Hybrid PAPR Reduction Schemes for MIMO-OFDM System

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Abstract. The emergence of both multiple-input-multiple-output (MIMO) systems and Orthogonal-Frequency-Division-Multiplexing (OFDM) is crucial to the recent rapid development of wireless communication, especially cellular communication. However, this MIMO-OFDM system inherits a significant disadvantage of using OFDM: the high peak-to-average-power ratio (PAPR). Thus, this paper proposes a hybrid PAPR reduction technique that combines three techniques: convolutional code, successive suboptimal cross-antenna rotation, inversion (SS-CARI), and modified companding. Results from the study show that a constraint length of four with a code rate of 1/4 is the value of parameters that maintains PAPR for the convolutional coding techniques, and 16 is the number of subblocks with the best PAPR performance for the SS-CARI technique. Finally, the parameter value that has the best PAPR performance for the μ-law companding technique is 255 for the companding parameter, one for the peak ratio (PR). Compared to the system without PAPR reduction schemes, this hybrid PAPR reduction scheme can reduce the PAPR by around 65.22% at the Complementary Cumulative Density Function (CCDF) of $10^{-3.}$

Keywords: Multiple-input-multiple-output (MIMO) · Orthogonal-Frequency-Division-Multiplexing (OFDM) · peak-to-average-power ratio (PAPR) · Complementary Cumulative Density Function (CCDF)

1 Introduction

The late twentieth century proved to be a new turning point for the field of communication. This is because the wireless communication system needs both performance and capacity in today's world. Multiple-input multiple-output (MIMO) systems are widely used because of these two needs. There will be multiple antennas at the transmitter and receiver to implement MIMO in practice. When MIMO is used with a flat fading Rayleigh fading channel or narrowband channel, it can provide better system capacity than a single-input, single-output (SISO) system. The benefit of using MIMO is even more appealing when orthogonal space-time block coding (STBC) is used because it provides space diversity via transmitting redundant copies of the original data from the

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transmitter to the receiver via an independent fading channel [1]. The significance of STBC and MIMO in developing wireless communication is certainly proved when they are adopted in the IEEE 802.11n standard [2]. However, the use of MIMO is only limited to narrowband channels because the application of this kind of system to a wideband channel will lead to an unwanted phenomenon called inter-symbol interference (ISI) [3]. ISI happens when a signal symbol interferes with the following symbol, distorting the signal. This interference happened because a higher data rate in a single carrier system will cause the symbol duration to be shortened.

Many types of research are being conducted to find a way to overcome the problem, and Orthogonal Frequency Division Multiplexing (OFDM) is the solution. OFDM is an example of Multi-carrier Modulation (MCM). It consists of parallel subcarriers that overlap without causing interference [4]. Interference does not happen because the subcarriers are orthogonal to each other. As a result, OFDM has deemed a way to utilize the bandwidth available fully. Therefore, the MIMO-OFDM system has been adopted. As the name suggests, the STBC MIMO-OFDM system is formed when MIMO and OFDM are combined with STBC. Thus, it can increase capacity, reduce ISI, and provide reliable reception. The simulation of hybrid PAPR mitigation using RGPW-PTS and dSLM in MIMO-OFDM showed hybrid approach is superior to PTS and original MIMO-OFDM [5]. Moreover, an effective hybrid partial transmits sequence (EHPTS) that reduces peak-to-average power ratio (PAPR) in RHS-MIMO-OFDM (OFDM) is studied [6], and the simulation findings suggest that EHPTS reduces PAPR effects on OFDM compared to PTS.

2 Basic Structure of the MIMO System

The technology of MIMO wireless communication technology has moved on from just being a mere academic concept to a significant component in real-world applications, particularly the communication system. It has been a part of the standard for many available wireless devices. The knowledge which facilitates the emergence of MIMO is a concept called antenna diversity. Antenna diversity is a concept that started to be known back in the 1920s [7]. Antenna diversity can be done in several ways, but spatial diversity is the most famous. There are four types of communication transmission models, as illustrated in Fig. 1 [8].

When the number of transmitters and receivers is one, it is called a single-input-single-output (SISO) system. When the number of transmitters is one, but the receiver

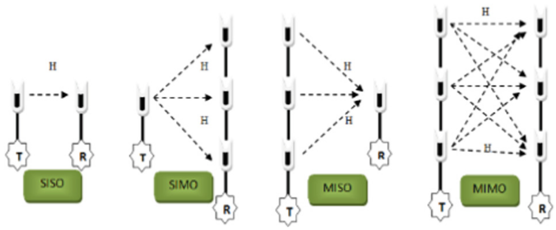

Fig. 1. Illustration of Several Communication Transmission Models

is more than one, it is called a single-input-multiple-output (SIMO) system. If the transmitters are more than one, but the receiver is only one, it is called multiple-inputs-single-output (MISO). If both transmitter and receiver are only one, it is called multiple-inputs-multiple-outputs (MIMO). The rationale for having MIMO as the most reliable is simply because of the spatial diversity that it can provide. Spatial diversity is a diversity technique to improve performance over a fading channel.

3 A Review of the MSP Scheme

There are two ways in which this technique can work. Firstly, the multiple signaling techniques will produce multiple ways in which the OFDM can be arranged. Then, the signal with the minimum PAPR will be transmitted. This technique is beneficial for systems with multiple antennas.

As for the probabilistic technique, sometimes it is also regarded as a signal scrambling technique. This kind of approach operates by altering multiple parameters of the OFDM signal. The alteration should optimize the parameters to reduce PAPR [9]. When this technique is used in a MIMO-OFDM system, it will significantly reduce the PAPR of the signal without needing to distort the signal. However, this technique will introduce side information which causes data rate loss [10]. For SS-CARI, the side information bit equals $2 + \log(M)$. . The receiver will need this information to retrieve back the choice made. Some of the most known techniques under this scheme are the Cross-Antenna Rotation and Inversion (CARI), Selected Mapping (SLM), and Partial Transmit Sequence (PTS).

3.1 Cross-Antenna Rotation and Inversion (CARI) Scheme

There are two CARI schemes: SS-CARI Scheme and Random Suboptimal-Cross-Antenna Rotation and Inversion (RS-CARI) scheme [11]. Tan *et al.* [11] claim that these two schemes offer a good compromise between performance and complexity. Their previous works have mentioned that this scheme can reduce the possibility of transmitting sequences with high PAPR. As the name suggests, this scheme involves rotation and inversion processes. The process happens in each subblock of the OFDM signal after it is divided equally into a certain number of subblocks. One of the advantages of this scheme is that it does not need to be applied to each transmit antenna in a MIMO-OFDM system. Hence, it can be said to utilize the extra degrees of freedom that multiple antennas give.

However, these schemes need extra side information, which will cause a negative impact on BER performance if it is not retained at the receiver. Thus, the 'blind' version of the CARI scheme is proposed [12]. They called the scheme "blind cross-antenna successive shifting rotation and inversion (Blind-CASSRI)". This scheme can operate without the need for side information (SI). They have run a simulation assuming the SS-CARI has ideal SI against the Blind-CASSRI. The Blind-CASSRI outperformed the SS-CARI scheme when the number of sub-blocks was equal to eight and 16.

Table 1. MSP scheme and Their Respective Basic Working Principle.

MSP scheme	Basic Working Principle
SLM (Choudhury, 2013)	1. Generate different versions of the OFDM symbols. 2. Choose a signal with the lowest PAPR.
PTS (Raqeeb, 2019)	1. Divide the original OFDM signal into a certain number of sub-blocks. 2. Add sub-blocks with the rotated phase. By doing this, numbers of signals are generated. 3. Choose a signal with the lowest PAPR.

Table 2. Summary of the Pros and Cons of Each PAPR Reduction Techniques

Technique	Advantages	Disadvantages
Coding Technique (Rahmatallah & Mohan, 2013)	Signals with high PAPR will not be sent	Very Complex
(MSP) Scheme (Sandoval et al., 2017)	Will not distort the signal	Loss in data rate Requires side information
Signal Distortion Technique (Sandoval et al., 2017)	Simple Low complexity	Introduce extra noise to the signal

3.2 SLM and PTS Scheme

For simplicity, the working principle of the SLM and PTS scheme is summarised in Table 1.

4 Review of Signal Distortion Technique

Three techniques can be regarded as signal distortion techniques: signal clipping, peak windowing, and companding. Each of these techniques has different operations from the others, but the idea between them is expected, which is to distort the signal.

4.1 Companding

Lastly, there is a companding technique, which is a method proposed in the past based on the μ-law [3]. Reducing the PAPR is also known as the compressing and expanding technique. The input signal is compressed to ensure that the signal so that the signal level is higher than the noise level during processing [13]. In other words, a signal with a smaller amplitude in the input is amplified, whereas the high peaks remain the same. The original input signal is obtained through attenuation.

The amplified version of the small OFDM signal is the key to reducing the PAPR. This is because the resulting signal will cause an increase in the system's average power and finally reduce the PAPR [14]. Other than the reduction of PAPR, the increase in the system's average power also causes most of the subcarriers to operate at maximum power, which has led to the increase in efficiency of the power amplifier [3]. In 2004, Vallaraj *et al.* modified the standard μ-law companding by introducing a new parameter called peak ratio (PR) [14]. He said PR could be adjusted to produce an unbiased amplification, where signals with smaller amplitudes will be amplified more than those with a bigger amplitude. This kind of amplification can be seen as non-uniform because the lower amplitude signal gets amplified more. Hence, one can make an OFDM system with improved BER performance and reduced PAPR if PR is optimized.

5 Hybrid PAPR Reduction Techniques

Generally, each of the PAPR reduction methods has its strengths and drawbacks. Table 2 is an effort to summarize them. Therefore, a hybrid technique is introduced. One or two schemes to produce a new PAPR reduction scheme will improve the targeted performance parameter by optimizing each technique's parameters. A combination of the PAPR technique is an effort to cover each technique's weaknesses. In 2013, Rahmatallah and Mohan agreed that all the PAPR reduction techniques are not perfect [9]. In 2014, Gangat and Shaikh reviewed multiple studies from the past [15]. They have concluded that the hybrid PAPR reduction technique does give positive results compared to the traditional standalone method.

6 STBC MIMO-OFDM with Proposed PAPR Reduction Techniques

This subsection will discuss the system model, PAPR properties of an OFDM signal, then two metrics to measure system performance.

6.1 System Model

The basis of the STBC MIMO-OFDM system is self-explanatory. It consists of MIMO, STBC, and OFDM. In this explanation, the system assumed to have N_t number of transmitters, N_r the number of receivers, N number of subcarriers. Since the signal is in the frequency domain. If k is the frequency index, N is the length of IFFT points from i th transmitter. Thus, this signal can be represented as $\{X_i[k]\}_{k=0}^{N-1}$. After the signal passes through the IFFT block, the OFDM signal is converted from frequency domain to time domain, given by Eq. (1).

$$\mathrm{x_i[n]} = \frac{1}{\sqrt{\mathrm{N}}}\sum_{\mathrm{k=0}}^{\mathrm{N-1}} \mathrm{X_i[k]e^{\frac{j2\pi kn}{LN}}} \tag{1}$$

Where n = 0, 1, …, LN-1, $\mathrm{j} = \sqrt{-1}$ n represents the time index in discrete form, j is an imaginary unit, and L is an oversampling factor. This discrete baseband OFDM signal will have the same peaks as a continuous-time baseband signal. However, this statement

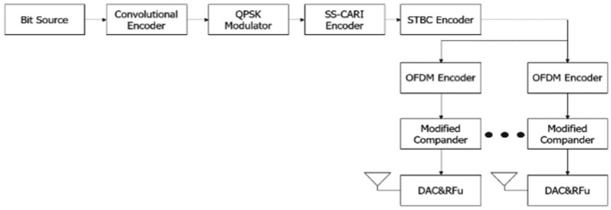

Fig. 2. Block Diagram of a MIMO-OFDM system with Proposed PAPR Reduction Techniques (Transmitter).

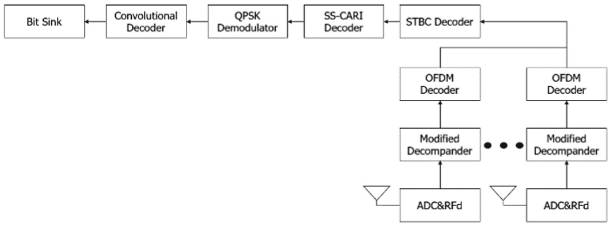

Fig. 3. Block Diagram of a MIMO-OFDM system with Proposed PAPR Reduction Techniques (Receiver).

is only valid when the oversampling factor, *L,* is greater or equal to four [12]. In the case when *L* is equal to one, this is known as the Nyquist rate sampling. Figure 2 and Fig. 3 show the block diagram of the transmitter and receiver of the MIMO-OFDM system with the hybrid PAPR reduction technique. The black three 'dots' represent an arbitrary distance.

6.1.1 PAPR Properties of an OFDM Signal

By definition, PAPR is the "ratio between maximum instantaneous power and its average power". Considering the PAPR is for *i* th transmitter, the PAPR is known as Eq. (2).

$$\mathrm{PAPR}(x_i[n]) \triangleq \frac{\max\left\{|x_i[n]|^2\right\}}{\left\{|x_i[n]|^2\right\}} \tag{2}$$

when each of the components is elaborated further, Eq. (3) is obtained as follows:

$$\mathrm{PAPR}(x_i[n]) \triangleq \frac{\max\limits_{0\le n\le N-1} |x_i[n]|^2}{\frac{1}{N}\sum\limits_{n=0}^{N-1} |x_i[n]|^2} \tag{3}$$

As for the MIMO-OFDM system, the PAPR is defined as the maximum PAPR out of the set of values calculated through all MIMO transmitters or paths [16]. It can be viewed as follow:

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

6.1.2 Metric of PAPR Performance

Metric is defined as the standard of measurement. As for the case of PAPR performance, the metric is known as the complementary cumulative distribution function (CCDF). CCDF is derived from the Cumulative Distribution Function (CDF). CCDF is mainly used for statistical hypothesis testing. Assuming the threshold value is $PAPR_0$, hence the CCDF for PAPR is given as follows:

$$\mathrm{CCDF} = \Pr\{\mathrm{PAPR} \geq \mathrm{PAPR}_0\} \tag{5}$$

6.1.3 Other Metric to Evaluate System Performance

Besides CCDF, the system is also evaluated using another metric, which is the BER. BER is the number of errors that occur in a number of transmitted bits. It is usually unitless because it is expressed as a ratio. BER is necessary to determine the system's quality in a communication system. It can be expressed as:

$$\mathrm{BER} = \frac{\mathrm{n_{errors}}}{\mathrm{n_{bits}}} \tag{6}$$

Where $\mathrm{n_{errors}}$ represent the total number of bit errors, and $\mathrm{n_{bits}}$ Represents the total number of received bits.

6.2 Incorporating PAPR Reduction Schemes into the STBC MIMO-OFDM System

The process of combining the PAPR reduction schemes with the STBC MIMO-OFDM system is done step by step, starting from convolutional coding, then SS-CARI, and lastly, the modified μ-law companding.

6.2.1 Coded STBC MIMO-OFDM

The first technique to be incorporated into the system is the convolutional technique. This technique involved the addition of a convolutional encoder at the transmitter part and the decoder at the receiver. The block diagram of the transmitter of an OFDM system is shown in Fig. 4 [17].

To build a coded STBC MIMO-OFDM system, another extra set of IFFT blocks and parallel-to-serial blocks are needed. The block diagram for the receiver side is the reverse of Fig. 4. But as a basic, it can be seen that the convolutional encoder will encode

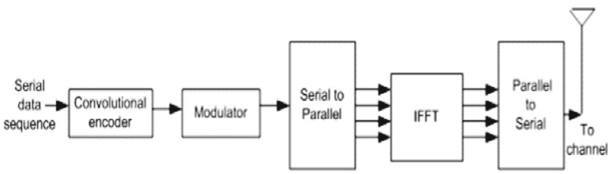

Fig. 4. Block Diagram of a Coded OFDM System (Transmitter).

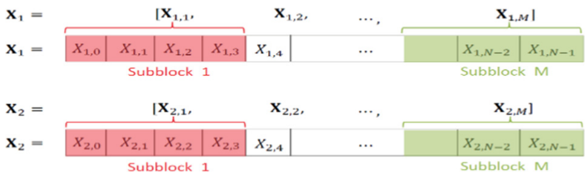

Fig. 5. Process of Partitioning Signal into M Number of Subblocks.

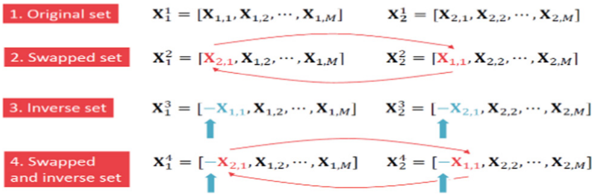

Fig. 6. Performing CARI on the Subblocks.

the information before it is modulated. Since convolutional coding needs to process the information on a bit-by-bit basis, thus, it needs memory. In this case, the memory used is a shift register.

6.2.2 Coded STBC MIMO-OFDM with SS-CARI Scheme

The SS-CARI description will consider the STBC MIMO-OFDM system with two transmitters and two receivers. To better illustrate the concept, Figs. 5 until Fig. 6 are provided [3]. Firstly, signal X_1 and X_2 are divided into M number of subblocks. These subblocks are said to have the same size. This process can be seen in Fig. 3.5.

After that, CARI operation is done on the subblocks. The operation resulted in four different sets of the signal: the original set swapped set, inverse set, and a swapped version of the inverse set. The process of CARI can be found in Fig. 6. Then, the PAPR of all four sets is calculated. The set which contains the smallest PAPR will be chosen.

This process is repeated until the operation is done across all subblocks. The summary of the SS-CARI algorithm is shown in Fig. 6 to enhance the understanding of the algorithm.

6.2.3 STBC MIMO-OFDM with μ-law Companding

The μ-law is companding which was initially used for speech. The idea was to amplify a specific region of the original signal. The region of the signal with a lower amplitude will be increased while the peak is kept the same. The formula for the original μ-law compression formula is as follows:

$$y = \mathrm{sgn}(x)\left(\frac{\ln(1+\mu|x|)}{\ln(1+\mu)}\right) \tag{7}$$

Where x is between −1 and 1, and sgn(x) is −1 for negative and 1 for positive numbers. |x| is the instantaneous amplitude of the signal. If the samples are quantized to eight bits, thus, μ is 255. However, a rule of thumb is that the μ must be greater than zero. At the receiver, the output is expanded back. Equation (7), an inverse of Eq. (6), is used.

$$d = \operatorname{sgn}(x)\left(\frac{(\mu + 1)^{|x|} - 1}{\mu}\right) \tag{8}$$

This technique was then modified and was introduced by Vallaraj *et al.* [17]. The difference between their version and the original version of the companding is the presence of the peak ratio. Vallaraj *et al.* define peak ratio as “the ratio between the peak amplitude of compressor with the peak of the actual signal”. By letting A equal the Peak Ratio times peak of signal x, the following equation is obtained:

$$y = \operatorname{sgn}(x)\frac{A}{\ln(1 + \mu)}\ln\left(1 + \frac{\mu}{A}|x|\right) \tag{9}$$

1) The inverse of Eq. (8) is again taken. Assuming sgn(x) = 1, and x is a positive number, the inverse process is demonstrated below:

$$y = \ln\left(1 + \frac{\mu}{A}|x|\right)^{\frac{A}{\ln(1+\mu)}} \tag{10}$$

2) Then, take the inverse natural logarithm on both sides:

$$e^{y} = e^{\ln\left(1+\frac{\mu}{A}x\right)^{\frac{A}{\ln(1+\mu)}}} \tag{11}$$

3) Multiply both sides by the inverse of $\frac{A}{ln(1+\mu)}$

$$\left[e^{y} = \ln\left(1 + \frac{\mu}{A}x\right)^{\frac{A}{\ln(1+\mu)}}\right]^{1\frac{\ln(1+\mu)}{A}} \tag{12}$$

4) Hence, it becomes

$$\left[e^{y*\frac{\ln(1+\mu)}{A}} = \ln\left(1 + \frac{\mu}{A}x\right)\right] \tag{13}$$

$$\left[e^{\frac{y}{A}}.e^{\ln(1+\mu)} = \left(1 + \frac{\mu}{A}x\right)\right] \tag{14}$$

5) After simplification and rearranging of the equation are done. Finally, the following decompanding equation is obtained:

$$x = \frac{A}{\mu}\left[(1 + \mu)e^{\frac{y}{A}} - 1\right] \tag{15}$$

When the PR is higher, lower amplitude signals can achieve higher amplitude when compared to the original μ-law companding.

7 Simulation Results and Discussion

In the simulation, two transmit antennas and two receive antennas are considered. The number of subcarriers used is 128. The guard interval is 25%, which means the length of the cyclic prefix is 32. The Modulation scheme used is Quadrature Phase-Shift Keying (QPSK), and the output is padded by zero with an oversampling factor of four. The range of signal-to-noise ratio (SNR) is from −5 dB to 40 dB. Table 3 shows the simulation parameters used.

The simulation results are presented starting from the size of IFFT to the CCDF plot of all PAPR reduction techniques. Lastly, there is a BER plot for MIMO-OFDM with a ZF equalizer.

7.1 Size of IFFT

It clearly shows that the theoretical value of the PAPR will increase when the number of IFFT points increases. The reason is that a higher number of IFFT points is taken due to a high number of subcarriers. However, with an increasing value of the number of subcarriers, the PAPR also increases. As mentioned in the previous chapter, the CCDF is the probability that the PAPR exceeds a given value. The theoretical expression for CCDF is given as:

$$\mathrm{CCDF} = 1 - \left(1 - \mathrm{e}^{-\mathrm{z}}\right)^{\mathrm{N}} \tag{16}$$

Where N is the number of subcarriers, and z is the threshold value [8].

As shown in Fig. 7, the least number of IFFT points have the best performance compared to the rest. At CCDF = 10^{-2}. The difference is around 1 dB between 64-IFFT points and 1024-points. In this paper, 512-IFFT points are chosen. The reason is that the

Table 3. Simulation Parameters and their Respective Descriptions.

Parameters	Descriptions
Number of Transmit Antennas	2
Number of Receive Antennas	2
Number of Subcarriers	128
Guard Interval	(25%) * 128 = 32
Number of OFDM symbols	1000
Type of Modulation Scheme	QPSK
Oversampling Factor, L	4
Type of Channel	Rayleigh Channel
Type of Channel Equalizer	Zero Forcing Equalizer
Starting SNR	−5 dB
End SNR	40 dB

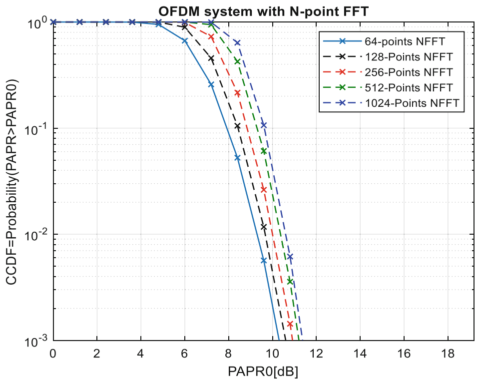

Fig. 7. CCDF of an OFDM System with Different Number of IFFT Points.

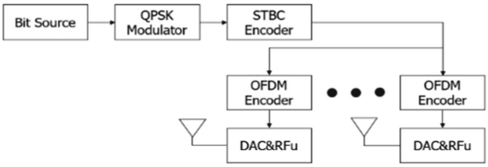

Fig. 8. Block Diagram of the MIMO-OFDM System without PAPR Reduction Schemes (Transmitter).

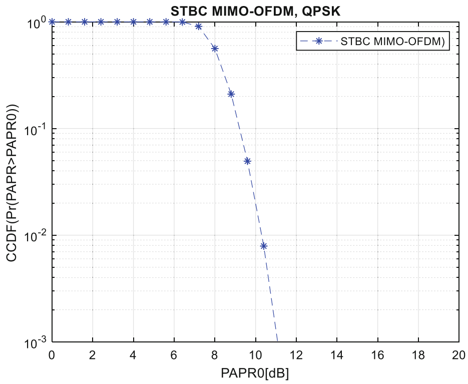

Fig. 9. CCDF of the STBC MIMO-OFDM System without any PAPR Reduction Scheme.

oversampling factor of four has extended the signal's length from 128 to 512. Figure 8 shows the block diagram for the block diagram of the MIMO-OFDM system without PAPR reduction schemes.

Referring to Fig. 9, the graph shows the CCDF of 10^{-3}. The PAPR is around 12 dB. This result tallies with the previous experiment, where 512 IFFT points have a PAPR around 12 dB at CCDF equal to 10^{-3}. The simulation has an iteration of 1000, and thus the CCDF is averaged over 1000 symbols, with 128 number of subcarriers for each symbol.

7.2 PAPR

The CCDF plot for all PAPR reduction techniques will be shown under this subsection, starting from convolutional coding to SS-CARI and finally the modified μ-law companding.

7.2.1 Convolutional Coding Technique

This section will present the results obtained from the convolutional coding (CC) technique with different combinations of parameters. Figure 10 shows the CCDF of the STBC MIMO-OFDM system when the convolutional coding technique is implemented. In this case, the constraint length is equal to 4. The constraint length of four means that the output pattern was yielded from the operation of the Boolean function on the current input bit and the last three input bits. CC refers to the convolutional coding.

Then, the coding technique is tried with the parameter of different rate, which is 1/4, 1/6, and 1/8, constraint length of four, and generator of [13 13 15 17], [17 17 13 13 15 15] and [17 17 13 13 13 15 15 17]. Thus, referring to Fig. 9, it can be observed that the performance of the coded STBC MIMO-OFDM system is worse by almost 2 dB at CCDF of 10^{-3} when compared to the uncoded system. Figure 10 shows that the coding technique works because a lower code rate can cause a worse PAPR performance. Thus, the code rate of 1/4 proved to have the best PAPR performance. Now, the constraint length will be determined. Table 4 shows the parameters of the convolutional coding technique that will be used in the next simulation.

Figure 11 shows the simulation results from using the different constraint lengths, as shown in Table 4 [15]. It can be observed that the best constraint length is 4. Hence, for this convolutional coding technique, the parameter's value with the best PAPR performance is the code rate of ¼ and constraint length of four.

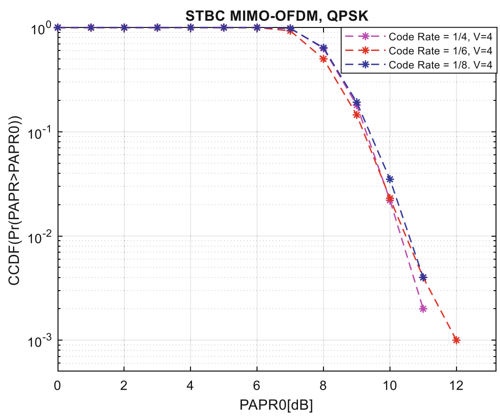

Fig. 10. CCDF of the STBC MIMO-OFDM System with Convolutional Coding (Constraint Length, V = 4, and Code Rate = 1/4).

Table 4. Parameters of Convolutional Coding Technique.

Constraint Length (V)	Generators in Octal Form		
3	5	3	5
4	13	4	13
5	25	5	25
6	53	6	53
7	135	7	135

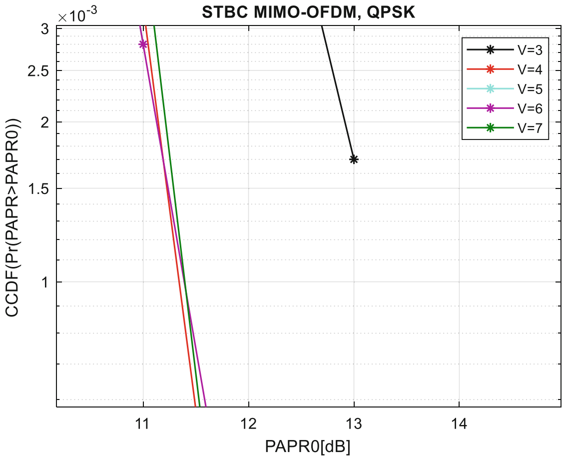

Fig. 11. CCDF of the STBC MIMO-OFDM System with Convolutional Coding (V = 3 until V = 7, Code Rate = 1/4).

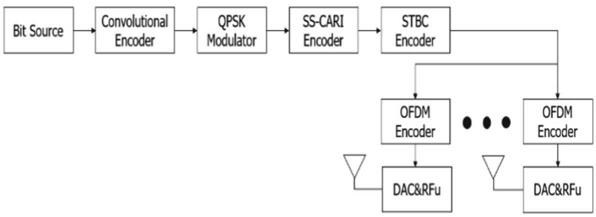

Fig. 12. Block Diagram of the MIMO-OFDM System with Convolutional Coding Technique and SS-CARI Technique (Transmitter).

7.2.2 SS-CARI Scheme

For this section, the number of subblocks for the SS-CARI scheme will be evaluated when equal to 8, 16, and 32. Figure 12 shows the block diagram for the system used for this subsection.

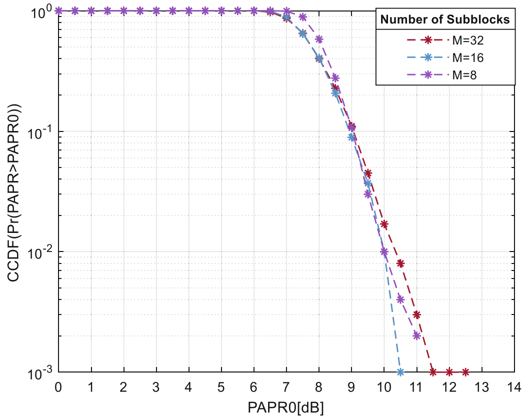

Fig. 13. CCDF of the STBC MIMO-OFDM System with CC and SS-CARI with M = 8, M = 16, and M = 32.

Figure 13 shows that the result with a number of subblocks of 16 has the best PAPR performance. Hence, it is chosen for the next experiment. Increasing the number of subblocks might be attractive because it has better PAPR performance. But it is important to note that a more significant number of subblocks means more complexity. However, it could be a bug in the coding because the higher number of subblocks should give better performance, but it seems like 16 number of subblocks is better when compared to 32 at CCDF of 10^{-3}.

7.2.3 Modified μ-law Companding

The accumulated parameters until now are constraint length of four, the code rate of ¼ from convolutional coding, and the number of subblocks, M of 16 from SS-CARI. Now, the parameters for the modified μ-law companding are being determined. There are two of them: the PR and the μ, companding parameter. Figure 15 shows the CCDF plot for the STBC MIMO-OFDM System with $\mu = 10$, $\mu = 255$ with different numbers of PR, which are 1.0, 1.2, and 1.4. Figure 15 shows that higher values of companding parameters generally have lower PAPR. However, the PAPR still degrades for the same companding parameter but higher peak ratio (Fig. 14).

For example, when μ is equal to 255 and PR is one, the PAPR level at CCDF is equal to 10^{-3} is 4, but it can be observed that the PAPR level is a bit higher when PR is equal to 1.2 and 1.4. It shows a direct relationship between the PR and also the PAPR level. The situation happened because higher PR will cause an increase in the signal power of the signal with greater signal amplitudes.

Thus, parameters with the best PAPR performance will be constraint length of four, the code rate of 1/4 for convolutional coding, 16 subblocks for SS-CARI, companding parameters of 255, and PR of one for the modified μ-law companding. Then, the CCDF of the STBC MIMO-OFDM system with hybrid PAPR reduction schemes and without the hybrid PAPR reduction schemes are plotted, as shown in Fig. 16. The drop of the PAPR is relatively high, whereas the system with the reduction shown has shown around

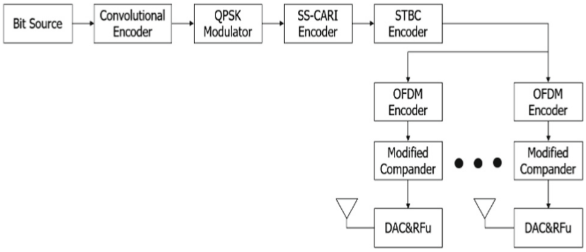

Fig. 14. Block Diagram of a MIMO-OFDM system with Hybrid PAPR Reduction Techniques (Transmitter).

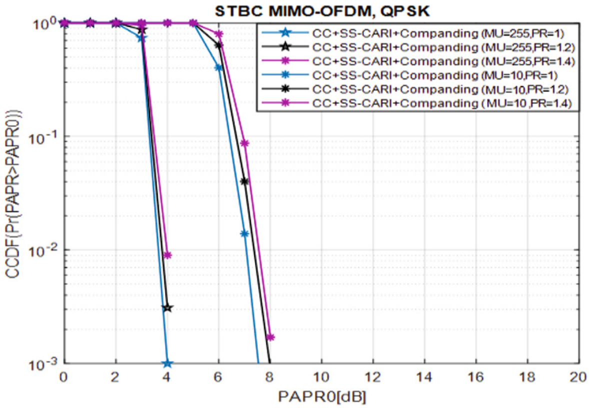

Fig. 15. CCDF of the STBC MIMO-OFDM System with CC, SS-CARI, and Modified Companding.

7 dB improvement (from 11 dB drop to 4 dB) at CCDF of 10^{-3}. This shows that the reduction technique is working and have reduced around 65.22% of the PAPR at CCDF of 10^{-3} when compared to the original plot.

Next, the results obtained from the experiment are compared with results from other literature. However, it isn't easy to find literature that uses the same simulation parameters. So, only one comparison is made. It is shown in Fig. 13. The only difference in a parameter value is the PR for the modified μ-law companding. The author chose to use a PR of two, but the PR used in this experiment is one. However, Fig. 17 shows that the result from this experiment is worse by almost 2 dB at CCDF of 10^{-3}. Thus, this shows that the PAPR reduction schemes from this project are less efficient when compared to the author's PAPR reduction schemes.

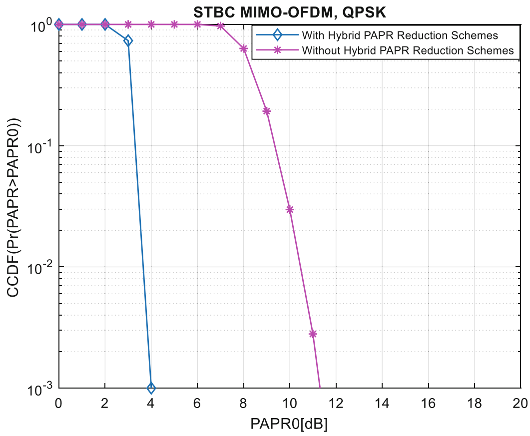

Fig. 16. CCDF of the STBC MIMO-OFDM System with Hybrid PAPR Reduction Schemes and without the Hybrid PAPR Reduction Schemes.

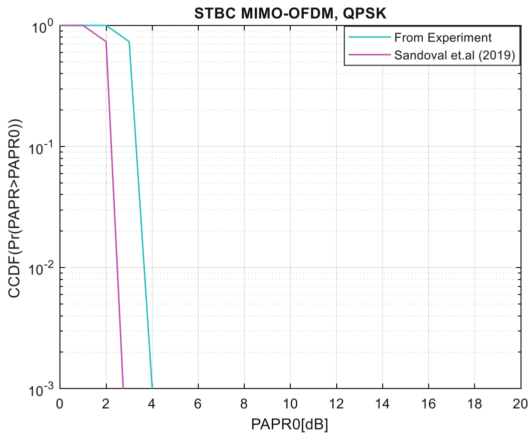

Fig. 17. CCDF from the Experiment and the Literature of Sandoval et al. (2019).

7.3 BER

As for the receiver part, a ZF equalizer is needed. Thus, a simulation to evaluate the BER of the ZF equalizer is done. The modulation technique used in this simulation is QPSK modulation. Referring to Fig. 18, the system with QPSK modulation shows a worse performance when compared to the BPSK modulation. This is true because a higher data rate means that more errors likely to happen. Thus, the equalizer can be used.

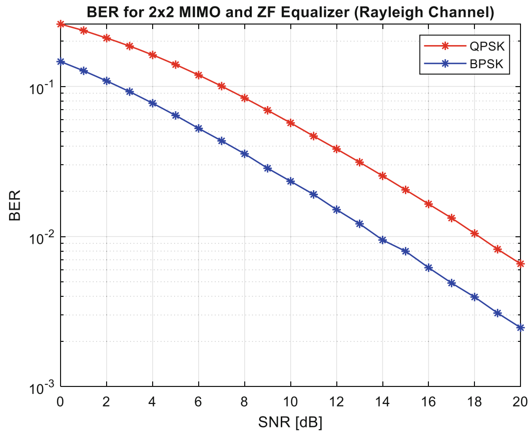

Fig. 18. BER Performance for 2x2 MIMO and ZF Equalizer (Rayleigh Channel).

8 Conclusion

An STBC MIMO-OFDM system with all proposed PAPR reduction techniques has been modeled. The constraint length of the chosen convolutional coding is 4, with a code rate of 1/4. As for the SS-CARI, the number of subblocks is 16. Lastly, the companding parameter is 255, whereas the PR is one for the modified companding. The results have shown that the hybrid PAPR reduction schemes have reduced the PAPR performance of the STBC MIMO-OFDM system at CCDF of 10^{-3} to around 65.22% of the original value. Thus, these techniques can solve the high PAPR in uplink communication. Uplink communication means that the transmitter side is for the users, whereas the receiver side is for the mobile base station. Since the introduction of 4G-LTE, the mobile phone is becoming an essential device for people in their daily life. People can enjoy fast internet when compared to the previous generation. However, 4G-LTE can only give such services because it uses OFDM, which means PAPR will be an issue. High PAPR will give rise to a problem such as the shorter battery life of a mobile phone. Since the PAPR is reduced, the efficiency issue due to the high PAPR is also solved. Hence, mobile phone users will enjoy better battery life and again in coverage.

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Authors' Contributions. The author suggests a hybrid PAPR reduction technique that combines three techniques: convolutional code, successive suboptimal cross-antenna rotation, inversion (SS-CARI), and modified companding.

References

1. Tarokh, V., Jafarkhani, H., & Calderbank, A. R. (1999). Space-time block codes from orthogonal designs. IEEE Transactions on Information Theory, (5), 1456–1467. https://doi.org/10.1109/18.771146

2. Kumar, R., & Saxena, R. (2014). Performance analysis of mimo-stbc systems with higher coding rate using adaptive semi-blind channel estimation scheme. The Scientific World Journal, 2014. https://doi.org/10.1155/2014/304901
3. Sandoval, F., Poitau, G., & Gagnon, F. (2019). On Optimizing the PAPR of OFDM Signals with Coding, Companding, and MIMO. IEEE Access, 7, 24132–24139. https://doi.org/10.1109/ACCESS.2019.2899965
4. Chore, Nitin M., and Nitiket N. Mhala. “A Hybrid Papr Reduction Technique For Mimo OFDM System With Qpsk.” https://www.researchgate.net/publication/335574090_A_Hybrid_Papr_Reduction_Technique_For_Mimo_OFDM_System_With_Qpsk
5. Shivaji, R., Nataraj, K.R., Mallikarjunaswamy, S. and Rekha, K.R., 2022. Implementation of an Effective Hybrid Partial Transmit Sequence Model for Peak to Average Power Ratio in MIMO OFDM System. In ICDSMLA 2020 (pp. 1343-1353). Springer, Singapore. https://link.springer.com/chapter/10.1007/978-981-16-3690-5_129
6. Gautam, P., Lohani, P., & Mishra, B. (2017). Peak-to-Average Power Ratio reduction in OFDM system using amplitude clipping. IEEE Region 10 Annual International Conference, Proceedings/TENCON, Singapore, Singapore, 1101–1104. https://doi.org/10.1109/TENCON.2016.7848179
7. Jensen, M. A. (2016). A history of MIMO wireless communications. 2016 IEEE Antennas and Propagation Society International Symposium, APSURSI 2016 - Proceedings, Fajardo, Puerto Rico, 681–682. https://doi.org/10.1109/APS.2016.7696049
8. Ghayoula, E., Bouallegue, A., Ghayoula, R., & Chouinard, J. Y. (2014). Capacity and Performance of MIMO systems for Wireless Communications. Journal of Engineering Science and Technology, Review, 7(3). https://www.researchgate.net/publication/280053298_Capacity_and_Performance_of_MIMO_systems_for_Wireless_Communications
9. Rahmatallah, Y., & Mohan, S. (2013). Peak-to-average power ratio reduction in ofdm systems: A survey and taxonomy. IEEE Communications Surveys and Tutorials, 15(4), 1567–1592. https://doi.org/10.1109/SURV.2013.021313.00164
10. Sandoval, F., Poitau, G., & Gagnon, F. (2017). Hybrid Peak-to-Average Power Ratio Reduction Techniques: Review and Performance Comparison. IEEE Access, 5, 27145–27161. https://doi.org/10.1109/ACCESS.2017.2775859
11. Tan, M., Latinović, Z., & Bar-Ness, Y. (2005). STBC MIMO-OFDM peak-to-average power ratio reduction by cross-antenna rotation and inversion. IEEE Communications Letters, 9(7), 592–594. https://doi.org/10.1109/LCOMM.2005.07017
12. Lee, K., Chang, I. J., Kim, J., & Lee, S. (2015). Combined channel estimation. ISOCC 2014 - International SoC Design Conference, Jeju, South Korea, 272–273. https://doi.org/10.1109/ISOCC.2014.7087644
13. Kumar, G. K., Reddy, S. L. K., & Kumar, K. S. (2015). PAPR Reduction of OFDM Using An Exponential Companding Technique. International Journal of Engineering and Computer Science, 4(04). http://103.53.42.157/index.php/ijecs/article/view/1712/1581
14. Vallavaraj, A., Stewart, B. G., & Harrison, D. K. (2010). An evaluation of modified μ-Law companding to reduce the PAPR of OFDM systems. AEU-International Journal of Electronics and Communications, 64(9), 844-857. https://doi.org/10.1016/j.aeue.2009.07.013
15. Gangat, M., & Shaikh, H. A Survey on MIMO OFDM PAPR Decreasing Methodologies. International Journal of Computer Applications, 975, 8887. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.742.1768&rep=rep1&type=pdf

16. Lee, K., Chang, I. J., Kim, J., & Lee, S. (2015). Combined channel estimation. ISOCC 2014 - International SoC Design Conference, Jeju, South Korea, 272–273. https://doi.org/10.1109/ISOCC.2014.7087644
17. Frontana, E., & Fair, I. (2007). Avoiding PAPR degradation in convolutional coded OFDM signals. IEEE Pacific RIM Conference on Communications, Computers, and Signal Processing - Proceedings, Victoria, BC, Canada, 312–315. https://doi.org/10.1109/PACRIM.2007.4313237.