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# On Optimizing the PAPR of OFDM Signals With Coding, Companding, and MIMO

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**ABSTRACT** One main disadvantage of the multiple-input-multiple-output orthogonal frequency-division multiplexing (MIMO-OFDM) system is that the signals transmitted on each antenna may experience high peak-to-average-power ratio (PAPR). We will present a new hybrid PAPR reduction technique that combines and optimizes three methods, namely convolutional code, successive suboptimal cross-antenna rotation and inversion (SS-CARI), and iterative modified companding and filtering. The results for the hybrid PAPR reduction technique show that this scheme significantly reduces the PAPR compared with SS-CARI alone; it can improve the bit error rate to levels better than what obtains with the space–time block coding MIMO-OFDM system, and the spectral splatter due to companding is also controlled by the use of frequency-domain filtering. In addition, it is a flexible technique in which the net gain can be optimized based on the requirements of scheme parameters, such as the code rate, the constraint length of the convolutional code, the number of subblocks for SS-CARI, and the companding parameters.

**INDEX TERMS** Companding, convolutional codes, multiple-input multiple-output (MIMO), orthogonal frequency division multiplexing (OFDM), peak-to-average power ratio (PAPR), signal scrambling, space-time block coding (STBC).

## I. INTRODUCTION

The use of multiple antennas both at the transmitter and at the receiver represents a standard method for improving the performance and increasing the capacity of wireless communications systems; furthermore, it can provide spatial diversity when an orthogonal space-time block coding (STBC) is used [1]. Multiple-input multiple-output (MIMO) can also improve the system capacity, as compared to single-input single-output (SISO) systems with flat Rayleigh fading or narrowband channels [2]. However, when MIMO is used in wideband channels, intersymbol interference (ISI) becomes a problem, and consequently orthogonal frequency division multiplexing (OFDM) is combined with MIMO to improve capacity and achieve ISI mitigation.

One of the main implementation drawbacks of OFDM is its inherent high peak-to-average power ratio (PAPR). This problem has been extensively studied, and multiple schemes have been proposed to reduce the PAPR in the OFDM signal. For example, [3] classifies PAPR reduction methods under four technique categories: coding, multiple signaling and probabilistic (MSP), signal distortion (SD), and hybrid. Coding schemes choose the codewords that produce the minimum PAPR for transmission; multiple signaling techniques generate a given number of multi-carrier signal permutations and select the one that minimizes the peaks in the envelope; probabilistic methods likewise try to minimize the PAPR by modifying and optimizing one or more parameters in the OFDM signal; signal distortion schemes are the simplest to implement, and distort the signal before the high power amplifier in order to reduce the PAPR. Finally, hybrid techniques take advantage of different individual methods and combine two or more schemes to realize optimal PAPR reduction.

High PAPR is also an issue in MIMO-OFDM systems, and usually, works that propose to reduce the peaks in such systems proceed by either the OFDM techniques or by taking advantage of MIMO architecture to propose new techniques.

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The companding scheme is an example of a signal distortion technique that can be extended to MIMO-OFDM; it compand the OFDM signal at the transmitter and decompand it at the receiver, based on different companding transforms [4], [5], such as $\mu-$law, $A-$law, exponential, etc. Unlike other distortion techniques, such as clipping, where the idea is to reduce the peaks of the OFDM signal, companding increases the average power of the signal, which can in turn substantially reduce the PAPR, in addition to operating the power amplifier more effectively [6], because when the mean power of the system increases, most subcarriers can operate at the maximum power available [7]; less input back-off (IBO) is then required than in the case of general OFDM or of the clipping OFDM signal [7]. However, in the classic $\mu-$law compander transform (uCT), the trade-off between PAPR reduction and bit error rate (BER) performance is critical, and the use of compander PAPR reduction technique can increase the out-of-band radiation. In that context, Vallavaraj *et al.* [8] proposed a modified $\mu-$law compander transform (MuCT) scheme that added a new companding profile parameter, called the peak ratio (PR), which can help achieve better BER performance [6].

However, distortion techniques, such as companding, have the disadvantage of possibly negatively affecting the performance of the system. In addition, they can increase the out-of-band radiation.

On the other hand, an MSP PAPR reduction scheme that uses the additional degree of freedom provided by the MIMO system is the successive suboptimal cross-antenna rotation and inversion (SS-CARI) proposed in [9]. However, the PAPR reduction obtained with the SS-CARI scheme is limited [10], and does not grow linearly with an increase in complexity or the number of permutations. Although SS-CARI does not change the BER performance of the system, the SS-CARI method requires additional side information (SI) that leads to a reduced data rate. In addition, the SI is a critical data that can significantly impact the BER if the SI is not recovered at the receiver. Consequently, the literature provides several proposals without side information as the blind cross-antenna successive shifting rotation and inversion (Blind-CASSRI) [11].

A coding PAPR reduction technique is interesting for the MIMO-OFDM system as a method for reducing the peaks in the OFDM signal while improving the BER performance. For instance, the impact of convolutional codes (CC) is analyzed in the OFDM system by [12], and shows that the selection of the generator polynomial for the CC can substantially affect the PAPR performance.

The aim of this paper is to propose a new hybrid PAPR reduction technique for an STBC MIMO-OFDM system, in which the convolutional code is optimized to avoid PAPR degradation; the technique combines the SS-CARI with iterative modified companding and filtering methods. This is a new technique aimed at considerably improving the system through significant PAPR reduction, BER gain as compared to the basic MIMO-OFDM system, low complexity, and reduced spectral splatter.

The paper is organized as follows. In Section II, we introduce the system model and the theoretical concepts. The third section covers the description of the new hybrid PAPR reduction technique, while its performance evaluation is presented in Section IV. The final section gives a brief summary and brings together the key findings.

## II. BACKGROUND

### A. SYSTEM MODEL

Generally, OFDM modulation and MIMO systems allow easy integration and an increase in spectral efficiency. If we consider a MIMO-OFDM system with $N_t$ transmit antennas, $N_r$ receive antennas, and $N$ subcarriers, the frequency-domain signal is therefore represented by $\{X_i[k]\}_{k=0}^{N-1}$ where $k$ is the frequency index, and an assumption of $N$ IFFT points from the $i$th transmit antenna. After applying the IFFT, the discrete-time baseband OFDM signal $x_i[n]$ is given by

$$x_i[n] = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_i[k] e^{\mathrm{j}2\pi \frac{kn}{LN}}, \; n = 0, 1, \ldots, LN-1, \quad (1)$$

where $n$ denotes the discrete-time index, j is the imaginary unit, and $L$ is the oversampling factor. The discrete-time baseband signal ($L$-times oversampled) can have about the same peaks as the continuous-time baseband signal when $L \geq 4$ [13].

The PAPR of the discrete-time OFDM baseband signal is defined as the ratio between the maximum instantaneous power and its average power [14], and from the $i$th transmit antenna, is

$$\mathrm{PAPR}(x_i[n]) \triangleq \frac{\max\limits_{0 \leq n \leq N-1} |x_i[n]|^2}{\frac{1}{N} \sum\limits_{n=0}^{N-1} |x_i[n]|^2}. \quad (2)$$

Frequently, the performance of a PAPR reduction technique is measured by the complementary cumulative distribution function (CCDF) given by:

$$\mathrm{CCDF} = \Pr\{\mathrm{PAPR} \geq \mathrm{PAPR}_0\}, \quad (3)$$

where the CCDF evaluates the probability of the PAPR of a OFDM signal exceeding a given threshold $\mathrm{PAPR}_0$.

Additionally, in MIMO-OFDM systems, the PAPR is defined as the maximum of all $N_t$ PAPR values evaluated in each MIMO path [15], that is:

$$\mathrm{PAPR}_{\mathrm{MIMO}} = \max_{1 \leq i \leq N_t} \mathrm{PAPR}(x_i[n]). \quad (4)$$

### B. CONVOLUTIONAL CODE

Convolutional codes (CC) are a type of forward error correction (FEC) codes that contain memory. These codes can thus be implemented simply by using a linear finite state shift register. Convolutional codes are characterized by three parameters $(\eta, k, V)$, with $\eta$ denoting the code word length,

$k$ the input length, and $V$ the constraint length, defined as the number of bits stored in each shift register, plus the current input bits. The code rate is therefore $k/\eta$.

It is clear that choosing different convolutional code parameters results in different bit error rate (BER) performances for the system. However, the PAPR of the system can also change according to the parameters selected for the convolutional code [12]. PAPR optimization therefore requires an adequate selection of CC parameters.

### C. SUCCESSIVE SUBOPTIMAL CROSS-ANTENNA ROTATION AND INVERSION (SS-CARI) SCHEME

To simplify the following description, we consider an Alamouti STBC MIMO-OFDM system [16] with two transmit antennas, and assume that the channel does not change during at least two OFDM symbol periods. However, the technique can be extended to cover other configurations. In the first symbol period, two data blocks $\mathbf{X}_1 = [X_1[0], X_1[1], \cdots, X_1[N-1]]$ and $\mathbf{X}_2 = [X_2[0], X_2[1], \cdots, X_2[N-1]]$ are transmitted from antennas 1 and 2, respectively, and in the second symbol period, antenna 1 transmits the data block $-\mathbf{X}_2^*$, and antenna 2 transmits $\mathbf{X}_1^*$, where $(\cdot)^*$ represents the elementwise complex conjugate operation.

In the SS-CARI technique proposed by Tan *et al.* [9], each data block is partitioned into $M$ equal size subblocks given by $\mathbf{X}_i = [\mathbf{X}_{i,1}, \mathbf{X}_{i,2}, \cdots, \mathbf{X}_{i,M}]$, where $i$ is the transmit antenna index. Next, a cross-antenna rotation and inversion (CARI) is performed only on the first subblocks $\mathbf{X}_{1,1}$, $\mathbf{X}_{2,1}$. As a result, we will obtain the four sets of transmit sequences: $\mathbf{X}_1^{(1)} = [\mathbf{X}_{1,1}, \mathbf{X}_{1,2}, \cdots, \mathbf{X}_{1,M}]$ and $\mathbf{X}_2^{(1)} = [\mathbf{X}_{2,1}, \mathbf{X}_{2,2}, \cdots, \mathbf{X}_{2,M}]$, the original set with the first subblock inverted $\mathbf{X}_1^{(2)} = [-\mathbf{X}_{1,1}, \mathbf{X}_{1,2}, \cdots, \mathbf{X}_{1,M}]$ and $\mathbf{X}_2^{(2)} = [-\mathbf{X}_{2,1}, \mathbf{X}_{2,2}, \cdots, \mathbf{X}_{2,M}]$, the original set with the first subblock rotated $\mathbf{X}_1^{(3)} = [\mathbf{X}_{2,1}, \mathbf{X}_{1,2}, \cdots, \mathbf{X}_{1,M}]$ and $\mathbf{X}_2^{(3)} = [\mathbf{X}_{1,1}, \mathbf{X}_{2,2}, \cdots, \mathbf{X}_{2,M}]$, and the original set with the first subblock inverted and rotated $\mathbf{X}_1^{(4)} = [-\mathbf{X}_{2,1}, \mathbf{X}_{1,2}, \cdots, \mathbf{X}_{1,M}]$ and $\mathbf{X}_2^{(4)} = [-\mathbf{X}_{1,1}, \mathbf{X}_{2,2}, \cdots, \mathbf{X}_{2,M}]$. Next, the PAPR for the four sets obtained are calculated, and the one with the smallest maximum PAPR is retained. This process is repeated with the next subblocks $\mathbf{X}_{1,2}$, $\mathbf{X}_{2,2}$, and successively for all $M$ subblocks. Finally, the set of sequences $\{\tilde{\mathbf{X}}_1, \tilde{\mathbf{X}}_2\}$ is found according to the minimax criterion. This process is summarized in Fig. 1.

Interestingly, when SS-CARI is used to reduce the PAPR over an orthogonal STBC (OSTBC) system, the process needs to be done run in the first symbol period, since $\mathbf{X}_i$ and $\pm\mathbf{X}_i^*$ have the same PAPR properties [9]. Additionally, when the SS-CARI technique is used, the number of possible permutations is $4M$ [9], and the number of side information bits is $S = 2 + \lfloor \log_2(M) \rfloor$, where $\lfloor x \rfloor$ denotes the smallest integer that does not exceed $x$.

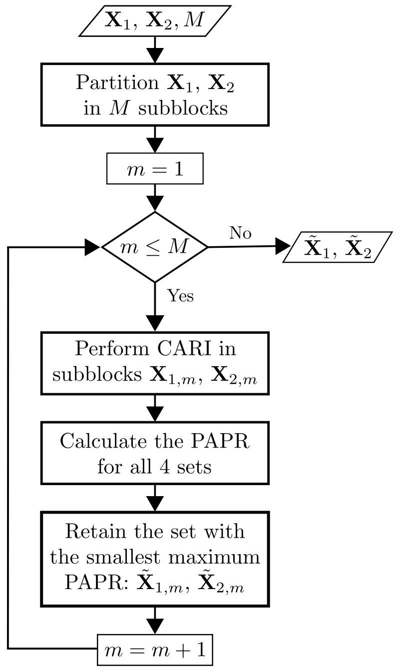


**FIGURE 1.** SS-CARI algorithm.

### D. MODIFIED $\mu$-LAW COMPANDING

$\mu$-law companding transform (uCT) is a nonlinear nonsymmetrical technique, in which the lower amplitude of the original signal is amplified while the peaks remain unchanged. It thus aims to improve the PAPR by increasing the mean power of the OFDM signal, without changing the signal peaks, unlike other techniques, such as clipping, where the peaks are clipped. The companding process requires compand of the OFDM signal at transmission and of the decompand at the receiver.

Let the peak ratio PR be the relation between the peak amplitude of companding ($A$) and the peak of the actual signal ($x_{\text{peak}}$). The modified $\mu$-law companding transform (MuCT) introduced by Vallavaraj *et al.* [8], performs the companding according to the law:

$$y = \text{sgn}(x)\frac{A}{\ln(1+\mu)} \ln\left(1 + \frac{\mu}{A}|x|\right), \tag{5}$$

where $A = \text{PR} \cdot x_{\text{peak}}$, $\mu > 0$, $|x|$ represents the instantaneous amplitude of the input signal, and $\text{sgn}(\cdot)$ is the sign function. The decompander is the inverse of (5).

Thus, selecting $\text{PR} = 1$ results in a classic $\mu$-law companding process. However, with $\text{PR} = 2$, the lower amplitude signals are much higher than in $\mu$-law companding. Additionally, the peaks are affected by a gain greater than unity, which can positively impact the performance of the system [6]. Thus, the MuCT parameters $\mu$ and PR need to be optimized for a good trade-off between PAPR and BER. In order to optimize the BER versus the PAPR for the new PAPR reduction technique proposed, we use the transform

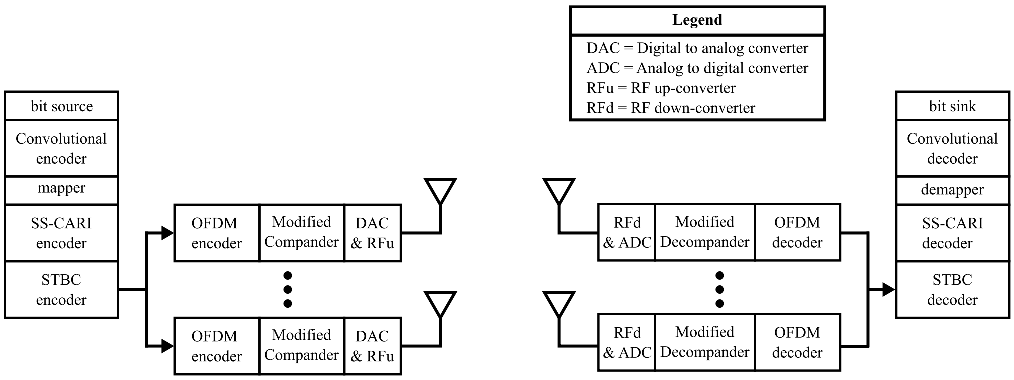


**FIGURE 2. Block diagram of the CSC technique.**

gain ($G$) concept, defined by [5] as:

$$G = \frac{\text{PAPR}_{\text{w/o}}}{\text{PAPR}_{\text{w}}}, \tag{6}$$

where $\text{PAPR}_{\text{w/o}}$ represents the original signal without applying a PAPR reduction scheme, and $\text{PAPR}_{\text{w}}$ is the PAPR of the signal when a PAPR reduction technique is used.

In this paper, the performance of the companded signal is compared to that of an uncompanded signal of equal power, based on the analyses Mattsson *et al.* [17] and Wang *et al.* [18]. It should be recalled that companding the OFDM signal effectively increases its signal strength [7]. Therefore, we include a normalization constant $K$ such that $E_s = E_{s_c}$ (the symbol energy of the uncompanded signal is equal to the symbol energy of the companded signal), and the companding equation at the transmitter is redefined as [18]:

$$y = K \cdot \text{sgn}(x) \frac{A}{\ln(1+\mu)} \ln\left(1 + \frac{\mu}{A}|x|\right), \tag{7}$$

where $K$ is given by [17]

$$K \approx \frac{\ln(1+\mu)}{\mu}. \tag{8}$$

At the receiver, to reverse the normalization operation, the signal is multiplied by $1/K$. In the case of MuCT, the normalization constant is redefined as:

$$K \approx \kappa \cdot \frac{\ln(1+\mu)}{\mu}, \tag{9}$$

where $\kappa$ is a constant that is a function of $\mu$ and PR, and we find it by simulation.

## III. PROPOSED HYBRID PAPR REDUCTION TECHNIQUE

A hybrid PAPR reduction technique based on convolutional codes, SS-CARI, and modified companding, identified here for convenience as CSC, is presented in Fig. 2. The bit source is processed by a convolutional encoder and a PSK or QAM is used for symbol mapping. Next, the SS-CARI defined in Section II-C is applied. In the original version of SS-CARI [9], side information bits with the set of sequences selected needs to be transmitted to the receiver. The STBC encoder is applied, and at each transmit antenna, the conventional OFDM modulator is employed to generate the OFDM symbol; the input signal is serial-to-parallel (S/P) converted, followed by an inverse fast Fourier transform (IFFT). Each OFDM symbol is parallel-to-serial (P/S) converted and a cyclic prefix (CP) of length $N_{\text{cp}}$ is added. Then, the modified companding, described in Section II-D, is applied, and the output is processed by the digital-to-analog converter (DAC), and by the RF up-converter as a final step, before the transmission.

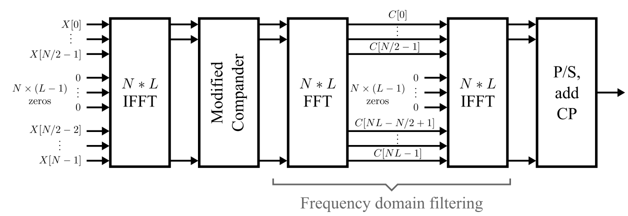


**FIGURE 3. Frequency domain filtering based on [19].**

One limitation of using companding for PAPR reduction is that it produces spectral splatter, as reported in [8]. Therefore, one solution is to use a filter to reduce the out-of-band radiation. In this work, a frequency domain filtering (FDF) [19] is implemented, as can be seen in Fig. 3, where after the signal is companded on the modified companding block, it is transformed back into a discrete frequency domain by the $N \times L$ FFT block. The out-of-band components of the companded signal, represented by $C_{N/2+1}, \cdots, C_{NL-N/2}$ are replaced by zeros before the second $N \times L$ IFFT, while the in-band components $C_0, \cdots, C_{N/2-1}$ and $C_{NL-N/2+1}, \cdots, C_{NL-1}$ do not change. After the second IFFT block, the signal is serial-to-parallel (P/S) converted, and the cyclic prefix (CP) is added.

However, the use of filtering in the system before the companding block results in "peak re-growing", which considerably increases the PAPR once again. So, we complement the PAPR reduction technique design with an iterative companding and filtering process, as can be seen in Fig. 4. This guarantees an optimal PAPR reduction, and controls the spectral splatter. In Fig. 4, $m$ represents the number of iterations the process is repeated.

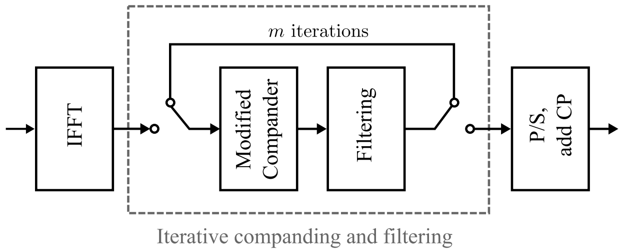


**FIGURE 4.** Iterative companding and filtering.

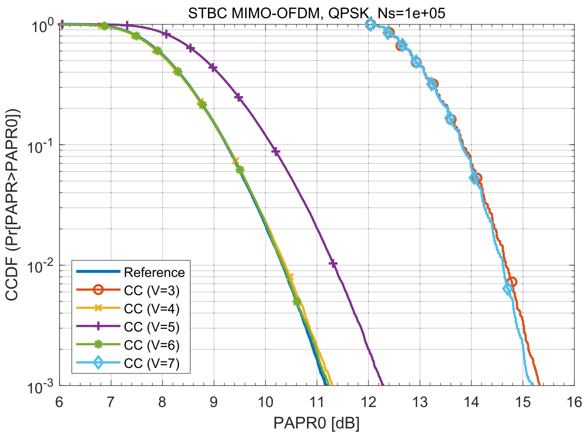


**FIGURE 5.** Comparison of CCDF in MIMO-OFDM system for different maximum free distance convolutional codes with $R = 1/4$. The reference is the STBC MIMO-OFDM system without coding.

**TABLE 1.** Rate 1/4 maximum free distance codes [20].

| Constraint Length ($V$) | Generators in Octal | | | | $d_{\text{free}}$ |
|---|---|---|---|---|---|
| 3 | 5 | 7 | 7 | 7 | 10 |
| 4 | 13 | 15 | 15 | 17 | 13 |
| 5 | 25 | 27 | 33 | 37 | 16 |
| 6 | 53 | 67 | 71 | 75 | 18 |
| 7 | 135 | 135 | 147 | 163 | 20 |

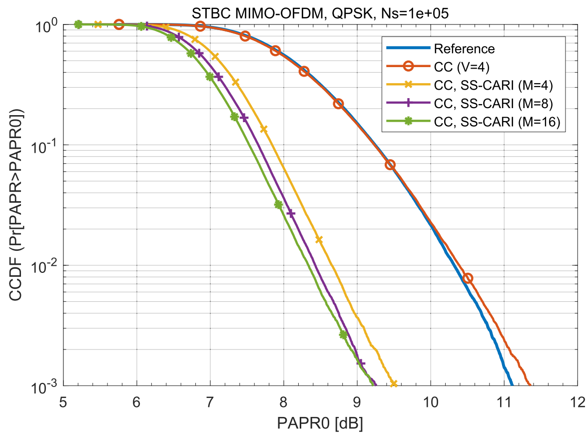


**FIGURE 6.** Comparison of CCDF in MIMO-OFDM system with SS-CARI technique with different numbers of subblocks. The reference is the STBC MIMO-OFDM system without coding.

In summary, we have presented a hybrid PAPR reduction technique for STBC MIMO-OFDM system based on convolutional code, SS-CARI, and an iterative modified companding and filtering.

## IV. PERFORMANCE OF HYBRID PAPR REDUCTION TECHNIQUE

We now present simulation results for a 128 subcarrier OFDM system with quadrature phase-shift keying (QPSK) modulation, 25% guard interval, and oversampling factor, $L = 4$, performed by padding zeros to the baseband modulated signals. An Alamouti space time code is used with 2 transmit antennas and 2 receiver antennas over a Rayleigh channel with Zero Forcing (ZF) equalization. In each case, the algorithm is executed $N_s = 10^5$ times.

The first experiment analyzes the CCDF of PAPR by including a convolutional code (see Fig. 5). For this, we take as an example a code rate equal to 1/4. The signal reference, in the figure, is the STBC MIMO-OFDM system without coding, and the polynomials used for each value of the constraint length ($V$) and its free distance are presented in Table 1. It is evident that the selection of the CC can considerably affect the PAPR of the system. For instance, for CCDF $= 10^{-3}$, with $V = 3$ and $V = 7$ the PAPR increase by 4 dB with respect to the reference. For $V = 5$, the PAPR increases by 1 dB. However, with $V = 4$ and $V = 6$, the PAPR is similar to the reference. Based on this, a CC with $R = 1/4$, $V = 4$, and polynomial [13, 15, 15, 17] is chosen for the following experiments.

In Fig. 6 the reduction of the PAPR obtained by the SS-CARI technique with different numbers of subblocks ($M = 4$, 8 and 16) is evaluated. It can be seen that a reduction of 1.6 dB of the PAPR is achieved, compared to the reference, with a $M = 4$, and a reduction of 1.9 dB with $M = 8$ with slight difference between the cases of $M = 8$ and $M = 16$. Therefore, as the number of subblocks increases, the complexity of the system and the size of the SI increase; however, the PAPR reduction increases at a lower rate each time $M$ increases.

Next, we evaluate the modified companding technique alone, i.e., without the influence of CC or the SS-CARI scheme. To this end, the BER for SNR $=$ 12 dB versus the gain $G$ in dBs for CCDF $= 10^{-3}$ is plotted for different $\mu$ (1, 5, 10, 20, 50, 100, and 255) and PR (1, 1.2, 1.4, 2, and 4) values (see Fig. 7). Some conclusions can be drawn. First, the best BER performance of the system is obtained in the case of small values of the $\mu$ parameter. In this region, the use of different values of PR produce only minor differences. However, by increasing the $\mu$ value, a significant gain in PAPR can be obtained, and we can see that when the PR increase, the BER decrees less, as compared to a classic companding method. It is also evident that for PR $= 1$, the highest possible gain of PAPR is obtained, but that the BER degradation is the largest as well.

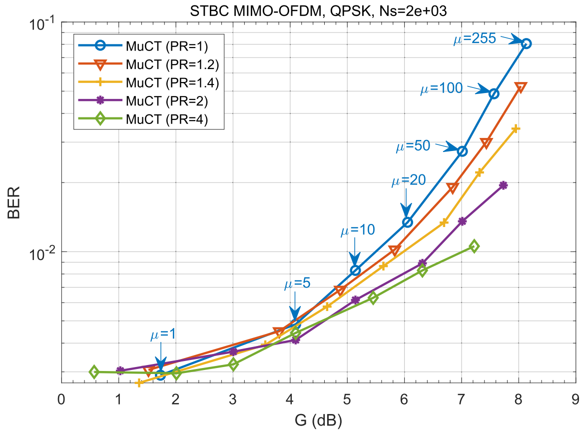


**FIGURE 7.** BER vs $G$ with modified companding transforms (QPSK, $L = 4$, $N = 128$, CCDF $= 10^{-3}$, and SNR $= 12$ dB).

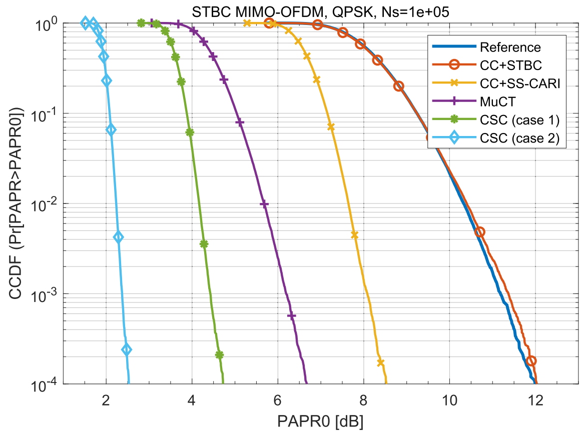


**FIGURE 8.** CCDF of PAPR curves for CSC hybrid PAPR reduction technique in STBC MIMO-OFDM system with $R = 1/4$, $V = 4$, $M = 16$, and two versions: $\mu = 10$, PR $= 1.2$ and $\kappa = 2.7$ (case 1), and $\mu = 255$, PR $= 2$ and $\kappa = 15.7$ (case 2). The reference is the STBC MIMO-OFDM system without coding.

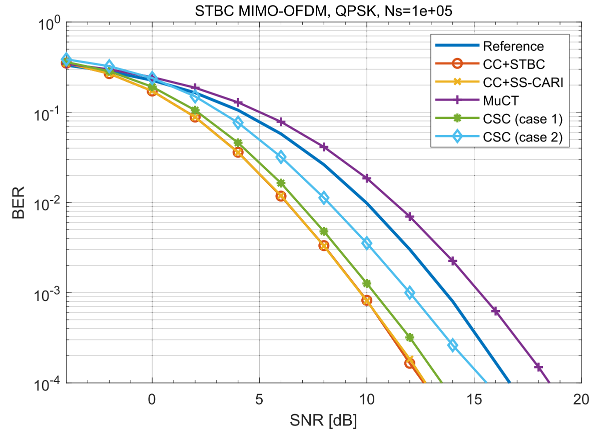


**FIGURE 9.** BER performance for CSC hybrid PAPR reduction technique in STBC MIMO-OFDM system with $R = 1/4$, $V = 4$, $M = 16$, and two versions: $\mu = 10$, PR $= 1.2$ and $\kappa = 2.7$ (case 1), and $\mu = 255$, PR $= 2$ and $\kappa = 15.7$ (case 2). The reference is the STBC MIMO-OFDM system without coding.

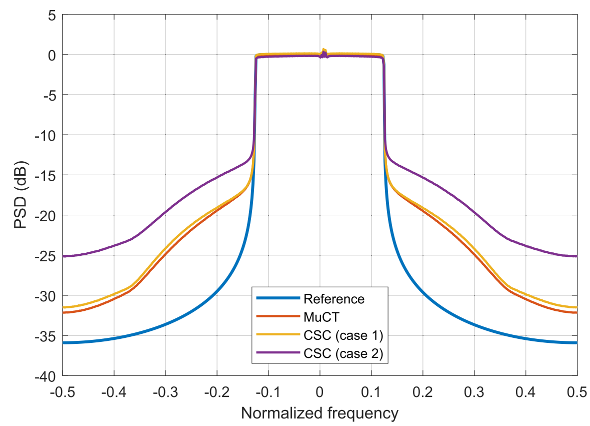


**FIGURE 10.** PSD curves for CSC hybrid PAPR reduction technique in STBC MIMO-OFDM system with $R = 1/4$, $V = 4$, $M = 16$, and two versions: $\mu = 10$, PR $= 1.2$ and $\kappa = 2.7$ (case 1), and $\mu = 255$, PR $= 2$ and $\kappa = 15.7$ (case 2). The reference is the STBC MIMO-OFDM system without coding.

Based on the previous analysis, we evaluate the hybrid CSC technique that combines CC with $R = 1/4$ and $V = 4$, SS-CARI method with $M = 16$ and MuCT with two versions: $\mu = 10$, PR $= 1.2$ and $\kappa = 2.7$ (case 1), and $\mu = 255$, PR $= 2$ and $\kappa = 15.7$ (case 2). The CCDF of PAPR, the BER performance and the power spectral density (PSD) for a CSC scheme are presented in Fig. 8, Fig. 9, and Fig. 10, respectively. As shown in Fig. 8 the use of the SS-CARI scheme allows to obtain a PAPR reduction of 2.5 dB (CCDF $= 10^{-4}$), and with the CSC scheme it is possible to achieve a reduction of 7.3 dB (CCDF $= 10^{-4}$) for case 1, and of 9.5 dB for case 2. As a second reference, the case where only the MuCT is used for $\mu = 10$ and PR $= 1.2$ is also plotted, where a reduction of 5.5 dB is presented.

The BER performance for a CSC technique is plotted in Fig. 9, where we can see a gain of 4 dB (BER $= 10^{-3}$) when the CC is added. In addition, degradation due to the inclusion of MuCT is clear; however, it is 0.5 dB for case 1, but 2 dB in case 2, when the BER is compared to the CC+STBC curve with BER $= 10^{-3}$. Nevertheless, we have a gain when it is compared to the basic reference without coding. It can also be seen that the case of MuCT alone has results in a worse performance.

The results of PSD versus the normalized frequency for the CSC technique are presented in Fig. 10. From the graph we can see that due to the MuCT there is out-of-band radiation that is similar to the CSC (case 1), and an increase for the CSC (case 2). The spectral splatter is evident as a limitation when using the MuCT. Because of this, a frequency domain filtering is added to the system.

As shown in Fig. 11, a PSD similar to the reference is obtained by the effect of using the filter in the system (see CSC-Filter (m = 1)). However, a problem when using a filter is that it can lead to peak regrowing, which can be seen in the Fig 10, where we compare the CCDF for the unfiltered signal (CSC) versus that for the filtered signal (CSC + Filter (m = 1)). We see here that there is an increase in PAPR of 1.8 dB. To tackle this drawback,

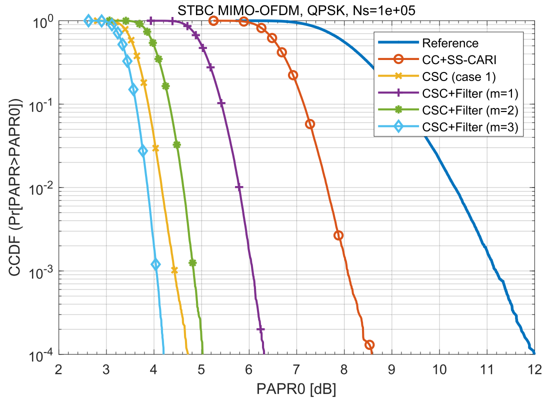


**FIGURE 11.** CCDF of PAPR curves for CSC hybrid PAPR reduction technique with iterative MuCT and filter in STBC MIMO-OFDM system with $R = 1/4$, $V = 4$, $M = 16$, $\mu = 10$, PR $= 1.2$, and $\kappa = 2.7$ (case 1). The reference is the STBC MIMO-OFDM system without coding.

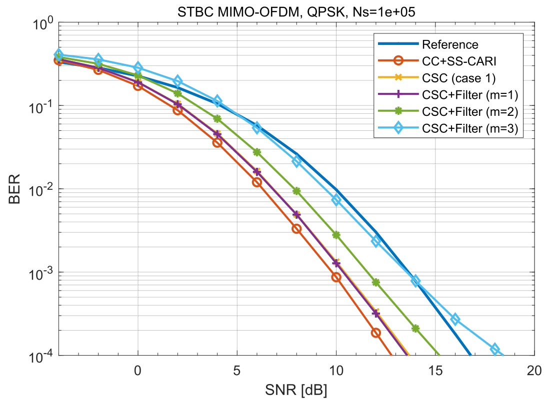


**FIGURE 12.** BER performance for CSC hybrid PAPR reduction technique with iterative MuCT and filter in STBC MIMO-OFDM system with $R = 1/4$, $V = 4$, $M = 16$, $\mu = 10$, PR $= 1.2$, and $\kappa = 2.7$ (case 1). The reference is the STBC MIMO-OFDM system without coding.

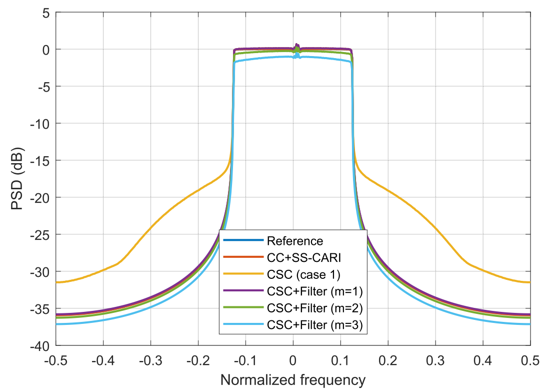


**FIGURE 13.** PSD curves for CSC hybrid PAPR reduction technique with iterative MuCT and filter in STBC MIMO-OFDM system with $R = 1/4$, $V = 4$, $M = 16$, $\mu = 10$, PR $= 1.2$, and $\kappa = 2.7$ (case 1). The reference is the STBC MIMO-OFDM system without coding.

the iterative system represented in Fig. 4 is implemented. As a result, the performance of the final proposals of the CSC technique with iterative MuCT and filtering are presented in Fig. 11, Fig. 12 and Fig. 13.

Fig. 11 presents the unfiltered signal, the filtered signal without iteration ($m = 1$), the filtered signal with 2 iterations, and the filtered signal with 3 iteration for a $\mu = 1.2$ and PR $= 1.2$. The case with three iterations produces the largest PAPR reduction of 7 dB. However, with two iterations the reduction is 6 dB. For BER performance, we can see that the use of filters and iterations degrades the signal; for example, in the case of $m = 3$, we have a slightly worse value than that of the reference for low SNR, and a slightly better value for high SNR. However, for $m = 2$, the BER is improved in relation to the reference by about 2.5 dBs. Finally, Fig. 13 presents the PSD for the CSC iterative filter and MuCT technique. For the cases of $m = 1$ and $m = 2$, a curve similar to the reference is obtained. In the case of $m = 3$, we can see a slight in-band radiation.

## V. CONCLUSION

STBC MIMO-OFDM is a key method in current wireless communication systems that can improve performance, increase capacity, provide spatial diversity, and achieve ISI mitigation. However, the high peak in the OFDM envelope can impact the non-linear components in the transmitter, and the PAPR increases when the number of transmit antennas increases.

The literature presents a number of techniques for PAPR reduction in OFDM, and more recently, methods have been proposed for MIMO-OFDM systems. However, these techniques may be limited by several factors, such as an increase in complexity, a requirement for side information, BER degradation, in-band or out-of-band radiation, increase in power requirements at the transmitter or limited PAPR reduction capabilities. In this context, a hybrid technique can therefore provide flexibility allowing an optimization of the net gain.

In this work, we introduced a new hybrid PAPR reduction technique based on convolutional codes and SS-CARI, which takes advantage of the MIMO structure, and a modified companding method. This method, provides a substantial reduction in PAPR while maintaining an adequate performance in comparison with the STBC MIMO-OFDM basic system, and controls out-of-band radiation produced by the companding of the transmitter through the use of iterative companding and filtering. The technique can be optimized by customizing several parameters such as the code rate, the constraint length of CC, the number of subblocks for the SS-CARI process, the $\mu$ and PR companding parameters, and the number of companding and filtering iterations, which guarantees flexibility for the method.

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