

# SFBC with clipping and filtering as a transmit diversity technique in SC-FDMA

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Original scientific paper

The paper presents Space-Frequency Block Coding (SFBC) as a transmit diversity technique in Single Carrier Frequency Division Multiple Access (SC-FDMA). SC-FDMA is known as a low Peak-to-Average Power Ratio (PAPR) modulation technique. SFBC requires changing the order of the samples in the frequency domain, which results in increase of the PAPR. Because of that, additional clipping and filtering is proposed to be performed after SFBC to preserve low PAPR level and to avoid the out-of-band radiation. This affects the performance, but still provides significant advantage to the existing techniques, as is shown using simulations

**Key words:** SC-FDMA, SFBC, Clipping and filtering, Transmit diversity, PAPR

**Prostorno-frekvencijsko blok kodiranje sa odsjecanjem i filtriranjem kao tehnika predajni diverziti u SC-FDMA.** Ovaj papir predstavlja prostorno-vremensko blok kodiranje (SFBC) kao tehniku predajnog diverzitija u Single Carrier Frequency Division Multiple Access (SC-FDMA) sustavima. SC-FDMA je poznat kao modulijska tehnika sa niskim omjerom vršne i srednje snage (PAPR). SFBC zahtjeva izmjenu redosljeda uzoraka u frekvencijskoj domeni, što rezultira povećanjem PAPR-a. Zbog toga, dodatno odsjecanje (clipping) i filtriranje signala nakon SFBC-a je predloženo u cilju očuvanja niske vrijednosti PAPR-a i izbjegavanja zračenja van opsega. Ovo utječe na performance, ali idalje pruža značajnu prednost nad postojećim tehnikama, kao što je pokazano kroz simulacije.

**Ključne riječi:** SC-FDMA, SFBC, odsjecanje i filtriranje, predajni diverziti, PAPR

## 1 INTRODUCTION

Single Carrier Frequency Division Multiple Access (SC-FDMA) has been selected as the modulation and the multiple access technique for the uplink of 3GPP LTE (3rd Generation Partnership Project Long Term Evolution) and LTE Advanced [1]. SC-FDMA is usually implemented as Discrete Fourier Transform (DFT) precoded Orthogonal Frequency Division Multiplexing (OFDM). Compared to OFDM, SC-FDMA has much lower Peak-to-Average Power Ratio (PAPR) while maintaining similar performance, making it attractive for mobile communications. Initially, LTE defined Multiple-Input Multiple-Output (MIMO) only for the downlink. Later, LTE Advanced extended MIMO to the uplink as well [1]. When implementing MIMO, it is necessary to maintain low PAPR levels on all transmit antennas, as it is the main advantage of SC-FDMA. One of the applications of MIMO is open-loop transmit diversity, which is analyzed in this paper.

Recently, different transmit diversity techniques have been proposed. Space-Time Block Coding (STBC) shows

good performance while maintaining low PAPR (the same PAPR level as SISO SC-FDMA). It is applied over the pairs of symbols, so its main drawback is the requirement of even number of the SC-FDMA data symbols inside the slot, which is not always the case. In LTE, this is known as the *orphan symbol problem* [2,3]. Space-Frequency Block Coding (SFBC) in SC-FDMA is performed over one SC-FDMA symbol, thus avoiding this restriction, but increases the PAPR. Alternative approaches have been proposed. Single Carrier SFBC (SC SFBC) [4-6] uses non-adjacent subcarriers for Alamouti-based [7] SFBC to preserve the same PAPR level, but it suffers from the performance loss in the cases of the large number of subcarriers or the small channel coherence bandwidth. A very similar approach is used in [8]. Three-time slots quasi-orthogonal STBC [2] uses three symbols for space-time coding, preserving the PAPR level and avoiding the restriction of even number of symbols, but requires higher receiver complexity and is slightly more sensitive to Doppler spread. One symbol STBC [3] applies STBC inside the duration of one symbol by splitting the SC-FDMA symbol into two shorter blocks,

but slightly decreases the capacity and requires changes in the LTE symbol structure.

In this paper, a novel method is proposed, that uses SFBC (as a transmit diversity technique) with clipping (to reduce the PAPR to an acceptable level) and filtering (to suppress the out-of-band radiation) (SFBC CF). Clipping and filtering (CF) is one of the simplest and widely used PAPR reduction techniques, used mainly for OFDM [9,10,13]. Clipping (without filtering) added to SC-FDMA spatial multiplexing has been analyzed in [11]. To the best of our knowledge, this is the first time that CF is being used for SC-FDMA with SFBC transmit diversity. SFBC CF is compared with conventional SFBC, STBC and SC SFBC, as it is an SFBC-based transmit diversity technique proposed for SC-FDMA.

In Section 2, SC-FDMA is presented. Section 3 gives an overview of transmit diversity techniques STBC, SFBC, SC SFBC, and SFBC CF. Section 4 presents the outcomes of the simulations where PAPR and BER performances for different channel models are compared. Finally, the conclusion and the direction of future work are given in Section 5.

## 2 SC-FDMA

In this paper, SC-FDMA with two transmit antennas, as it is the most probable case for user equipment (UE), is studied. Its block diagram is presented on Fig. 1. The input bit sequence is mapped to a QAM symbols sequence (LTE defines QPSK, 16-QAM and 64-QAM). The block of  $M$  QAM symbols is then converted to the frequency domain (FD) using an  $M$ -point FFT (Fast Fourier Transform) operation.

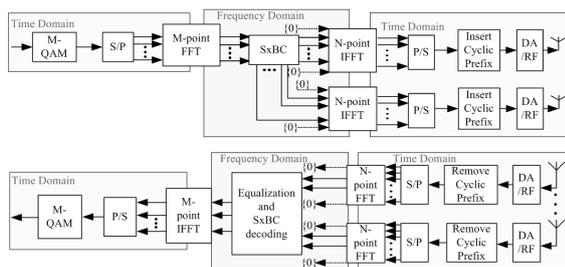


Fig. 1. The block diagram of SC-FDMA  $S_xBC$  transmitter and receiver

$S_xBC$  (STBC, SFBC or alternative coding) is usually performed in the FD.  $M$  samples in the FD are coded and two blocks, each of  $M$  samples, are generated and mapped to two OFDM modulators, occupying  $M$  out of  $N$  possible subcarriers ( $N - M$  inactive subcarriers are set to zero).  $M$  active subcarriers belong to one user and

LTE defines using a block of subsequent subcarriers – L-SC-FDMA (Localized SC-FDMA) [1]. The OFDM part of the transmitter includes an  $N$ -point IFFT (Inverse FFT) block, which generates the signal in the time domain (TD), and cyclic prefix (CP) insertion. The CP length should be longer than the channel delay spread to avoid intersymbol interference between consecutive SC-FDMA symbols.

At the receiver, which can have more than one receiving antenna, the signals undergo symmetric process. After CP removal and an  $N$ -point FFT operation for each antenna, in the FD, unused subcarriers are omitted and the signals are  $S_xBC$  decoded and equalized. In this paper, the focus is on transmit diversity, so the receiver is assumed to use the maximum ratio combining (MRC) to achieve receive diversity. After the equalization, the signal is converted to the TD using an  $M$ -point IFFT operation. Finally, QAM demodulation is performed.

## 3 SC-FDMA TRANSMIT DIVERSITY

As this paper covers only the two transmit antenna case, all coding is based on Alamouti coding [7]. Original Alamouti coding scheme is space-time coding performed with coding matrix  $S_{Alamouti}$ :

$$S_{Alamouti} = \begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix}, \quad (1)$$

where  $s_1$  and  $s_2$  are two symbols, \* represents complex conjugate, the columns correspond to transmit antennas and the rows correspond to symbol intervals. For Alamouti-based SFBC, the rows correspond to the subcarriers. It is worth noting that different matrices can also be used and the receiver will maintain the same complexity level. For example, if the coding matrix is  $S$ :

$$S = \begin{bmatrix} s_1 & -s_2^* \\ s_2 & s_1^* \end{bmatrix}, \quad (2)$$

then the first antenna transmits the unchanged signal, as it would be sent in the case of one transmit antenna, while the second antenna transmits coded symbols.

Because of the fact that the computationally complex convolution in the TD can be reduced to the simple multiplication in the FD, SFBC or STBC in SC-FDMA, as in OFDM, is easily performed in the FD. Let  $S_1$  and  $S_2$  represent two samples in the FD and the system has two transmit and one receive antenna (The extension to more than one receive antenna is straightforward.). Using  $S$  (2), the received signals in the FD are:

$$Y_1 = S_1 H_1 - S_2^* H_2 + N_1, \quad (3)$$

$$Y_2 = S_2 H_1 + S_1^* H_2 + N_2, \quad (4)$$

where  $Y_1$  and  $Y_2$  are two received signals in the FD on two adjacent subcarriers (SFBC) in one SC-FDMA symbol or on one subcarrier in two adjacent SC-FDMA symbols (STBC);  $H_1$  and  $H_2$  are the channel frequency responses from two transmit antennas;  $N_1$  and  $N_2$  are complex additive Gaussian noises of variances  $\sigma^2$ . In practical implementations, such as LTE, reference signals are used for channel estimation at the receiver, so it is assumed that  $H_1$  and  $H_2$  are known at the receiver side. As in [7], it is assumed that the channel frequency response remains unchanged over two consecutive symbols (in STBC) or two adjacent subcarriers (SFBC). After conjugation, (4) can be written as:

$$Y_2^* = S_1 H_2^* + S_2^* H_1^* + N_2^*. \quad (5)$$

From (3) and (5):

$$\begin{pmatrix} Y_1 \\ Y_2^* \end{pmatrix} = \begin{pmatrix} H_1 & -H_2 \\ H_2^* & H_1^* \end{pmatrix} \begin{pmatrix} S_1 \\ S_2^* \end{pmatrix} + \begin{pmatrix} N_1 \\ N_2^* \end{pmatrix}. \quad (6)$$

Or:

$$Y = HS_T + N, \quad (7)$$

where  $Y$  represents the vector of the received signals,  $H$  is the channel matrix,  $S_T$  is the vector of two transmitted samples in the FD and  $N$  represents the additive noise. The equalization is performed by multiplying  $Y$  with  $W$  ( $WY$ ), where  $W$  for zero-forcing equalization is:

$$W = (H^H H)^{-1} H^H. \quad (8)$$

And for minimum mean-square error (MMSE) equalization, it is:

$$W = (H^H H + \sigma^2 I)^{-1} H^H. \quad (9)$$

It can be easily shown that the size of the inverse matrix is  $2x2$ , regardless of the number of the receive antennas, so the computational complexity is not too high.

### 3.1 SC-FDMA STBC

STBC for two transmit antennas is applied using Alamouti coding [7] on the blocks of two symbols. In order for the assumption of the same channel characteristics [7], it is assumed that two consecutive SC-FDMA symbols are coded together.

Let  $S_1^i, S_2^i, \dots, S_M^i$  represent  $M$  samples in the FD of the  $i$ th SC-FDMA symbol, obtained after an  $M$ -point FFT operation. Then, STBC, using (2), can be applied as in Table 1 for  $m=1, \dots, M$ .

Table 1. STBC coding scheme

STBC	Antenna 1	Antenna 2
$i$ -th symbol	$S_m^i$	$-(S_m^{i+1})^*$
$(i+1)$ -th symbol	$S_m^{i+1}$	$(S_m^i)^*$

Obviously, the coding is performed over the same subcarrier in two SC-FDMA symbols, so the order of the samples on subcarriers is not changed and the samples of different SC-FDMA symbols are not interleaved.

With this coding scheme, antenna 1 transmits the unchanged signal, while antenna 2 applies conjugation (and negation) on all subcarriers of one SC-FDMA symbol. Negation of all samples in the TD is equal to negation in the FD. Also, it can be easily shown that if:

$$(X_0, X_1, \dots, X_{k-1}) = FFT_k(x_0, x_1, \dots, x_{k-1}). \quad (10)$$

Then,

$$(X_0^*, X_1^*, \dots, X_{k-1}^*) = FFT_k(x_0^*, x_{k-1}^*, \dots, x_1^*), \quad (11)$$

where  $X_0, X_1, \dots, X_{k-1}$  are the samples in the FD and  $x_0, x_1, \dots, x_{k-1}$  are the samples in the TD. From (10) and (11), conjugation of all samples in the FD can be performed easily by conjugation and reordering of the samples in the TD and this property can be used to reduce the complexity of the transmitter. The block diagram of the SC-FDMA transmitter with STBC performed in the TD is presented on the Fig. 2.

As the coding performed in the TD includes operations that maintain the same amplitude level (only phase is changed), it is obvious that the PAPR of the signal on antenna 2 is unchanged and it will be confirmed in the simulations. Due to the assumption that the channel characteristics are unchanged over two consecutive SC-FDMA symbols, poorer performances can be expected in the channels with large Doppler spread when this assumption cannot be used.

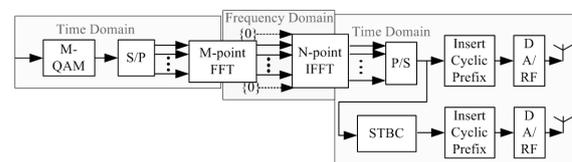


Fig. 2. STBC transmitter block scheme

In practical implementations, such as in LTE, the main drawback of STBC is the problem of odd number of SC-FDMA symbols where this coding cannot be applied, i.e. one symbol, known as “orphan”, will remain.

Table 2. SFBC coding scheme

SFBC	Antenna 1	Antenna 2
$(2m-1)$ -th subcarrier	$S_{2m-1}^i$	$-(S_{2m}^i)^*$
$2m$ -th subcarrier	$S_{2m}^i$	$(S_{2m-1}^i)^*$

### 3.2 SC-FDMA SFBC

SFBC based on Alamouti coding [7] is applied over the FD samples of one SC-FDMA symbol. In order to hold the assumption of the same channel characteristics [7], it is assumed that two adjacent subcarriers are coded together.

Let  $S_1^i, S_2^i, \dots, S_M^i$  represent  $M$  samples in the FD of the  $i$ th SC-FDMA symbol, obtained after an  $M$ -point FFT operation. Then, SFBC, using (2), can be applied as in Table 2 for  $m=1, \dots, M$ .

Since the coding is performed over one SC-FDMA symbol there is no restriction on the number of the symbols inside the block. The restriction exists on the number of used subcarriers (it has to be even), but is easy to satisfy it (In LTE, the number of subcarriers is a multiple of 12, so it is always satisfied.). For SFBC, it is assumed that the channel characteristics are the same for two adjacent subcarriers, which is usually a reasonable assumption for LTE channel, since the subcarrier spacing is 15 kHz [1]. As STBC is sensitive to the larger Doppler spread, SFBC is sensitive to the larger channel delay spread.

Obviously, this coding does not change the order of the samples in the FD for antenna 1, but it does for antenna 2. Hence, antenna 1 transmits an unchanged signal, while antenna 2 transmits signal after conjugation, negation and reordering in the FD. This increases the PAPR level on antenna 2, as will be shown in the simulations, and is the main reason why SFBC should not be directly applied to SC-FDMA.

It is worth noting that the coding matrix  $S$  (2), which leaves the order of the samples on the first antenna unchanged, is intentionally proposed. It is also possible to use matrix  $S_{Alamouti}$  (1), but it would increase the PAPR on both antennas, making it even less attractive.

### 3.3 SC SFBC

To avoid the restriction of even number of SC-FDMA symbols of STBC and the increase of PAPR of SFBC, this technique was proposed in [4] and later extended to four antenna case [6] and multiuser MIMO [5]. In order to preserve the same PAPR level, SC SFBC applies SFBC coding over non-adjacent subcarriers. This shows very good performance in the cases of smaller number of subcarriers or the channels with large coherence bandwidths because the

difference in the channel frequency responses of the non-adjacent subcarriers is sufficiently small. When this is not the case, the performances are not satisfactory, as it will be shown in the simulations.

In order to apply SFBC over non-adjacent subcarriers, the channel matrix  $H$  (7) has to be slightly changed. In this case, the channel frequency response at non-adjacent subcarriers is different, so if  $H_{ij}$  presents complex channel gain from  $i$ -th transmit antenna at the  $j$ -th subcarrier, then:

$$H = \begin{pmatrix} H_{11} & -H_{21} \\ H_{22}^* & H_{12}^* \end{pmatrix}. \quad (12)$$

### 3.4 SFBC CF

In order to reduce the PAPR, which is increased because of the SFBC processing, using a simple CF method on the signal for antenna 2 is proposed in this paper. Here, it is assumed that SFBC with matrix  $S$  (2) is used, as it transmits an unchanged signal from antenna 1 and increases the PAPR only on antenna 2. If matrix  $S_{Alamouti}$  (1) is used, then CF needs to be added for both transmit antennas. The block diagram of the output part of the SFBC transmitter with CF is shown in Fig. 3. The distortion, created by clipping, cannot be recovered at the receiver side [9], so the receiver for SFBC CF is the same as for the conventional SFBC.

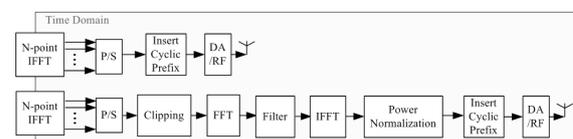


Fig. 3. Part of SFBC CF transmitter

Clipping is performed on the signal in the TD, after an  $N$ -point IFFT operation. This operation can be defined as:

$$x_c = \begin{cases} x, & |x| \leq A \\ Ae^{j\varphi(x)}, & |x| > A \end{cases}. \quad (13)$$

Where  $x_c$  is clipped signal,  $x$  is input signal,  $\varphi(x)$  is phase of  $x$  and  $A$  is positive amplitude clipping level. The effect of clipping on the instantaneous power level is that the power level is limited to  $P_{clip} = A^2$

Clipping decreases the PAPR, decreases the signal average power level, changes the frequency spectrum generating out-of-band components and creates in-band signal distortion. Out-of-band components are suppressed with filtering, which can be easily applied in the FD and after the clipping operation. The block of  $N$  samples in the TD of the clipped signal is converted using an  $N$ -point FFT to

the FD, where  $N - M$  inactive subcarriers are suppressed (set to zero) and  $M$  active subcarriers are kept unchanged. Thus, filtering causes no inband distortion and no intersymbol interference, as it operates on symbol-by-symbols basis [13]. After that, an  $N$ -point IFFT is performed. The signal has the desired spectrum, but lower power level, so it is normalized to the same power level as the signal for antenna 1. This filtering operation actually slightly increases PAPR level again, so the PAPR regrowth is possible. To avoid this, CF can be repeated [13,9].

In-band distortion is the drawback of this approach as it presents the interference that degrades the performance. Its impact on the performances will be seen in the simulations outcomes.

Another important part of this approach is the amplitude clipping level  $A$ . As shown in [11], the PAPR level of the SC-FDMA signal depends on the underlying QAM modulation. Because of that, different clipping levels should be chosen, depending on QAM modulation (QPSK, 16-QAM or 64-QAM) that is used.

#### 4 SIMULATIONS OUTCOMES

For comparison of the transmit diversity techniques, an LTE 5 MHz channel with  $N = 512$  was chosen. The user occupies  $M$  subcarriers ( $M \leq 300$ ). One LTE slot with six data SC-FDMA symbols and one SC-FDMA symbol with DMRS (Demodulation Reference Signal) was chosen to enable using STBC in comparison (even number of data symbols). Normal [1] cyclic prefix length was used. Perfect channel estimation was performed during DMRS symbol and linear interpolation over the time was used to calculate the channel frequency responses for data symbols between two consecutive DMRS. MIMO Minimum Mean Square Error (MMSE) equalization (9) on the pairs of the subcarriers (for SFBC-based transmit diversity) or the pairs of the samples on the same subcarrier (for STBC) was used. In order to have the accurate comparison, the generalization of the channel matrix (12) is applied for STBC, SFBC and SFBC CF as well. It slightly improves the performances in the cases of larger Doppler spread (STBC) or smaller coherence bandwidth (SFBC). Error correction coding was not used. The channel models were taken from the LTE specifications [12].

It is worth discussing the effect of CF on DMRS. If clipping above the limit occurs while DMRS is sent, it would affect the channel estimation and, thus, the overall performance. SC-FDMA implementation in LTE uses time-multiplexing of the data symbols and DMRS, so CF can be disabled while DMRS is sent. Because the transmitter in SISO case is already designed to transmit DMRS with known PAPR level, it is a reasonable approach and is used in the simulations. Another approach is to select the

clipping limit above the PAPR level of DMRS to ensure that CF will not be applied on DMRS.

#### 4.1 The PAPR limit

First, the PAPR limit for SFBC CF had to be selected. Figure 4 presents the BER for EVA-70 (EVA [12] channel model with 70 Hz Doppler spread) for different SNR levels as a function of the clipping limit when 16-QAM modulation is used. MIMO 2x4 was used. Similar results were obtained in other channel models. It is observed that increasing the power clipping limit above 4 dB does not provide significant performance gain for all observed SNR values and decreasing it below 4 dB has a greater impact on the performance.

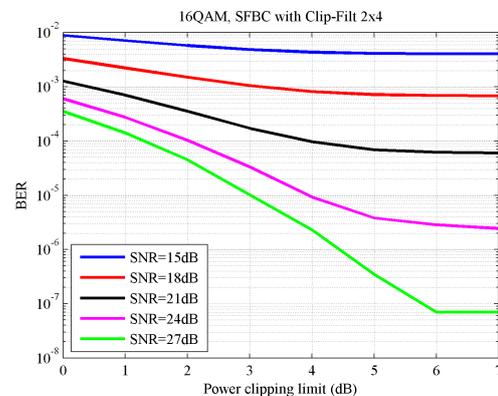


Fig. 4. SC-FDMA SFBC CF with 16-QAM. BER as a function of the clipping limit for different SNR levels

Thus, for 16-QAM, 4 dB can be chosen as the PAPR limit and the performance will not be significantly affected. Decreasing the limit affects the performance for lower SNR values, whereas increasing it improves the performance for higher SNR values. On the other side, if the SNR level is high, it is likely that some other MIMO mode, rather than transmit diversity, will be used.

The PAPR is usually measured using the CCDF (Complementary Cumulative Distribution Function) of the output power [10, 11]. It expresses the probability that the instantaneous power level is greater than the level  $PAPR_0$ :

$$CCDF(PAPR_0) = P(PAPR > PAPR_0). \quad (14)$$

The PAPR levels of transmit diversity techniques given in Section 3. were obtained via simulations and are presented in Fig. 5. Additionally, it also shows the PAPR of DMRS. The PAPR for the signals of the antenna 1 are not shown, as, for all techniques, it is the same signal as in

the SISO/SIMO case. STBC and SC SFBC preserve the same PAPR level on antenna 2 as SISO/SIMO case, so it is hard to distinguish them on Fig. 5 SFBC shows increase of the PAPR, but still has much better PAPR than OFDM. For the proposed SFBC CF, the power limit was set to 4 dB. Obviously, SFBC CF provided lower PAPR than the SISO case of the PAPR level higher than roughly 4.5 dB, i.e., it has a lower probability of the PAPR above 4.5 dB than SISO. Figure 5 also shows that the PAPR level above 3.5 dB will have no impact on DMRS (if CF is enabled during the transmission of DMRS).

Figure 6 shows the PAPR CCDF curves for SFBC CF for different power limits and the curves when the repeated CF for 4 dB limit was used. If repeated CF, which increases the complexity of the transmitter, can be added, then the PAPR reaches very close to the limit (after three times repeated CF, it is almost equal to the limit), so the probability that the limit will be exceeded is very small. Due to the power normalization performed after the CF, the power limit is slightly increased (from 4 dB to 4.5 dB).

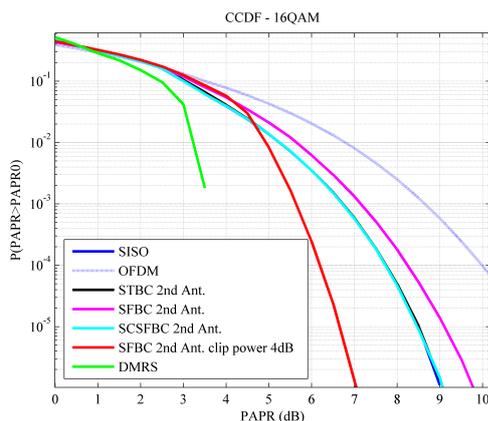


Fig. 5. SC-FDMA with 16-QAM CCDF PAPR curves for transmit diversity techniques

It can be observed from Fig. 4 and Fig. 6 that low power limit (2 dB) has poorer BER performance, but very good PAPR curve. On the other hand, increasing the PAPR limit (6 dB) has very low impact on the BER performance, but shows the PAPR increase (both BER and PAPR curves approach near conventional SFBC, as can be expected). As a tradeoff, 4 dB PAPR limit was used for the clipping limit when 16-QAM is used.

4.2 BER Performance

To observe the BER performance of all transmit diversity techniques, an EPA channel with 5 Hz Doppler spread (EPA-5) [12] was used first. All techniques are of very

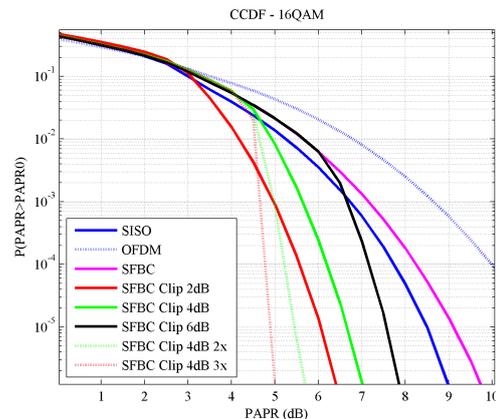


Fig. 6. SFBC CF with different clipping limits and repeated CF

similar performance (with smaller or greater number of subcarriers, one or more receive antennas, different QAM modulations) and the performances for the case of two receive antennas and  $M = 300$  subcarriers is given on Fig. 7. Because of large coherence bandwidth, SC SFBC shows performance very similar to STBC and SFBC, despite the large number of subcarriers. SFBC CF has slightly better performance than SC SFBC. Due to small Doppler spread and large coherence bandwidth, SFBC and STBC are of very similar performances.

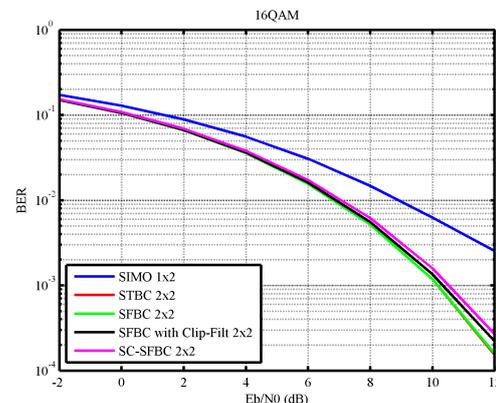


Fig. 7. SC-FDMA with 16-QAM, 300 subcarriers, 2 Rx antennas in EPA-5 channel

Channel model EVA-5 has smaller coherence bandwidth and the same Doppler spread as EPA-5. Figure 8 shows the performance for 16-QAM,  $M = 120$  subcarriers (or 10 LTE resource blocks) and four receive antennas.

Again, STBC and SFBC have very similar performance, SC SFBC has slightly degraded performance and

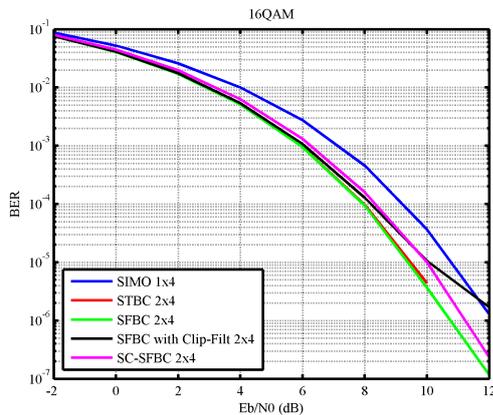


Fig. 8. SC-FDMA with 16-QAM, 120 subcarriers, 4 Rx antennas in EVA-5 channel

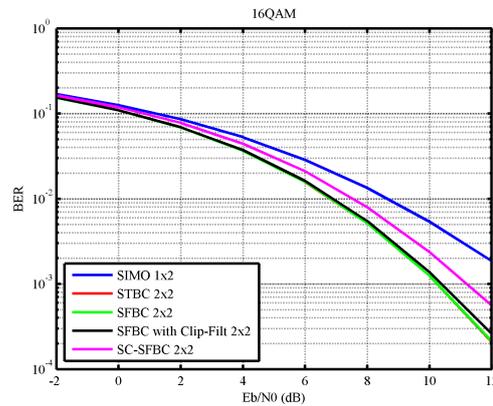


Fig. 9. SC-FDMA with 16-QAM, 120 subcarriers, 2 Rx antennas in EVA-70 channel

SFBC CF has better performance for lower SNR values than SC SFBC, but worse for higher SNR values. This degradation for higher SNR values exists because the effect of CF remains, regardless of the SNR level. On the other hand, in 2x4 MIMO and high SNR values, it is more likely that some other MIMO mode, than transmit diversity, will be used. If the number of subcarriers is decreased, modulation switches from 16-QAM to QPSK or the number of receive antennas is increased, SC SFBC performance approaches near the performance of SFBC and STBC. On the other hand, when the number of subcarriers is increased, modulation changes from 16-QAM to 64-QAM or only one receive antenna is used, SC SFBC shows poorer performance.

Figure 9 shows the performances for the case of two receive antennas in EVA-70 (Doppler spread is 70 Hz). Because of smaller number of the receive antennas, SC SFBC performances are degraded, compared to STBC and SFBC. SFBC CF maintains good performance. The degradation seen on Fig. 8 would appear in this case only for larger SNR values.

For the even more severe channel model, ETU [12], which has some reflected components with delay even longer than the CP, with Doppler spread of 70 Hz (ETU-70),  $M = 60$  and 16-QAM, it can be observed from the Fig. 10 that the proposed method showed relatively good performance, significantly better than SC SFBC, and very near SFBC. I.e. in ETU-70, for even smaller number of subcarriers than in the case of Fig. 9, SC SFBC has degraded performance.

Finally, the performances of the repeated CF are presented on Fig. 11. If CF can be repeated, the performance is not significantly affected, compared to SFBC, whereas the probability is much lower than in the SISO case for

the PAPR above 4.5 dB (Fig. 6). Additionally, the number of the subcarriers is increased to  $M = 300$  and the performance of SFBC CF is not affected. Due to the small coherence bandwidth of ETU channel, SFBC shows poorer performance than STBC. If the Doppler spread is increased (ETU-300 channel model), STBC performance is affected.

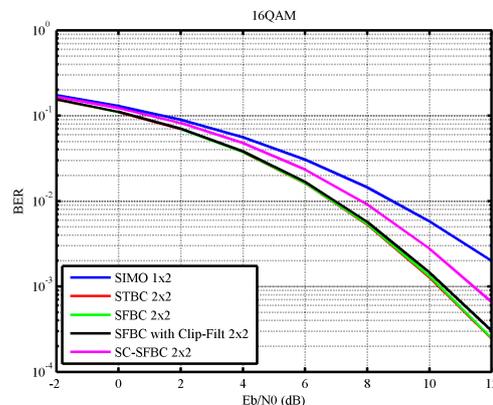


Fig. 10. SC-FDMA with 16-QAM, 60 subcarriers, 2 Rx antennas in ETU-70 channel

## 5 CONCLUSION

The overall conclusion is that the conventional STBC and SFBC show the best performance in all channel models. SFBC is more sensitive to small coherence bandwidth (EVA or ETU channels) and STBC to large Doppler spread (300 Hz). Due to the STBC restriction for even number of the symbols and the SFBC problem of the increased PAPR, they are not directly suitable for SC-FDMA. SC SFBC uses non-adjacent subcarriers for SFBC, to preserve

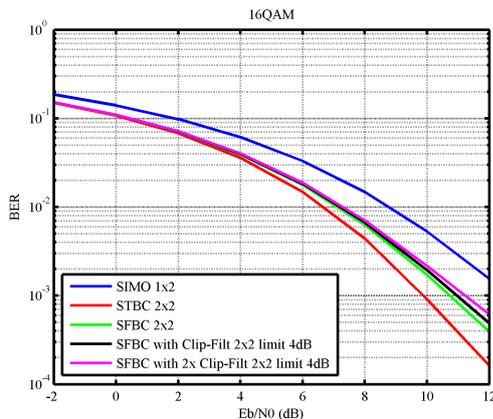


Fig. 11. SC-FDMA with 16-QAM, 300 subcarriers, 2 Rx antenna in ETU-70 channel for different CF

the same PAPR level, but shows performance loss in cases of small coherence bandwidth or large number of subcarriers.

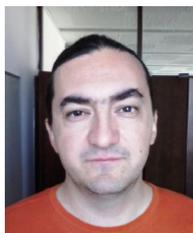
This paper proposed SFBC with CF as a possible open-loop transmit diversity technique, which avoids the restriction of even number of symbols of STBC, shows good performance for different scenarios and maintains low PAPR level. Unlike other proposed methods [2-6, 8] that force preserving the same PAPR level, our proposed method allows the PAPR level to be increased and later decreases it using CF. If repeated CF can be added, the PAPR level above the limit will have very low probability whereas the performance will not be significantly affected. If SNR level is high, the receiver has high number of antennas or robust modulation (QPSK) is used the degradation of performance of SFBC CF becomes significant, as can be seen on Fig. 8. On the other hand, in these cases, it is not likely that transmit diversity MIMO mode will be used. In other cases, it can be seen that performance loss introduced by CF is not significant, while the PAPR property is improved. Unlike SC SFBC, its performance is not degraded when the number of subcarriers is increased. The main drawback of the proposed technique is CF at the SC-FDMA transmitter (User Equipment in LTE) which increases its complexity. With a proper SFBC coding matrix (2), CF is required for only one antenna.

Extending this approach to more than two transmit antennas is straightforward as, for example, quasi-orthogonal STBC [14] can be applied with CF on three antennas (if a proper matrix that sends the unchanged signal over one antenna is chosen). In addition, the usage of other more effective PAPR reduction techniques [9, 10] with SC-FDMA should be investigated.

## REFERENCES

- [1] [1] [3GPP TS 36.211. LTE, Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Channel and Modulation; (3GPP TS 36.211 version 11.3.0 Release 11.)
- [2] Z. Lei, C. Yuen, F. Chin, "Three-Time-Slot Quasi-Orthogonal Space-Time Block Codes," in *2010 IEEE International Conference on Communications (ICC)*. (Cape Town, South Africa), pp. 1-5, May 2010.
- [3] X. Luo, P. Gaal, W. Chen, X. Zhang, J. Montojo, "Transmit Diversity Scheme over Single SC-FDM Symbol for LTE-Advanced," in *IEEE Global Telecommunications Conference, 2009. (GLOBECOM 2009)* (Honolulu, Hawaii, USA), pp. 1-6, December 2009.
- [4] C. Ciochina, D. Castelain, D. Mottier, H. Sari, "New PAPR-preserving mapping methods for single-carrier FDMA with space-frequency block codes" in *IEEE Transactions on Wireless Communications*, vol. 8, no. 10, pp. 5176-5186, 2009.
- [5] C. Ciochina, D. Mottier, D. Castelain, "Low PAPR space frequency block coding for multiuser MIMO SC-FDMA systems: specific issues for users with different spectral allocations," *EURASIP Journal on Advances in Signal Processing*, vol. 54, pp. 1-10, 2011.
- [6] C. Ciochina, D. Castelain, D. Mottier, H. Sari, "Mapping techniques for transmit diversity precoding in SC-FDMA systems with four transmit antennas," in *2009 IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications*, (Tokyo, Japan), pp. 2504-2508, 2009.
- [7] S. M. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE Journal on Selected Areas in Communications*, vol. 16, no. 8, pp. 1451-1458, 1998.
- [8] Y. Meng, M. You, J. Liu, "A novel transmit diversity scheme for LTE-Advanced uplink," in *2009 IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications*, (Tokyo, Japan), pp. 221-225, 2009.
- [9] T. Jiang, Y. Wu, "An Overview: Peak-to-Average Power Ratio Reduction Techniques for OFDM Signals," *IEEE Transactions on Broadcasting*, vol. 54, no. 2, pp. 257-268, 2008.

- [10] S. H. Han, J. H. Lee, "An overview of peak-to-average power ratio reduction techniques for multicarrier transmission," *IEEE Wireless Communications*, vol. 12, no. 2, pp. 56-65, 2005.
- [11] H. G. Myung, J.-L. Pan, R. Olesen, D. Grieco, "Peak Power Characteristics of Single Carrier FDMA MIMO Precoding System," in *2007 IEEE 66th Vehicular Technology Conference*, 2007. (Baltimore, Maryland, USA), pp. 477-481, 2007.
- [12] ETSI TS 136 101. LTE, Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception; (3GPP TS 36.101 version 11.4.0 Release 11.
- [13] J. Armstrong, "Peak-to-average power reduction for OFDM by repeated clipping and frequency domain filtering," *Electronics Letters*, vol. 38, no. 5, pp. 246-247, 2002.
- [14] H. Jafarkhani, "A quasi-orthogonal space-time block code," *IEEE Transactions on Communications*, vol. 49, no. 1, pp. 1-4, 2001.



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