Mapping Techniques for Transmit Diversity Precoding in SC-FDMA Systems with Four Transmit Antennas

Cristina Ciochina, David Mottier, Damien Castelain
Communications Technology Division
Mitsubishi Electric R&D Centre Europe
Rennes, France
[c.ciochina, d.mottier, d.castelain]@fr.merce.mee.com

Hikmet Sari
Department of Telecommunications
Supélec - École Supérieure d'Électricité
Gif sur Yvette, France
hikmet.sari@supelec.fr

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. This paper presents the key design criteria for space-time and space-frequency transmit diversity precoding in SC-FDMA with four transmit antennas. In particular, we propose a novel quasi-orthogonal space-time-frequency precoding. We show that our proposed precoding conserves the single-carrier property of the signal on all of the four transmit antennas with improved performance at the expense of a slight increase of the frame granularity with respect to existing space-frequency solutions.**

Keywords- SC-FDMA, PAPR, Single-Carrier Space-Frequency Block Code (SC-SFBC), Quasi-orthogonal Space-Time-Frequency Block Code (QOSTFBC), Frequency Switched Transmit Diversity (FSTD), extended Alamouti, MIMO.

I. Introduction

Multiple-input multiple-output (MIMO) techniques have become an indispensable part of wireless communications. The use of multiple antennas both at the base station and at the terminal can improve the performance by providing spatial diversity, increase the transmitted data rate through spatial multiplexing, reduce interference from other users, or make some trade-off among the above [1]. MIMO techniques have been incorporated in all recent wireless communications standards (*e.g.*, IEEE 802.11n for wireless local area networks - WLAN, IEEE 802.16e-2005 for WiMAX, 3GPP Long Term Evolution (LTE)) and are actually under discussion at the 3GPP LTE-Advanced. Not only base stations, but also mobile stations in future wireless communication systems will be equipped with at least two or four transmit antennas.

In 3GPP LTE and LTE-Advanced, OFDMA (Orthogonal Frequency Division Multiple Access) and SC-FDMA (Single-Carrier FDMA) have been chosen to embody the downlink and uplink air interfaces, respectively. On the uplink, this choice is motivated by the fact that SC-FDMA combines most of the well-known advantages of OFDMA [2] with the low envelope fluctuations of single-carrier (SC) systems. Thus, the lower Peak-to-Average Power Ratio (PAPR) of SC-FDMA limits the nonlinear effects (spectrum regrowth, performance degradation) avoiding the use of expensive high power amplifiers at the mobile station [3]. The PAPR problem is even more stringent for terminals situated at cell-edge, which are typically power-limited and are subject to bad propagation conditions. For these terminals, it is interesting to use their transmit antennas in order to implement some transmit diversity techniques, allowing them to improve the performance and extend the coverage.

Compatibility between any transmit-diversity technique and SC-FDMA is not guaranteed. The direct use of existing techniques involves either restrictions on the frame duration, or spectrum manipulations that result in significantly increasing the PAPR of the SC-FDMA signal. For two transmit antennas, we have already proposed in [4] an innovative mapping allowing the combination of space-frequency coding with SC-FDMA, with neither restriction on the frame format, nor increase of the PAPR. This solution, called SC-SFBC (SC-Space-Frequency Block Code), was extended to a SC quasi-orthogonal (QO) SFBC [5]. In this paper, we review the existing transmit diversity techniques using four antennas and introduce a new space-time-frequency approach in order to improve the performance of cell-edge terminals.

The paper is organized as follows: The design constraints for implementing transmit diversity in SC-FDMA systems are given in Section II, along with a review of the SC-SFBC and SC-QOSFBC techniques. Section III introduces a new QO space-time-frequency approach. Section IV assesses the performance of these schemes, and conclusions are drawn in Section V.

II. Design Constraints for Transmit Diversity Precoding in SC-FDMA

SC-FDMA recently became popular due to its low-PAPR advantage over OFDMA, while keeping FDMA-like multiple access. SC-FDMA is a precoded OFDMA scheme. The high PAPR problem of OFDMA is alleviated in SC-FDMA by choosing as precoder a DFT (Discrete Fourier Transform), which counter-balances the effects of the inverse-DFT involved by OFDMA processing, thus re-establishing the SC envelope of the signal. Figure 1 shows how space-time (ST), space-frequency (SF) or space-time-frequency (STF) precoding techniques can be implemented in a SC-FDMA transmitter with N_{Tx} transmit antennas and M out of the N subcarriers allocated to one user. At time i, data block vector $\mathbf{x}^{(i)}$, containing M modulation symbols, *e.g.*, Quaternary Phase Shift

This work was supported by the French ANR APOGEE project.

Keying (QPSK) symbols, is *DFT-precoded* by means of an M-sized DFT denoted in its matrix form by $\mathbf{F}_M$. M-sized vectors $\mathbf{s}^{(i)}$ thus obtained are *ST/SF/STF precoded* and the resulting signals $\mathbf{s}^{\mathrm{Tx}_j,(i)}$ (j=0…N_{Tx}-1) go through classical OFDMA modulation (user-specific subcarrier mapping $\mathbf{Q}$, N-sized IDFT and cyclic prefix (CP) insertion), resulting in (N+CP)-sized block $\mathbf{y}^{\mathrm{Tx}_j,(i)}$ to be sent onto the N_{Tx} transmit antennas.

To design precoding techniques for transmit diversity in SC-FDMA systems, we need to make a trade-off between three key constraints: Framing granularity, PAPR, and performance. Indeed, transmit diversity precoding techniques (like, *e.g.*, Alamouti-based codes for $N_{\mathrm{Tx}} = 2$, Jafarkhani-based codes for $N_{\mathrm{Tx}} = 4$, *etc.*) need to code between N_{Tx} samples, at subcarrier level. When precoding is performed as an ST code, samples on the same subcarrier f_k but belonging to N_{Tx} consecutive SC-FDMA symbols are involved (*i.e.*, $s_k^{(i)\ldots(i+N_{\mathrm{Tx}}-1)}$). This increases the system's framing granularity to N_{Tx}, since it imposes that all uplink frames contain a multiple of N_{Tx} SC-FDMA data symbols. Since in many systems control and/or pilot signals are dynamically inserted into the fixed-duration frame, they need to dispose of a flexible number of data symbols in a frame and this granularity increase is not tolerable.

To keep the system's framing granularity to one SC-FDMA symbol, precoding needs to be performed between frequency samples belonging to the same SC-FDMA symbol. This leads to a SF code classically involving N_{Tx} adjacent samples, *i.e.*, $s_{k\ldots k+N_{\mathrm{Tx}}-1}^{(i)}$. Since in practical implementations the size of DFT modules is generally a power of 2 (or it is at least even), imposing that each SC-FDMA symbols contains a multiple of N_{Tx} data subcarriers does not bring any supplementary constraint. But, as we have proven in [4]-[5], performing this type of frequency-domain manipulation leads to important PAPR degradation. We have proposed in [4]-[5] innovative mapping techniques for $N_{\mathrm{Tx}} = 2$ and 4 antennas respectively, allowing PAPR-lossless precoding in the frequency domain. These techniques, coined SC-SFBC and SC-QOSFBC respectively, have a granularity of 1 and SC-like low PAPR, achieved at the expense of some performance loss.

Let us briefly introduce these two techniques and comment on the origin of the performance loss. When two transmit antennas are used, the most straightforward way of implementing the ST/SF precoder is to rely on the elegant yet efficient Alamouti scheme [6]. To avoid the PAPR increase inherent to classical SFBC and the doubled granularity of STBC, we proposed in [4] to precode between the non-adjacent frequency samples s_{k_0} and s_{k_1}, $k_{0,1}$=0…M-1, with k_0 even and:

$$k_1 = \left(p-1-k_0\right) \bmod M\ , \qquad (1)$$

We can ignore the time superscript i, since precoding is performed within the same data block. SC-SFBC consists of choosing $\mathbf{s}^{\mathrm{Tx}_0} = \mathbf{s}$ and $\mathbf{s}^{\mathrm{Tx}_1} = \mathrm{SC}_M^p\left(\mathbf{s}\right)$, where SC_M^p is an operation transforming an M-sized vector $\mathbf{s}$ into an M-sized vector containing the complex conjugate elements of vector $\mathbf{s}$ in reversed order, with alternative sign changes and cyclically shifted down by p positions, where p is an even parameter. This is depicted in the example in Figure 2. We say that $\mathbf{s}^{\mathrm{Tx}_0}$ and $\mathbf{s}^{\mathrm{Tx}_1}$ are "SC-orthogonal". $\mathrm{SC}_{M=12}^{p=6}$ Alamouti-precodes together pairs of frequency samples of index (k_0,k_1) = {(0,5), (4,1), (2,3), (6,11), (8,9), (10,7)}. As we have proven in [4], SC_M^p does not modify the PAPR. The maximum distance between two occupied subcarriers precoded together is $\max(p, M-p)$, which attains a minimum of M/2 for p=M/2.

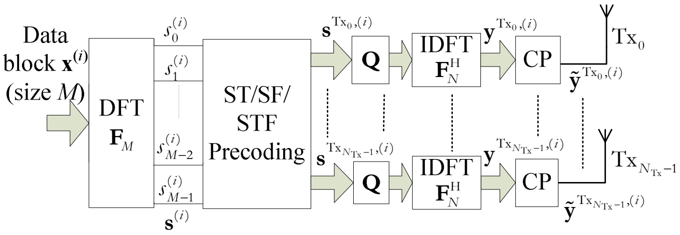

Figure 1. SC-FDMA transmitter block diagram (N_{Tx} antennas).

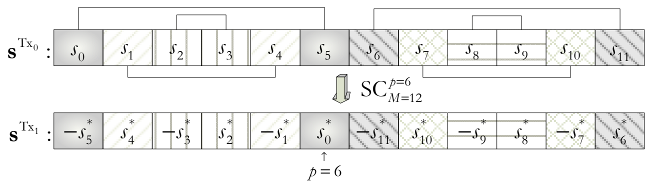

Figure 2. SC-SFBC precoding; example for M=12, p=6.

In the four antenna case, complex orthogonal designs of rate one symbol per channel use do no longer exist [7]. Relaxing the orthogonality condition leads to the family of QO codes [8], whose properties were investigated in [9]. A modified version of this code, also seen as an extended Alamouti code (its generator matrix $\mathbf{A}$ can be expressed based on the generator matrix of the Alamouti code $\mathbf{A}_{01}$/$\mathbf{A}_{23}$), is:

$$\mathbf{A} = \left(\begin{array}{cc} \overbrace{\boxed{\begin{matrix} a_0 & -a_1^* \\ a_1 & a_0^* \end{matrix}}}^{\mathbf{A}_{01}} & \overbrace{\boxed{\begin{matrix} a_2 & -a_3^* \\ a_3 & a_2^* \end{matrix}}}^{\mathbf{A}_{23}} \\ \underbrace{\boxed{\begin{matrix} a_2 & -a_3^* \\ a_3 & a_2^* \end{matrix}}}_{\uparrow\ \mathbf{A}_{23}\ \uparrow} & \underbrace{\boxed{\begin{matrix} a_0 & -a_1^* \\ a_1 & a_0^* \end{matrix}}}_{\uparrow\ \mathbf{A}_{01}\ \uparrow} \end{array}\right) \begin{array}{llll} & \mathrm{ST} & \mathrm{SF} & \mathrm{STF} \\ \leftarrow & i_0 & f_{k_0} & f_{k_0} \\ \leftarrow & i_1 & f_{k_1} & f_{k_1} \\ \leftarrow & i_2 & f_{k_2} & f_{k_0} \\ \leftarrow & i_3 & f_{k_3} & f_{k_1} \end{array} \begin{array}{l} \\ \left.\begin{matrix} \\ \\ \end{matrix}\right\} \text{time } i_0 \\ \left.\begin{matrix} \\ \\ \end{matrix}\right\} \text{time } i_1 \end{array} \qquad (2)$$

$$\mathrm{Tx}_0 \quad \mathrm{Tx}_1 \qquad \mathrm{Tx}_2 \quad \mathrm{Tx}_3$$

QO codes can be classically implemented in SC-FDMA systems by choosing four samples adjacent in the time or in the frequency domain. In QOSTBC for example, we choose time instants $i_{0\ldots3}$ in the ST column from the right-hand part of (2) to be consecutive, ($a_{0\ldots3}$= $s_k^{(i+0\ldots3)}$). This increases the system's granularity to 4. QOSFBC, coding between adjacent occupied carriers $f_{k_{0\ldots3}}$ (SF column from the right-hand part of (2)) at a fixed time i ($a_{0\ldots3}$=$s_{4k+0\ldots3}^{(i)}$, k=0…M/4) degrades the PAPR with up to 1.6 dB [5]. A more detailed description of these codes is given in [5].

To alleviate this problem, we proposed in [5] a novel mapping method, SC-QOSFBC. It consists in applying the code (2) to the frequency samples situated onto non-adjacent occupied subcarriers $f_{k_{0\ldots3}}$ by selecting $a_{0\ldots3}$=$s_{k_{0\ldots3}}^{(i)}$ such that:

$$\begin{cases} k_1 = (p-1-k_0) \bmod M \\ k_2 = (k_0 + M/2) \bmod M \\ k_3 = (p + M/2 - 1 - k_0) \bmod M \end{cases}, \text{ with } k_0 < \frac{M}{2} \text{ even }, \quad (3)$$

where p is an even parameter. The solution is illustrated in Figure 3. for $M = 12$ and $p = 4$. We find that groups (k_0, k_1, k_2, k_3) belong to the set {(0, 3, 6, 9), (2, 1, 8, 7), (4, 11, 10, 5)}. Let us isolate the data carried by a group of subcarriers precoded together, $(f_{k_0}, f_{k_1}, f_{k_2}, f_{k_3})$.

By relaxing the QOSFBC constraints of jointly precoding the data carried by 4 contiguous subcarriers, SC-QOSFBC allows by construction an SC-like PAPR onto all transmit antennas: All signals undergo, two by two, SC-type PAPR-conserving operations. But the maximum distance between subcarriers precoded together is increased from 4 (in classical QOSFBC) to $\max(p + M/2, M - p)$ [5], with a minimum of $3M/4$ for $p=M/4$.

Both SC-SFBC and SC-QOSFBC have low PAPR and a framing granularity of 1, but precoding is performed between non-adjacent subcarriers, separated by a maximum distance of $M/2$ and $3M/4$ subcarriers, respectively. If the subcarriers involved in precoding are rather far apart from each other in the spectrum (typically separated by more than the coherence bandwidth of the frequency selective propagation channel), the Alamouti and/or Jafarkhani codes, originally designed to be mapped onto a static channel, suffer important self-interference which obviously leads to performance degradation. Performance loss occurs and is related to the maximum distance between subcarriers precoded together, when this distance is higher than the channel's coherence bandwidth.

III. Alternative Diversity Precoding Schemes for SC-FDMA with four transmit antennas

A. *Single-Carrier Quasi-Orthogonal Space-Time-Frequency Block Codes*

We propose here a space-time-frequency approach for SC-FDMA with 4 transmit antennas, coined SC-QOSTFBC, and leading to a compromise between the high granularity of QOSTBC and the large maximum distance between subcarriers precoded together of SC-QOSFBC. SC-QOSTFBC relies on precoding together the four samples located onto two distinct subcarriers $f_{k_{0,1}}$ during two intervals of time $i_{0,1}$ (usually consecutive) as illustrated in the last column of the right-hand part of (2). Subcarriers $f_{k_{0,1}}$ are chosen to fulfill (1), in order to ensure low PAPR. We choose $a_{0,1} = s_{k_{0,1}}^{(i_0)}$ and $a_{2,3} = s_{k_{2,3}}^{(i_1)}$. This corresponds to the mapping depicted in Figure 4. A synthetic representation of SC-QOSTFBC is given in Figure 5. We decompose the SC_M^p operation into two separate operations: The first one, named Flip_p, consists of inverting the order of a vector's elements and then cyclically shift them down by p positions. The second one, that we will call $\mathrm{Altconj}$, consists in complex conjugation and sign alternations of the vector it is applied to. In order to prove that SC-QOSTFBC is PAPR invariant, we rely on Figure 5. We already know that signals sent on Tx_0 naturally have a low PAPR, since they are SC-FDMA signals obtained from a classical constellation, *e.g.*, QPSK. Since SC_M^p operations do not modify the PAPR, signals on Tx_1 are also SC-like. To prove that Altconj operations do not modify the PAPR, we rely onto known properties of the DFT. By denoting $\mathbf{s}$=DFT($\mathbf{x}$), let us see how Altconj operation applied in the frequency-domain impacts the time-domain equivalent signal $\mathbf{x}_{\text{equiv}}$=IDFT(Altconj($\mathbf{s}$)).

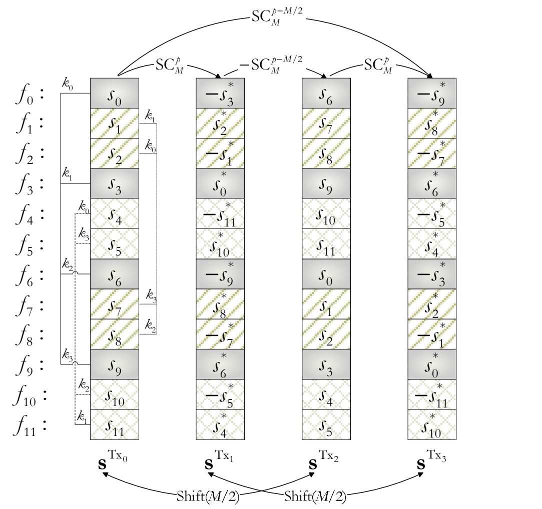

Figure 3. SC-QOSFBC precoding, example for M=12, p=4; (k_0, k_1, k_2, k_3)={(0, 3, 6, 9), (2, 1, 8, 7), (4, 11, 10, 5)}.

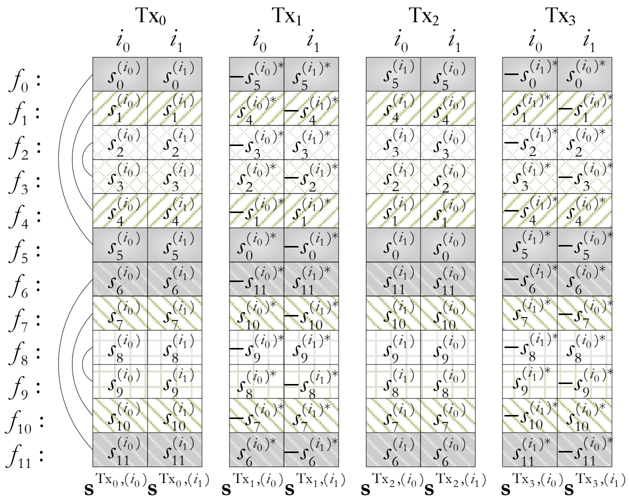

Figure 4. SC-QOSTFBC precoding for M=12, p=6.

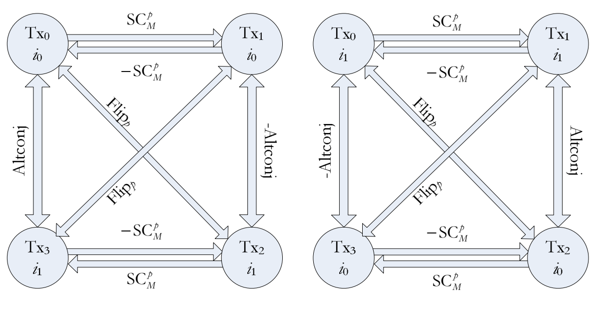

Figure 5. SC-QOSTFBC precoding: relationships between the antennas in the frequency domain.

By further denoting ω_M a M-th order primitive root of unity, we have:

$$x_{\text{equiv}}(n) = \text{IDFT}\left(\underbrace{(-1)^m}_{\omega_M^{mN/2}} s^*(m)\right) = \sum_{m=0}^{M-1} s^*(m)\omega_M^{m(n+N/2)}$$
$$= \left(\sum_{m=0}^{M-1} s\ (m)\omega_M^{m(N/2-n)}\right)^* = x^*\left(N/2-n\right) \tag{4}$$

If $\mathbf{x}$ is a block of QPSK symbols, complex conjugating and changing the order of the symbols does not affect the signal constellation. The SC-FDMA signals sent on Tx3 and based on constellations of type $\mathbf{x}_{\text{equiv}}$ are therefore also SC-like. Finally, the fact that signals on Tx_4 are obtained via SC-SFBC transformation from the signals on Tx_3 suffices to completely prove that SC-QOSTFBC is PAPR-invariant.

From a performance point of view, to limit the self-interference within the group of symbols precoded together, we choose $i_{0,1}$ consecutive (STBC-like) so as to minimize the channel variations in the time domain, and p=M/2 (SC-SFBC like) to minimize the channel variations in the frequency domain. With respect to QO-SFBC, this scheme imposes a doubled frame granularity of 2 symbols, but reduces the maximum distance between precoded subcarriers from 3M/4 to M/2. Aiming at a tradeoff between framing granularity and performance all in conserving the low PAPR, SC-QOSTFBC is a good alternative to SC-QOSFBC when M is not a multiple of 4 or when we cannot guarantee the frame to be composed of a quadruple number of symbols.

B. SC-SFBC with frequency-domain switching

As an alternative to SC QO schemes, which by construction cannot provide full orthogonality between precoded vectors, we consider in this section the combination of SC-SFBC with frequency-domain switching, also called FSTD (Frequency Switched Transmit Diversity). The principle of FSTD is to use different groups of non-overlapping subcarriers for the transmission from different transmit antennas. The space diversity provided by the presence of multiple antennas is hence converted into frequency diversity and recovered via an error correcting code.

In SC-SFBC with frequency-domain switching, the occupied spectrum (M subcarriers) is split into two groups of M/2 subcarriers. Each group of M/2 subcarriers is encoded together in an SC-SFBC manner. This principle, also presented in [10], is depicted in Figure 6. Data block $\mathbf{x}^{(i)}$ of size M is split into 2 parallel streams, $\mathbf{x}'^{(i)}$ and $\mathbf{x}''^{(i)}$ by the serial to parallel (S/P) module. Each stream is processed as in SC-FDMA systems employing SC-SFBC precoding and using M/2 data subcarriers. Groups of antennas (Tx_0, Tx_1) and (Tx_2, Tx_3) are completely decoupled, since they use different groups of subcarriers selected by the $N \times M/2$ subcarrier mapping matrices $\mathbf{Q}'$ and $\mathbf{Q}''$. Here, we consider localized subcarrier mapping: $\mathbf{Q}'$ and $\mathbf{Q}''$ select the first and last M/2 occupied subcarriers, respectively. This scheme can of course also be combined with SFBC, in which case some PAPR degradation is to be expected.

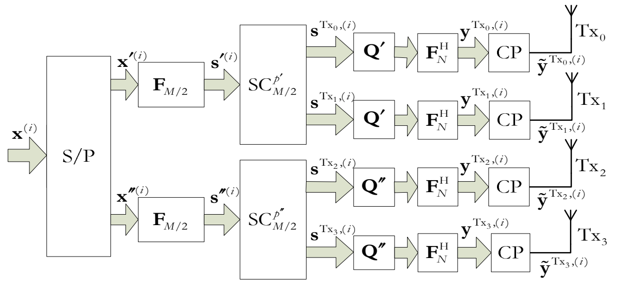

Figure 6. Block diagram of an SC-FDMA transmitter employing SC-SFBC with FSTD (N_{Tx}=4 transmit antennas).

All signals on the 4 transmit antennas preserve the low PAPR properties. On $\text{Tx}_{0,2}$ we send SC-FDMA signals based on the original constellation $\mathbf{x}$, and signals on $\text{Tx}_{1,3}$ are obtained through PAPR-invariant operations of type SC.

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 Figures 1 and/or 6. Among N=512 subcarriers, M_{max}=300 are modulated data carriers, the remaining 212 being reserved as guard bands. After data scrambling, we use a turbo code with rate 1/2 prior to QPSK signal mapping. Each user is allocated a group of M localized, *i.e.*, contiguous subcarriers. A CP of length 31 samples is employed. Groups of 12 SC-FDMA symbols are encoded together and sent through a Vehicular A [11] multipath channel with 6 taps and a delay spread of 2.5μs (corresponding to a correlation bandwidth of about 26 subcarriers in the considered system). Two pilot symbols based on Zadoff-Chu sequences are inserted in each frame of 14 SC-FDMA symbols on the 4th and 11th positions. At the receiver side, we perform Minimum Mean Square Error (MMSE) low-complexity joint equalization and ST/SF/STF decoding in the frequency domain. When QO precoding is employed, we separate groups of 4 subcarriers encoded together and perform MMSE detection as in the narrowband case. In the schemes based on SC-SFBC with frequency switching, the two groups of M/2 subcarriers are easily separated at the receiver and the Alamouti MMSE decoding process can be carried out by pairs of subcarriers coded together. At the base station, we prefer MMSE decoding to maximum ratio combining (MRC) in order to limit the effect of self-interference within the coded pair due to precoding onto subcarriers subject to different fading.

If perfect channel knowledge and two receive antennas are assumed in a system with M=60 subcarriers as in Figure 7, we notice that at a target frame error rate (FER) of 1%, QOSTBC/QOSFBC outperform SC-QOSTFBC, SFBC/SC-SFBC with FSTD, and SC-QOSFBC by 0.1 dB, 0.3 dB, 0.4 dB and 0.5 dB, respectively. SC-QOSFBC is penalized by the large distance between subcarriers precoded together. SC-QOSTFBC diminishes the importance of the self-interference term by reducing the maximum precoding distance, at the expense of doubling the framing granularity. Figure 8, including simple real channel estimation (11 taps Wiener filtering), gives more insight on the performance of the analyzed schemes. Due to precoding on non-adjacent subcarriers, SC-QOSFBC and SC-QOSTFBC still lose 0.4 dB

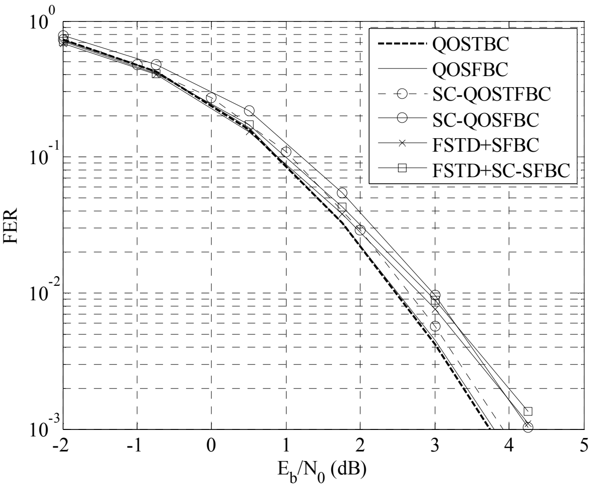

Figure 7. Performance of transmit diversity schemes with 4 Tx antennas: 3 km/h, 60 localized subcarriers, QPSK 1/2, MMSE decoding, 2 receive antennas, perfect channel knowledge.

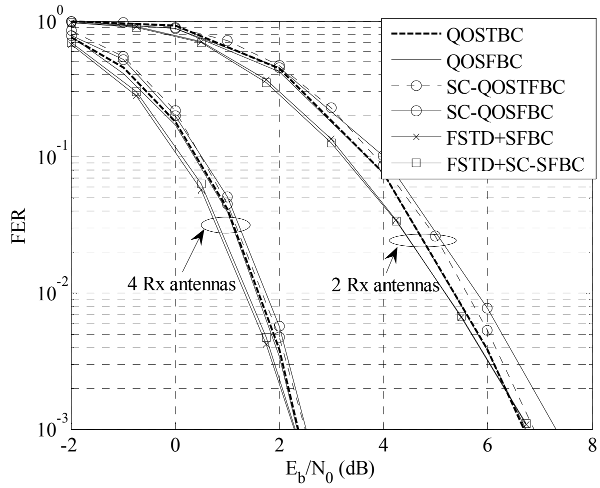

Figure 8. Performance of transmit diversity schemes with 4 Tx antennas: 3 km/h, 60 localized subcarriers, QPSK 1/2, MMSE decoding, 2 and 4 receive antennas, real channel estimation.

and 0.2 dB, respectively, with respect to QOSTBC and QOSFBC when two Rx antennas are employed at the base station. As opposed to the situation in Figure 7, the scheme combining FSTD with SFBC/SC-SFBC outperforms here QOSTBC by 0.2 dB. The good performance of FSTD-based schemes is explained by the fact that, due to the separation in the frequency domain of the four transmit antennas in two groups of two transmit antennas, channel estimation has better performance than in the case of QO codes: In FSTD-based schemes with 2 (resp. 4) Rx antennas, we need to estimate two 2×2 (resp. 2×4) MIMO channels, while in the QO case we need to estimate one 4×2 (resp. 4×4) MIMO channel. When estimating the coefficients of a channel from one transmit antenna, the Wiener filter needs to eliminate both the transmission noise and the jammer signal consisting in the pilots of the other Tx antennas, which is a more difficult task in the 4 antennas case.

Adding more receive antennas diminishes the relative performance difference between the studied schemes: QOSTBC and QOSFBC outperform SC-QOSFBC/SC-QOSTFBC by 0.1 dB/0.05 dB and are outperformed by FSTD with SFBC/SC-SFBC by 0.15 dB. In terms of PAPR, QOSTBC, SC-QOSFBC and SC-SFBC with frequency switching have SC-like performance, while SFBC with frequency switching and QOSFBC lose up to 0.9 dB and 1.6 dB, respectively (for conciseness, simulation results are not presented here). Thus, as a whole, SC-like schemes outperform the others.

V. Conclusions

After reviewing the different approaches to implementing transmit diversity schemes in SC-FDMA systems with 4 transmit antennas, we have proposed a novel space-time-frequency block coding approach (SC-QOSTFBC) that makes a trade-off between framing granularity and FER performance while preserving low PAPR.

Classical QOSTBC and QOSFBC have the problem of high granularity (multiple of 4 data symbols per frame) and PAPR degradation, respectively. The proposed SC-QOSFBC has both framing flexibility and good PAPR properties at the expense of a small performance loss. The novel SC-QOSTFBC thus turns out to be an interesting compromise with a granularity of 2, better performance than SC-QOSFBC, and SC-like PAPR.

References

[1] D. Tse and P. Viswanath, *Fundamentals of Wireless Communications*, Cambridge University Press, 2005.

[2] H. Sari, Y. Levy, and G. Karam, "An Analysis of Orthogonal Frequency-Division Multiple Access," *GLOBECOM '97 Proc.*, vol. 3, pp. 1635-1639, November 1997, Phoenix, Arizona.

[3] C. Ciochina, D. Mottier and H. Sari, "An analysis of three multiple access techniques for the uplink of future cellular mobile systems," *European Transactions on Telecommunications ETT*, no. 19, pp. 581-588, June 2008.

[4] C. Ciochina, D. Castelain, D. Mottier and H. Sari, "A Novel Space-Frequency Coding Scheme for Single Carrier Modulations," *PIMRC'07*Athens, Greece, September 2007.

[5] C. Ciochina, D. Castelain, D. Mottier and H. Sari, "A Novel Quasi-Orthogonal Space-Frequency Block Code for Single-Carrier FDMA," *VTC 2008 Spring Proc.*, Singapore, May 2008.

[6] S.M. Alamouti, "A Simple Transmit Diversity Technique for Wireless Communications," *IEEE Journal on Select Areas in Communications*, vol. 16, no. 8, October 1998.

[7] V. Tarokh, H. Jafarkhani and A. R. Calderbank, "Space-Time Block codes from Orthogonal Designs," *IEEE Transactions on Information Theory*, vol. 45, no. 5, July 1999.

[8] H. Jafarkhani, "A Quasi-Orthogonal Space-Time Block Code," *IEEE Transactions on Communications*, vol. 49, no. 1, Jan. 2001.

[9] M. Rupp and C. F. Mecklenbräuker, "On Extended Alamouti Schemes for Space-Time Coding," *WPMC'02,* Honolulu, Hawaii, October 2002.

[10] Huawei, "Uplink 4 transmit antennas transmit diversity for LTE-Advanced," contribution R1-083021, *3GPP RAN WG1 #54 meeting*, Jeju, South Coreea, Aug 2008.

[11] 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Spatial channel model for MIMO simulations, 3GPP TR 25.996 v8.0.0 (2008-12).