 and 100 are evaluated. Figure 3 shows that when no PAPR reduction is applied, the PAPR with the N of 100 is greater than that with the N of 8. This is due to the increased variation in the transmission power due to BF among the transmitter antennas as N is increased. However, by using PCCNC, the distribution of the PAPR is improved when N is larger. This is because the increased dimensions of the null space in the MIMO channel help PCCNC to generate a more appropriate PAPR reduction signal.

In Fig. 3, the PAPR distribution of PCCNC with the three PC signal generation methods is quite comparable. As shown in Fig. 4, the throughput distributions for PCCNC with PC signal generation methods 1 and 2 are degraded compared to that for method 3 especially when N is as large as 100. The throughput level of PCCNC with PC signal generation method 3 is close to ideal, which is that in the no PAPR reduction case. This observation is due to the following reasons. Even in methods 1 and 2, BF vector $\mathbf{w}^{(j)}$ of the PC signal is directed to the null space of the MIMO channel.

Fig. 5 Average throughput as a function of average PAPR for PCCNC with PC signal generation methods 1, 2, and 3.

Therefore, the PC signal in method 1 or 2 by itself does not interfere with the data stream. However, in methods 1 and 2, the PAPR reduction capability per iteration tends to be limited compared to method 3, due to the restriction that methods 1 and 2 generate $\mathbf{w}^{(j)}$ by selecting a vector from predetermined set $\{\mathbf{v}_1, \dots, \mathbf{v}_{N-M}\}$. In the evaluation in Figs. 3 and 4, PAPC with $J_{\text{add}} = 60$ iterations is performed after PCCNC with $J = 100$ iterations for all three methods. If PCCNC can sufficiently suppress the PAPR, the subsequent PAPC does not need to generate much of a PC signal. However, if PCCNC cannot sufficiently suppress the PAPR, the PC signal generated in the subsequent PAPC to suppress the residual peak signals causes significant interference to the data stream. Therefore, a higher level of interference occurs in the subsequent PAPC process in PCCNC with PC signal generation methods 1 and 2 compared to that with method 3 and the throughput is degraded. In short, the subsequent PAPC process compensates for the degraded PAPR levels in methods 1 and 2 at the cost of throughput degradation (PAPR loss is translated to throughput loss).

Figure 5 shows the average throughput as a function of the average PAPR for PCCNC with PC signal generation methods 1, 2, and 3 with N as a parameter. The relationship between the average PAPR and average throughput is varied by changing the P_{th} value for the respective PAPR reduction methods. J and J_{add} are set to 100 and 60, respectively. When comparing the three PC signal generation methods in PCCNC, PC signal generation method 3 achieves the best throughput-vs.-PAPR performance. This is because PC signal generation method 3 is designed with the aim of generating the most effective $\mathbf{w}^{(j)}$ to reduce PAPR at the j -th iteration. Since PC signal generation methods 1 and 2 generate $\mathbf{w}^{(j)}$ by selecting a vector from predetermined set $\{\mathbf{v}_1, \dots, \mathbf{v}_{N-M}\}$, the achievable throughput-vs.-PAPR performance is degraded compared to PC signal generation method 3. This degradation becomes more pronounced as the average PAPR decreases (in other words, threshold P_{th} is set lower) since more severe interference is generated in the

Table 1 Number of real multiplications per iteration for PCCNC with PC signal generation methods 1, 2, and 3.

Process	Number of real multiplications		
	PC signal generation method 1	PC signal generation method 2	PC signal generation method 3
Power measurement of transmission signal	$2NF$	$2NF$	$2NF$
Calculation of amplitude and phase	2	$2(N-M)$	$4N + 4N^2$
Generation of BF vector $\mathbf{w}^{(j)}$	0	$(N-M)(2+6N) + 2(N-1)(N-M)$	
Generation of PC signal vector	$2 + 4N + NF$	$2 + 4N + NF$	NF

Fig. 6 Average throughput as a function of number of real multiplications for PC signal generation methods 1, 2, and 3 in PCCNC.

PAPC process after PCCNC to suppress the residual peak power in PCCNC with PC signal generation methods 1 and 2. The performance degradation using PC signal generation method 1 is especially clear since this method prioritizes lowering the computational complexity. However, since the required calculation cost per iteration is different among all the evaluated methods, in the following we compare the throughput-vs.-PAPR performance levels of all methods assuming the same computational complexity.

Table 1 gives the number of real multiplications per iteration required for PCCNC with the respective PC signal generation methods to evaluate the computational complexity. The number of real multiplications is a function of N , M , and F .

Based on Table 1, Fig. 6 shows the average throughput as a function of the number of real multiplications of the respective PC signal generation methods in PCCNC for a given PAPR requirement. The required average PAPR is set to 7 dB. The relationship between the number of real multiplications and the average throughput is varied by changing the J and J_{add} values for the respective PC signal generation methods. Figure 6 shows that PC signal generation method 3 is the best method among the three investigated methods considering the tradeoff between the computational complexity and the throughput-vs.-PAPR performance. In the

Fig. 7 CCDF of PAPR for respective PAPR reduction methods.

Fig. 8 CCDF of throughput for respective PAPR reduction methods.

following evaluation, we use PC signal generation method 3 for PCCNC and compare this with conventional CFCNC and the per-antenna independent PAPR reduction approach such as PACF and PAPC.

Figures 7 and 8 show the CCDF of the PAPR and throughput for each of the PAPR reduction methods, respectively. N is 100 in Fig. 7 and N of 8 and 100 are compared in Fig. 8. Threshold P_{th} and J are set to 7 dB and 100, respectively. J_{add} in PCCNC is 60. The PAPR distributions for all the methods are quite comparable. The throughput levels of CFCNC and PCCNC (shown as two overlapping blue lines) are much better than those of PACF and PAPC (shown as two overlapping red lines). This is because the peak reduction signal is concentrated in the null space in the MIMO channel in CFCNC and PCCNC; therefore, it does not interfere with the data stream on the receiver side. The achievable throughput distributions of CFCNC and PCCNC are nearly the same and very close to that without PAPR reduction. This confirms that the proposed PCCNC works well as PAPR reduction using the null space in the MIMO channel.

Fig. 9 Average throughput as a function of average PAPR for respective PAPR reduction methods.

Figure 9 shows the average throughput as a function of the average PAPR with N as a parameter. The relationship between the average PAPR and average throughput is varied by changing the P_{th} value for the respective PAPR reduction methods. Here, J is set to 100. J_{add} in PCCNC is set to 60. When using the per-antenna PAPR reduction approach such as PACF and PAPC, the degradation in the throughput accompanying the reduction in the PAPR is large. This degradation is remarkable especially under conditions where N is large. This is because the interference due to the peak reduction signal becomes a dominant factor in the degradation in the throughput when N is large as the increased BF gain diminishes the impact of noise. On the other hand, the adaptive PAPR reduction method using the null space in the MIMO channel employing CFCNC and PCCNC suppresses the degradation in the throughput caused by the reduction in the PAPR. The throughput-vs.-PAPR performance of PCCNC is quite comparable to that of CFCNC. However, when N becomes large, throughput degradation in the low PAPR region is observed. This is mainly because this figure compares the performance levels of the respective PAPR reduction methods assuming the same J . PCCNC requires more iterations than CFCNC since one peak is cancelled at each iteration in PCCNC while CFCNC reduces multiple peaks simultaneously through clipping. We note that the same number of iterations does not mean the same computational complexity among the evaluated PAPR reduction methods.

Table 2 gives the number of real multiplications per iteration required for the respective PAPR reduction methods to evaluate the computational complexity. The number of real multiplications is a function of N , M , and F . Table 2 suggests that the reduction in computational complexity by using PCCNC compared to CFCNC is enhanced as N increases. Based on Table 2, Fig. 10 shows the average throughput as a function of the number of real multiplications of the respective PAPR reduction methods for a given PAPR requirement. The required average PAPR is set to 7 dB. The relationship between the number of real multipli-

Table 2 Number of real multiplications per iteration for respective PAPR reduction methods.

PAPR reduction method		Process	Number of real multiplications
Per-antenna PAPR reduction method	PACF	Power meas. of transmission signal	$2NF$
		Amplitude clipping	$3NF$
		FFT	$4NF\log_2 F$
		IFFT	$4NF\log_2 F$
	PAPC	Power meas. of transmission signal	$2NF$
		Time shift of $g[t]$	0
		Calculation of amplitude and phase	$2N$
		Generation of PC signal	$N(2+F)$
Adaptive PAPR reduction method using null space in MIMO channel	CFCNC	Power meas. of transmission signal	$2NF$
		Amplitude clipping	$3NF$
		FFT	$4NF\log_2 F$
		Inverse BF (projection onto null space)	$4FN(N-M)$
		BF	$4FN(N-M)$
		IFFT	$4NF\log_2 F$
	PCCNC with PC signal generation method 3	Power meas. of transmission signal	$2NF$
		Time shift of $g[t]$	0
		Calculation of amplitude and phase	$4N+4N^2$
		Generation of BF vector $w^{(i)}$	NF

Fig. 10 Average throughput as a function of number of real multiplications for respective PAPR reduction methods.

cations and the average throughput is varied by changing the J value (and J_{add} in PCCNC) for the respective PAPR reduction methods. Irrespective of N , PAPC achieves better throughput than PACF between the two per-antenna PAPR reduction methods for the same computational complexity. When we focus on the two PAPR reduction methods using the null space in the MIMO channel, the proposed PCCNC achieves a better tradeoff between the throughput and complexity than the conventional CFCNC. For example, PCCNC reduces the required computational complexity compared to CFCNC by approximately 1/10 and 1/100 for $N = 8$ and 100, respectively. The performance gain using PCCNC is especially significant when N is large. This is

because the reduction in computational complexity by using PCCNC compared to that for CFCNC increases as N increases. Therefore, when considering a massive MIMO scenario, the proposed PCCNC is attractive because it achieves approximately the same throughput-vs.-PAPR performance as that for the CFCNC with much lower computational complexity.

6. Conclusion

This paper proposed a computational complexity-reduced algorithm, PCCNC, for our previously reported adaptive PAPR reduction method using the null space in a MIMO channel for MIMO-OFDM signals. The proposed PCCNC performs PC signal-based PAPR reduction jointly considering all the transmission signals for all antennas. Thus, the PC signal is constructed in vector form and by setting the BF vector of the PC signal orthogonal to the MIMO channel, the interference to the data streams is eliminated on the receiver side. Among the three investigated generation methods to control the BF vector in the PC signal, the method in which the ideal peak reduction vector is projected onto the null space in the MIMO channel achieves the best PAPR reduction performance for a given computational complexity. Since complex FFT/IFFT operations are not required in the proposed PCCNC, PCCNC with the best PC signal generation method among the three investigated methods achieves better throughput than the conventional CF-based iterative algorithm, CFCNC, for the same computational complexity. The performance gain by using PCCNC is especially significant when the number of transmitter antennas is large. Therefore, when considering a massive MIMO scenario where the number of antennas at the base station transmitter is very large, the proposed PCCNC is attractive because it achieves great throughput-vs.-PAPR performance with very low computational complexity. This paper assumes a frequency nonselective channel. The extension of the proposed method to accommodate the frequency selective channel is left for future study.

References

- [1] T.L. Marzetta, "Noncooperative cellular wireless with unlimited numbers of base station antennas," *IEEE Trans. Wireless Commun.*, vol.9, no.11, pp.3590–3600, Nov. 2010.
- [2] H. Papadopoulos, C. Wang, O. Bursalioglu, X. Hou, and Y. Kishiyama, "Massive MIMO technologies and challenges towards 5G," *IEICE Trans. Commun.*, vol.E99-B, no.3, pp.602–621, March 2016.
- [3] S.H. Han and J.H. Lee, "An overview of peak-to-average power ratio reduction techniques for multicarrier transmission," *IEEE Wireless Commun.*, vol.12, no.2, pp.56–65, April 2005.
- [4] X. Li and L.J. Cimini, Jr., "Effect of clipping and filtering on the performance of OFDM," *IEEE Commun. Lett.*, vol.2, no.5, pp.131–133, May 1998.
- [5] A. Gatherer and M. Polley, "Controlling clipping probability in DMT transmission," *Proc. 31st Asilomar Conference on Signals, Systems, and Computers*, pp.578–584, Nov. 1997.
- [6] J. Armstrong, "Peak-to-average power reduction for OFDM by repeated clipping and frequency domain filtering," *Electron. Lett.*,

- vol.38, no.8, pp.246–247, Feb. 2002.
- [7] B.S. Krongold and D.L. Jones, “PAR reduction in OFDM via active constellation extension,” *IEEE Trans. Broadcast.*, vol.49, no.3, pp.258–268, Sept. 2003.
 - [8] J. Tellado and J.M. Cioffi, “Efficient algorithms for reducing PAR in multicarrier systems,” *Proc. IEEE Int. Symp. Inf. Theory*, p.191, Cambridge, MA, Aug. 1998.
 - [9] H. Ando and K. Higuchi, “Comparison of PAPR reduction methods for OFDM signal with channel coding,” *Proc. IEEE APWCS2009*, Seoul, Korea, Aug. 2009.
 - [10] H. Lee, D.N. Liu, W. Zhu, and M.P. Fitz, “Peak power reduction using a unitary rotation in multiple transmit antennas,” *Proc. IEEE ICC2005*, pp.2407–2411, Seoul, Korea, May 2005.
 - [11] G.R. Woo and D. L. Jones, “Peak power reduction in MIMO OFDM via active channel extension,” *Proc. IEEE ICC2005*, pp.2636–2639, Seoul, Korea, May 2005.
 - [12] S. Suyama, H. Adachi, H. Suzuki, and K. Fukawa, “PAPR reduction methods for eigenmode MIMO-OFDM transmission,” *Proc. IEEE VTC2009-Spring*, Barcelona, Spain, April 2009.
 - [13] R.W. Bauml, R.F.H. Fischer, and J.B. Huber, “Reducing the peak-to-average power ratio of multicarrier modulation by selected mapping,” *Electron. Lett.*, vol.32, no.22, pp.2056–2057, Oct. 1996.
 - [14] S.H. Muller and J.B. Huber, “OFDM with reduced peak-to-average power ratio by optimum combination of partial transmit sequences,” *Electron. Lett.*, vol.33, no.5, pp.368–369, Feb. 1997.
 - [15] C. Studer and E.G. Larsson, “PAR-aware large-scale multi-user MIMO-OFDM downlink,” *IEEE J. Sel. Areas Commun.*, vol.31, no.2, pp.303–313, Feb. 2013.
 - [16] H. Prabhu, O. Edfors, J. Rodrigues, L. Liu, and F. Rusek, “A low-complex peak-to-average power reduction scheme for OFDM based massive MIMO systems,” *Proc. ISCCSP2014*, Athens, Greece, May 2014.
 - [17] Y. Sato, M. Iwasaki, S. Inoue, and K. Higuchi, “Clipping and filtering-based adaptive PAPR reduction method for precoded OFDM-MIMO signals,” *IEICE Trans. Commun.*, vol.E96-B, no.9, pp.2270–2280, Sept. 2013.
 - [18] S. Inoue, T. Kawamura, and K. Higuchi, “Throughput/ACLR performance of CF-based adaptive PAPR reduction method for eigenmode MIMO-OFDM signals with AMC,” *IEICE Trans. Commun.*, vol.E96-B, no.9, pp.2293–2300, Sept. 2013.
 - [19] R. Kimura, Y. Tajika, and K. Higuchi, “CF-based adaptive PAPR reduction method for block diagonalization-based multiuser MIMO-OFDM signals,” *Proc. IEEE VTC2011-Spring*, Budapest, Hungary, May 2011.
 - [20] Y. Matsumoto, K. Tateishi, and K. Higuchi, “Performance evaluations on adaptive PAPR reduction method using null space in MIMO channel for eigenmode massive MIMO-OFDM signals,” *Proc. APCC2017*, Perth, Australia, Dec. 2017.
 - [21] M. Suzuki, Y. Kishiyama, and K. Higuchi, “Combination of beamforming with per-antenna power constraint and adaptive PAPR reduction method using null space in MIMO channel for multiuser massive MIMO-OFDM transmission,” *Proc. WPMC2018*, Chiang Rai, Thailand, Nov. 2018.
 - [22] A. Ivanov, A. Volokhatyi, D. Lakontsev, and D. Yarotsky, “Unused beam reservation for PAPR reduction in massive MIMO system,” *Proc. IEEE VTC2018-Spring*, Porto, Portugal, June 2018.
 - [23] T. Hino and O. Muta, “Adaptive peak power cancellation scheme under requirements of ACLR and EVM for MIMO-OFDM systems,” *Proc. IEEE PIMRC2012*, Sydney, Australia, Sept. 2012.
 - [24] T. Kageyama, O. Muta, and H. Gacanin, “An adaptive peak cancellation method for linear-precoded MIMO-OFDM signals,” *Proc. IEEE PIMRC2015*, Hong Kong, Aug.–Sept. 2015.
 - [25] M. Suzuki, T. Suzuki, Y. Kishiyama, and K. Higuchi, “Complexity-reduced algorithm for adaptive PAPR reduction method using null space in MIMO channel for MIMO-OFDM signals,” *Proc. IEEE APWCS2019*, Singapore, Aug. 2019.
 - [26] T. Suzuki, M. Suzuki, Y. Kishiyama, and K. Higuchi, “Method for

generating peak cancellation signals in complexity-reduced PAPR reduction method using null space in MIMO channel for MIMO-OFDM signals,” *Proc. IEEE APWCS2019*, Singapore, Aug. 2019.

- [27] M. Sharif, M. Gharavi-Alkhansari, and B.H. Khalaj, “On the peak-to-average power of OFDM signals based on oversampling,” *IEEE Trans. Commun.*, vol.51, no.1, pp.72–78, Jan. 2003.

- [28] H. Ochiai and H. Imai, “Performance analysis of deliberately clipped OFDM signals,” *IEEE Trans. Commun.*, vol.50, no.1, pp.89–101, Jan. 2002.

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