A Novel Quasi-Orthogonal Space-Frequency Block Code for Single-Carrier FDMA

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***Abstract*—Single-Carrier Frequency Division Multiple Access (SC-FDMA) is a recent modulation technique combining most of the advantages of Orthogonal Frequency Division Multiple Access (OFDMA) with the low Peak-to-Average Power Ratio (PAPR) of single-carrier transmission. For these reasons, it has been adopted as a possible air interface on the uplink of future wireless networks. It is also suitable for any other system in which a low PAPR is desired. In this paper, we highlight the severe limitations of existing space-time and space-frequency block codes when combined with SC-FDMA, and we propose a novel quasi-orthogonal space-frequency block code compatible with a SC-FDMA system with four transmit antennas. We show that our proposed precoding keeps the single-carrier property of the signal on all of the four transmit antennas and we also prove the good performance of our scheme on frequency selective channels with spatial correlation.**

***Keywords*—SC-FDMA, PAPR, Quasi-orthogonal Space-Time Block Code (QOSTBC), Quasi-orthogonal Space-Frequency Block Code (QOSFBC), extended Alamouti, MIMO.**

I. INTRODUCTION

The debate between multi-carrier (MC) and single carrier (SC) systems, opened with the introduction of Orthogonal Frequency Division Multiplexing (OFDM) is still not closed. Orthogonal Frequency Division Multiple Access (OFDMA) or its precoded derivatives have been adopted in many existing standards and also seem to be preferred for the downlink of the air interface of Beyond Third Generation (B3G) and Fourth Generation (4G) cellular systems. MC systems have, nevertheless, the disadvantage of a high Peak-to-Average Power Ratio (PAPR). This causes undesired effects, especially on the uplink, where special precautions need to be taken: The use of costly power amplifiers should be avoided, and requirements of good coverage and efficient power utilization must be fulfilled. For these reasons, the 3GPP (Third Generation Partnership Project), which focuses on the Long Term Evolution (LTE) of UMTS (Universal Mobile Terrestrial Systems) radio access, has chosen Single-Carrier FDMA for the uplink.

The use of Multiple Input Multiple Output (MIMO) techniques in future wireless systems is inevitable. The presence of multiple antennas both at the transmitter and at the receiver side opens the way to significant improvements towards meeting the ever higher demands in data rate and reliability. In future generation wireless communications networks, mobile terminals used for data transmission will be equipped with multiple antennas (typically 2 or 4), that can be used for various reasons: increasing throughput, increasing diversity and/or reduce interference from other users [1]. Transmit diversity techniques have lately gained much attention, and are very attractive especially in the case of a terminal with bad propagation conditions (e. g., located at cell edge), whose priority will not necessarily be increasing data rate by spatial multiplexing, but rather increasing diversity and coverage by spatial precoding. When only two transmit antennas are available, the well-known Alamouti scheme [2] gives a very simple and elegant orthogonal design which does not increase the throughput but provides full diversity. It has been proven 0 that complex orthogonal designs with full diversity and transmission rate one are not possible for more than 2 transmit antennas. Extended Alamouti schemes resulting in quasi-orthogonal (QO) designs for more than two transmit antennas have already been introduced [4] and analyzed [5].

Combining transmit diversity techniques with SC-FDMA modulation is not always straightforward: The direct use of existing techniques suppose either restrictions on the frame duration or manipulations that result in significantly increasing the PAPR of the SC-FDMA signal. We have already solved the case of a two antenna system in 0. In this paper, we address the case of a terminal with 4 transmit antennas. The paper is structured as follows: Section II gives a brief description of a SC-FDMA system and highlights the limitations of existing QO designs. A novel QO space-frequency block code compatible with SC-FDMA for 4 transmit antennas is proposed in Section III. Section IV assesses the performance of this new scheme and conclusions are drawn in section V.

II. QUASI-ORTHOGONAL DESIGNS IN A SC-FDMA CONTEXT

SC-FDMA has lately attracted much attention due to the low PAPR advantage over OFDMA, while keeping FDMA-like access. In 3GPP LTE, SC-FDMA was adopted for the uplink, in a frequency-domain implementation also called

DFT (Direct Fourier Transform) – Spread OFDMA. Frequency-domain implementation is more flexible than a time-domain implementation and it also opens the way to channel-dependent subcarrier allocation.

A. SC-FDMA System Model

Fig. 1 shows the structure of a SC-FDMA transmitter with 4 antennas. This is equivalent to a DFT-precoded OFDMA scheme, where the DFT precoder re-establishes the SC envelope of the signal. Blocks $\mathbf{x}^{(i)}$of M data symbols are precoded with a DFT. Then, output vectors $\mathbf{s}^{(i)}$ are passed through a quasi-orthogonal precoder so as to form 4 parallel streams $\mathbf{s}^{Txj,(i)}$ (j=1…4) intended to be transmitted on the 4 transmit antennas (Tx). Each stream is then treated as in a classical OFDMA modulator: symbols are mapped on M out of N inputs of an inverse DFT according to the user-specific subcarrier mapping and a cyclic prefix (CP) is also inserted, so as to form (N+CP)-sized block $\mathbf{y}^{Txj,(i)}$ at the inverse DFT output in order to combat the effects of the frequency selective channel from Txj.

B. Quasi-Orthogonal Block Coding

In a wireless system with four transmit antennas, it is known 0 that a complex orthogonal design with full diversity and transmission rate one does not exist. For this reason, transmit diversity is provided via quasi-orthogonal precoding, based either on ST (space-time), SF (space-frequency), or STF (space-time-frequency) block codes. In order to explicit the construction of QO codes, let us first denote the original Alamouti code as defined in [2] by:

$$\mathbf{A}_{12}^{'} = \begin{pmatrix} a_1 & a_2 \\ -a_2^* & a_1^* \end{pmatrix} \tag{1}$$

This full-diversity code is very simple to decode, due its orthogonality. Equivalent versions are given by:

$$\mathbf{A}_{12}^{(I)} = \begin{pmatrix} a_1 & -a_2^* \\ a_2 & a_1^* \end{pmatrix} \text{ and } \mathbf{A}_{12}^{(II)} = \begin{pmatrix} a_1 & a_2^* \\ a_2 & -a_1^* \end{pmatrix}. \tag{2}$$

To design a rate-1 code for more than two antennas, we need to relax the orthogonality condition. Let us consider the following Jafarkhani construction given in [4]:

$$\mathbf{A} = \begin{pmatrix} \mathbf{A}_{12} & \mathbf{A}_{34} \\ \mathbf{A}_{34} & \mathbf{A}_{12} \end{pmatrix}, \tag{3}$$

where $\mathbf{A}_{12,34}$ can be built considering any of the matrices given in (1), (2). If ν_j is the jth column of $\mathbf{A}$ and $\langle .,. \rangle$ denotes the scalar product, the following QO condition takes place:

$$\langle \nu_1, \nu_2 \rangle = \langle \nu_1, \nu_3 \rangle = \langle \nu_2, \nu_4 \rangle = \langle \nu_3, \nu_4 \rangle = 0\,. \tag{4}$$

The columns of this matrix can thus be divided into groups; the columns within each group are not orthogonal to each other, but the different groups are orthogonal to each other.

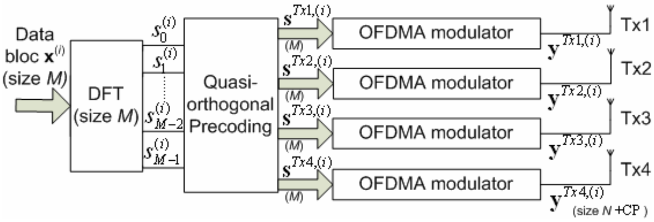

Figure 1. SC-FDMA transmitter block diagram.

This allows pairs of symbols to be decoded separately. This code keeps the transmission rate 1, with a small penalty in diversity that has been thoroughly analyzed in [5].

1) Quasi-Orthogonal STBC

With these definitions, the QO precoding block in Fig. 1 can be implemented in several ways. Let us first consider that matrix $\mathbf{A}$ describes a ST code: The element on the ith row and the jth column of matrix $\mathbf{A}$ is sent at time t_i on antenna Txj, for example:

$$\mathbf{A} = \begin{pmatrix} \mathbf{A}_{12}^{(I)} & \mathbf{A}_{34}^{(I)} \\ \mathbf{A}_{34}^{(I)} & \mathbf{A}_{12}^{(I)} \end{pmatrix} = \begin{array}{cc} \begin{pmatrix} a_1 & -a_2^* & a_3 & -a_4^* \\ a_2 & a_1^* & a_4 & a_3^* \\ a_3 & -a_4^* & a_1 & -a_2^* \\ a_4 & a_3^* & a_2 & a_1^* \end{pmatrix} & \begin{array}{l} \leftarrow t_1 \\ \leftarrow t_2 \\ \leftarrow t_3 \\ \leftarrow t_4 \end{array} \\ \begin{array}{cccc} \uparrow & \uparrow & \uparrow & \uparrow \\ \text{Tx1} & \text{Tx2} & \text{Tx3} & \text{Tx4} \end{array} & \end{array} \;. \tag{5}$$

Let us split the output of the DFT into groups of 4 time-consecutive blocks $\mathbf{s}$; the nth group will be precoded as in matrix $\mathbf{A}$, by taking:

$$a_j = s_k^{(4n+j)}, \quad j = 1...4, \ \forall k = 0....M-1\,. \tag{6}$$

This results into a QOSTBC. Examining (5) and (6), we notice that precoding is performed in the time domain on all frequency samples at once; since the frequency samples order remains unchanged through this operation, it is as if precoding were performed at $\mathbf{s}^{(i)}$ block level: The SC nature of the signal is conserved on all 4 transmit antennas. We can see from the construction that QOSTBCs have one major weakness: They impose that the transmitted burst should be always composed of a multiple of 4 SC-FDMA symbols. This may be not be the case in practical systems [7]. Moreover the presence of dynamic pilot and control signals requires a flexible data structure composed of a variable number of SC-FDMA symbols in order to fill the uplink burst and to maximize the throughput. All these constraints related to the burst structure make QOSTBC hardly applicable for the design of new SC-FDMA based radio access schemes. Multiplying the burst granularity by 4 also makes impossible the use of some algorithms such as idle period shortening methods [8]. Another known drawback of ST codes is their sensitivity to high vehicular speeds [9].

2) Quasi-Orthogonal SFBC

It has been shown in [10] that, in OFDM-based systems, ST codes may be employed in the frequency domain as SF codes with virtually no additional loss of capacity (with respect to their use as ST codes). The available frequency and time diversity can be picked up by an outer forward error correction decoder. We can thus alleviate the restrictions of QOSTBC by using a more flexible QO space-frequency block code (SFBC). Equation (5) becomes:

$$\mathbf{A}=\begin{pmatrix}\mathbf{A}_{12}^{(I)} & \mathbf{A}_{34}^{(I)}\\ \mathbf{A}_{34}^{(I)} & \mathbf{A}_{12}^{(I)}\end{pmatrix}=\begin{array}{cc}\begin{pmatrix} a_1 & -a_2^* & a_3 & -a_4^*\\ a_2 & a_1^* & a_3 & a_4^*\\ a_3 & -a_4^* & a_1 & -a_2^*\\ a_3 & a_4^* & a_2 & a_1^*\end{pmatrix} & \begin{matrix}\leftarrow f_1\\ \leftarrow f_2\\ \leftarrow f_3\\ \leftarrow f_4\end{matrix}\\ \begin{matrix}\uparrow & \uparrow & \uparrow & \uparrow\\ \mathrm{Tx1} & \mathrm{Tx2} & \mathrm{Tx3} & \mathrm{Tx4}\end{matrix} & \end{array}. \quad (7)$$

This QOSFBC will be applied on frequency samples belonging to the same time block $\mathbf{s}^{(i)}$. We split $\mathbf{s}^{(i)}$ into groups of 4 adjacent frequency samples; the nth group will be precoded by taking in matrix $\mathbf{A}$:

$$a_j = s_{4n+j}^{(i)},\quad j=1...4,\ \forall i \quad (8)$$

This type of QOSFBC coding is more flexible and it does not impose any particular constraint on burst duration, as OFDM typically includes a very large number of modulated subcarriers which may be easily adapted to a multiple of 4 without impacting significantly the signal bandwidth.

However, with this construction of matrix $\mathbf{A}$, the signal on Tx1 is single-carrier-like, but the signals on Tx2, Tx3 and Tx4 are no longer SC: The performed manipulations shuffle the order of the frequency samples and disrupt the spectrum of the original signal. This manipulation obviously breaks the SC property and substantially increases the PAPR, as it will be shown in the sequel. Besides, the drawback of SF designs relies on the fact that coding is performed between subcarriers which are subjected to different channel frequency responses, leading thus to some performance degradation.

III. SINGLE-CARRIER QOSFBC

The key advantage of SC-FDMA over its counterparts is known to be its low PAPR. We would like to benefit from the flexibility and robustness of QOSFBC without breaking the SC nature of SC-FDMA (and implicitly increase the PAPR of the transmitted signal). We propose a modified QOSFBC scheme compatible with SC-FDMA. In the following, this modified scheme will be referred to as SC-QOSFBC.

Let us first construct a family of QO extended codes for 4 transmit antennas and let us suppose that they are to be used as space-frequency codes. The quasi-orthogonality equation (4) will still stand These codes, with similar properties and performance as the Jafarkhani codes described in [3], are given by:

$$\mathbf{A}^{(I)}=\begin{pmatrix}\mathbf{A}_{12}^{(I)} & \mathbf{A}_{43}^{(I)}\\ \mathbf{A}_{34}^{(II)} & \mathbf{A}_{21}^{(II)}\end{pmatrix}=\begin{pmatrix} a_1 & -a_2^* & a_4 & -a_3^*\\ a_2 & a_1^* & a_3 & a_4^*\\ a_3 & a_4^* & a_2 & a_1^*\\ a_4 & -a_3^* & a_1 & -a_2^*\end{pmatrix}\begin{matrix}\leftarrow f_{k_1}\\ \leftarrow f_{k_2}\\ \leftarrow f_{k_3}\\ \leftarrow f_{k_4}\end{matrix},$$

$$\mathbf{A}^{(II)}=\begin{pmatrix}\mathbf{A}_{12}^{(II)} & \mathbf{A}_{43}^{(II)}\\ \mathbf{A}_{34}^{(I)} & \mathbf{A}_{21}^{(I)}\end{pmatrix}=\begin{array}{cc}\begin{pmatrix} a_1 & a_2^* & a_4 & a_3^*\\ a_2 & -a_1^* & a_3 & -a_4^*\\ a_3 & -a_4^* & a_2 & -a_1^*\\ a_4 & a_3^* & a_1 & a_2^*\end{pmatrix} & \begin{matrix}\leftarrow f_{k_1}\\ \leftarrow f_{k_2}\\ \leftarrow f_{k_3}\\ \leftarrow f_{k_4}\end{matrix}\\ \begin{matrix}\uparrow & \uparrow & \uparrow & \uparrow\\ \mathrm{Tx1} & \mathrm{Tx2} & \mathrm{Tx3} & \mathrm{Tx4}\end{matrix} & \end{array}. \quad (9)$$

To render SFBC compatible with SC signals, our proposal consists in performing the precoding with frequency samples on subcarriers (k_1, k_2, k_3, k_4) which are no longer adjacent, but given by:

$$\begin{cases} k_2 = (p-1-k_1) \bmod M\\ k_3 = (p-M/2-1-k_1) \bmod M\\ k_4 = (k_1 - M/2) \bmod M\end{cases} \quad (10)$$

where p is an even integer. We shall choose:

$$a_i = s_{k_i},\quad i=1...4 \quad (11)$$

(where $s_{0...M-1}$ are the M outputs of the DFT at a considered time instant) and perform QOSFBC coding considering the coding matrices $\mathbf{A}^{(I)}$ when k_1 is even and $\mathbf{A}^{(II)}$ when k_1 is odd.

At SC-FDMA block level, in the frequency domain, the coding (9) and mapping (10) proposed above result in the following relationships between the frequency samples on the 4 antennas:

$$\begin{cases} s_k^{\mathrm{Tx1}} = s_k\\ s_k^{\mathrm{Tx2}} = (-1)^{k+1} s_{(p-1-k)\bmod M}^*\\ s_k^{\mathrm{Tx3}} = s_{(k-M/2)\bmod M}\\ s_k^{\mathrm{Tx4}} = (-1)^{k+1} s_{(p-M/2-1-k)\bmod M}^*\end{cases},\ (k=0...M-1)\,. \quad (12)$$

An example of such a mapping for $M=12$ and $p=4$ is given in Fig. 2. Let us now denote by $\mathbf{SC}_p$ an operation transforming a vector $\mathbf{s}$ of length M into another vector $\mathbf{s}$' of the same length given by:

$$s_k^{'} = (-1)^{k+1} s_{(p-1-k)\bmod M}^* \quad (13)$$

Applied onto a vector, $\mathbf{SC}_p$ inverses the order of the elements of this vector, cyclically shifts them by p positions, complex conjugates them, and then applies alternative sign inversions. This is an orthogonal operation ($\mathbf{s}$ and $\mathbf{SC}_p(\mathbf{s})$ are orthogonal). With these notations, the relationships between the signals on the 4 transmit antennas are illustrated in Fig. 3.

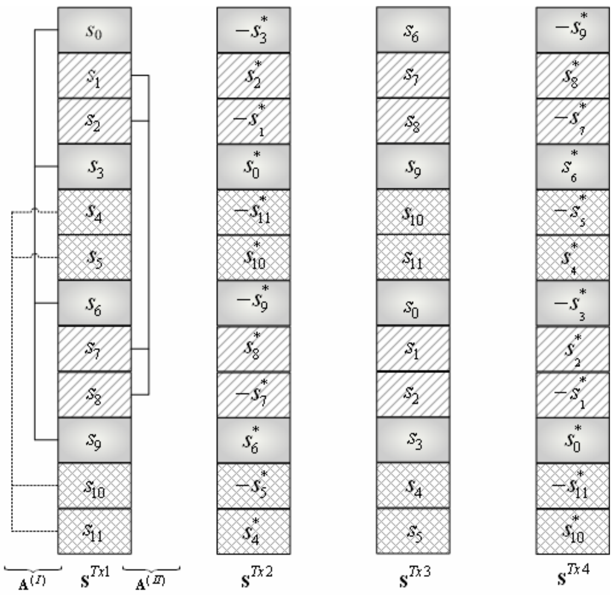

Figure 1 SC-QOSFBC mapping for $M = 12$, $p = 4$; (k_1, k_2, k_3, k_4)={(0, 3, 9, 6), (1, 2, 8, 7), (4, 11, 5, 10)}.

Note that in the case where only 2 Tx antennas are used, employing the particular precoding $\mathbf{s}^{\text{Tx2}}=\mathbf{SC}_p(\mathbf{s}^{\text{Tx1}})$ results in the coding scheme proposed and analyzed in 0.

Because of the rule proposed in (10), the distance between the frequency components which are jointly precoded may vary within one precoded block, and from one precoded block to another. That is why we should minimize the maximum distance between pairs of frequency components that are jointly encoded. Thus, in order to minimize the maximum distance between two subcarriers involved in the QO precoding, p must be chosen as close as possible to $M/4$, which leads to a maximum separation of at most $3M/4$ subcarriers.

Let us denote by x_n , $n = 0 \ldots M\text{-}1$, the modulation symbols forming the data block $\mathbf{x}$ prior to SC-FDMA modulation, *e. g.*, QPSK (Quadrature Phase Shift Keying). The constellation $\mathbf{x}$ will be transmitted on Tx1, after having undergone SC-FDMA modulation. Let us denote by $\mathbf{x}^{\text{equiv,Tx}j}$ the constellation that is equivalently being sent, via SC-FDMA modulation, on antenna Txj ($\mathbf{x}^{\text{equiv,Tx}j}$ is the inverse DFT of the SF precoded frequency samples $\mathbf{s}^{\text{Tx}j}$). With this convention, the time-domain equivalent of (12) becomes:

$$\begin{cases} x_n^{\text{equiv,Tx1}}\Big|_{SC-QOSFBC} = x_n \\ x_n^{\text{equiv,Tx2}}\Big|_{SC-QOSFBC} = e^{j2\pi\frac{(p-1)n}{M}} x^*_{(n+M/2)\bmod M} \\ x_n^{\text{equiv,Tx3}}\Big|_{SC-QOSFBC} = (-1)^n x_n \\ x_n^{\text{equiv,Tx4}}\Big|_{SC-QOSFBC} = e^{j2\pi\frac{(p-M/2-1)n}{M}} x^*_{(n+M/2)\bmod M} \end{cases} .(14)$$

Should x_n be a QPSK symbol, we notice that $\mathbf{x}^{\text{equiv,Tx3}}$ is also formed by QPSK symbols. Thus, after SC-FDMA modulation, transmitted vectors $\mathbf{y}^{\text{Tx1}}$ and $\mathbf{y}^{\text{Tx3}}$ are both SC-

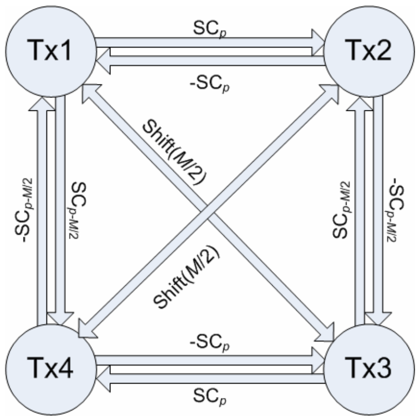

Figure 2 SC-QOSFBC mapping: relationships between the antennas in the frequency domain.

FDMA signals based on QPSK constellations, and they consequently have strictly the same PAPR.By further analyzing (14), we notice that $\mathbf{x}^{\text{equiv,Tx2}}$ and $\mathbf{x}^{\text{equiv,Tx4}}$ are built by rotating a QPSK constellation with phase steps belonging to a finite fixed set of phases. This results in a M'-PSK (Phase Shift Keying) constellation with $M' = M/\gcd(M,p\text{-}1)$ and in a M''-PSK constellation with $M'' = M/\gcd(M,p\text{-}M/2\text{-}1)$, respectively. Here, $\gcd(a,b)$ is the greatest common divisor of the integers a and b. The resulting PSK constellations have the same PAPR as the original QPSK constellation, and since the PAPR of the signal after SC-FDMA modulation is proportional to the PAPR of the original constellation, we can conclude that we will have SC-like signals also on Tx2 and Tx4. This conclusion will be also confirmed by simulations in the next section. Since the channel frequency response is usually different for subcarriers (k_1, k_2, k_3, k_4), we expect some performance degradation. This will be evaluated in the next section.

IV. Simulation Results

We consider the uplink of a cellular system where the SC-FDMA mobile station transmitter has four transmit antennas as described in Fig. 1. Among $N = 512$ subcarriers, 300 are modulated data carriers, the remaining 212 being reserved as guard bands. The 300 data carriers are split into 25 resource units of $M = 12$ subcarriers. After data scrambling, we use a $(753,531)_8$ convolutional code with rate 1/2 prior to QPSK signal mapping. A cyclic prefix with a length of 31 samples is employed. Groups of 16 SC-FDMA symbols are encoded together and sent through a BRAN E [11] multipath channel with spatial correlation among the different transmit/receive antennas. The correlation profile at the mobile station (MS) and base station (BS), respectively, is described in Table I. At the receiver side, a Minimum

TABLE I. Channel Correlation Profile

	Antenna Spacing	Power Azimuth Spectrum	Angle Spread	Direction of Arrival
MS	0.5λ	Laplacian	68°	67.5°
BS	10λ	Laplacian	8°	50°

Mean Square Error (MMSE) detector is used for combining the signals from two receive antennas.

Let us first evaluate the PAPR performance of the schemes presented in Sections II and III. We define the Complementary Cumulative Distribution Function (CCDF) of PAPR as the probability that the PAPR of the analyzed signal be above a certain threshold γ^2. In order to correctly evaluate the PAPR of the signal after digital-to-analog conversion, we applied an oversampling factor of 4, reported in the literature to be sufficient for an accurate PAPR estimation [12]. Fig. 3 comparatively depicts the PAPR performance of QOSTBC, QOSFBC and SC-QOSFBC. As already anticipated, we can see that the proposed SC-QOSFBC has very good PAPR performance and keeps the SC nature of the SC-FDMA signal, just as QOSTBC. On the other hand, as expected from (7), the frequency manipulations involved by QOSFBC lead to an increased PAPR on transmit antennas Tx2, Tx3 and Tx4. At a clipping probability of 10^{-4}, we can lose up to 1.6 dB due to the incompatibility between QOSFBC and SC-FDMA.

Fig. 4 presents comparative performance results in the case 5 localized resource units ($M = 60$ adjacent subcarriers) are allocated to the same user. At a target Bit Error Rate

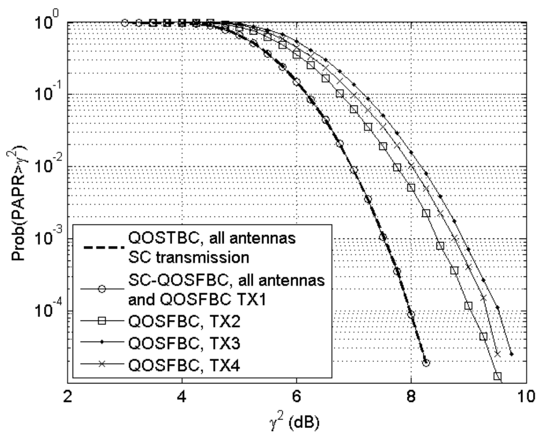

Figure 3: CCDF of PAPR.
(QPSK, oversampling with a factor 4)

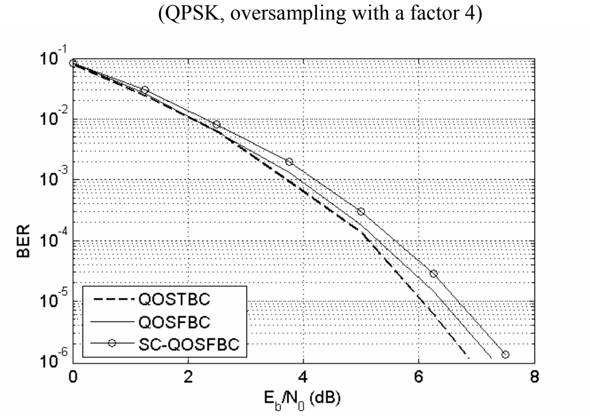

Figure 4: Performance of 4 Tx antennas transmit diversity schemes.
(QPSK 1/2, 60 localized subcarriers)

(BER) of 10^{-4}, we can see that QOSFBC not only loses 1.6 dB in PAPR with respect to QOSTBC, but it also loses 0.2 dB in terms of E_b/N_0 where E_b if the transmit energy per information bit and N_0 is the noise spectral density. In contrast to QOSTBC, SC-QOSFBC offers compatibility with any burst structure at the price of 0.4 dB, but since it keeps the SC nature of the signal, it is overall better than QOSFBC. Note also that we did not take into account any Doppler effect, and therefore QOSTBC is favored with respect to its SF coding counterparts in this analysis.

V. CONCLUSIONS

In this paper, we have analyzed the impact of different types of open loop transmit diversity techniques on the performance of SC-FDMA when four transmit antennas and radio-frequency chains are available at the MS transmitter. We have shown the drawbacks of existent antenna precoding techniques (namely QOSTBC, QOSFBC) and we have proposed a new single-carrier quasi-orthogonal SFBC (SC-QOSFBC) that is compatible with SC-FDMA and that has the flexibility and robustness of classical QOSFBC. This scheme was shown to have only a slight performance degradation compared to QOSTBC and QOSFBC. The strict framing constraints imposed by QOSTBC can be therefore relaxed at the price of a small performance degradation. Compared to classical QOSFBC, the proposed SC-QOSFBC has significantly better performance in the presence of power amplifier nonlinearity.

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