A Space-Frequency Block Code for Single-Carrier FDMA

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A full-diversity space-frequency block code (SFBC) for Single-Carrier Frequency-Division Multiple Access (SC-FDMA) systems is presented. The code is designed for 2 transmit antennas and preserves the low envelope fluctuations of SC signals. We prove the good performance of the proposed scheme over multiple-input multiple-output (MIMO) channels, both in static and in high-speed mobility scenarios.

Introduction: For the Long Term Evolution (LTE) of UMTS (Universal Mobile Terrestrial Systems), the Third Generation Partnership Project (3GPP) chose for the uplink a Single-Carrier Frequency-Division Multiple Access (SC-FDMA) solution, which combines the advantages of the OFDMA-like multiple-access with the low envelope fluctuations of SC-like transmission. In a frequency-domain implementation, SC-FDMA is equivalent to a Direct Fourier Transform (DFT)-precoded Orthogonal Frequency Division Multiple Access (OFDMA), where the DFT transform restores the low envelope fluctuations of the signal, reducing thus the high peak-to-average power ratio (PAPR) of OFDMA. Lately, the use of multiple antennas both at the transmitter and at the receiver gained much interest since it leads to important performance enhancements. In this Letter we will focus on transmit diversity techniques, which increase robustness to signal fading and thereby extend the cell coverage.

System description: The most well-known transmit diversity technique was introduced by Alamouti [1]. This orthogonal code ensures full diversity for a rate of one symbol per channel use (half of the full rate). Fig. 1 shows how Alamouti-type precoding can be implemented in a SC-FDMA transmitter with two transmit antennas and M out of the N subcarriers allocated to that user. The frequency samples $\mathbf{s}^{(t)}$ (corresponding to the data block $\mathbf{x}^{(t)}$ of modulation symbols at instant t) is Alamouti precoded and than fed to a classical OFDMA modulator. The Inverse DFT (IDFT) is usually followed by a Cyclic Prefix (CP) insertion.

As shown in [2], Alamouti precoding can be implemented either as a Space-Time Block Code (STBC) or as a Space-Frequency Block Code (SFBC):

- STBC implementation: On the kth data subcarrier (k=1…M), Alamouti precoding is applied to samples $s_k^{(t)}$ and $s_k^{(t+1)}$ coming from time-consecutive data blocks. This constrains all the bursts to contain an even number of data blocks. Also, STBC is known to be sensitive to high vehicular speeds.
- SFBC implementation: Alamouti precoding is applied to adjacent samples $s_k^{(t)}$ and $s_{k+1}^{(t)}$ within the same data block. This frequency shuffling breaks the SC structure of the signal and significantly increases the PAPR [2].

SC-SFBC: Our target is to build a flexible code (suitable for any burst size), which preserves the SC-like structure and thus the low PAPR properties of SC-FDMA. The main idea relies on performing Alamouti precoding within the same SC-FDMA block (the superscript t can be thus omitted), between non-adjacent frequency samples, following the next procedure:

1) Form pairs (k_1, k_2) ($k_{1,2} \in \{0,\ldots,M-1\}$), where $k_2 = (p-1-k_1)\mathrm{mod}M$; p is an even integer and M stands for the size of the DFT (always even in practice).

2) Perform SFBC-like precoding between samples on the k_1th and k_2th data subcarrier, using the following Alamouti coding matrices:

$$\mathbf{A}^{(I)} = \begin{pmatrix} s_{k_1} & -s_{k_2}^* \\ s_{k_2} & s_{k_1}^* \end{pmatrix}, \quad \mathbf{A}^{(II)} = \begin{pmatrix} s_{k_1} & s_{k_2}^* \\ s_{k_2} & -s_{k_1}^* \end{pmatrix} \begin{matrix} \rightarrow f_{k_1} \\ \rightarrow f_{k_2} \end{matrix}$$
$$\begin{matrix} \uparrow & \uparrow \\ \mathrm{Tx1} & \mathrm{Tx2} \end{matrix} \qquad\qquad \begin{matrix} \uparrow & \uparrow \\ \mathrm{Tx1} & \mathrm{Tx2} \end{matrix} \qquad (1)$$

where $s_{0\ldots M-1}$ are the M outputs of the DFT, to be mapped on the first transmit antenna; $\mathbf{A}^{(I)}$ is used when k_1 is even and $\mathbf{A}^{(II)}$ when k_1 is odd.

Fig. 2 gives an example of SC-SFBC precoding for $M = 8$ and $p = 4$. If the constellation symbols composing $\mathbf{x}$ are sent after SC-FDMA modulation on the transmit antenna (Tx) 1, then a SC-FDMA signal corresponding to $\mathbf{x}^{\mathrm{equiv,Tx2}}=\mathrm{IDFT}(\mathbf{s}^{\mathrm{Tx2}})$ is being sent on Tx2, with:

$$x_n^{\mathrm{equiv,Tx2}}\Big|_{\mathrm{SC\text{-}SFBC}} = e^{j2\pi\frac{(p-1)n}{M}} x^*_{(n+M/2)\mathrm{mod}M} \quad (n = 0\ldots M-1). \qquad (2)$$

We notice that this virtual equivalent constellation $\mathbf{x}^{\mathrm{equiv,Tx2}}$ has the same PAPR as the original constellation $\mathbf{x}$, and since the PAPR of the SC-FDMA modulated signals $\mathbf{y}^{\mathrm{Tx1,2}}$ is proportional to the PAPR of the original constellations, we can conclude that the signal sent on Tx2 ($\mathbf{y}^{\mathrm{Tx2}}$) has SC-type envelope fluctuations, like $\mathbf{y}^{\mathrm{Tx1}}$.

Results: Fig. 3 presents simulation results for a SC-FDMA system with M=60, N=512 and p=30 onto a BRAN-E [3] 2x2 MIMO channel. Compared to SFBC, SC-SFBC has a performance loss in the order of 0.3 dB, due to Alamouti precoding between non-adjacent frequency samples (at a target Bit Error Rate of 10^{-4}). We may note that this 0.3 dB degradation will be reduced with more receive antennas, or less subcarriers, or a less time dispersive channel. In addition, our analysis (not reported here for conciseness) shows that SFBC loses up to 1.1 dB in terms of PAPR with respect to SC-SFBC and STBC. Therefore, SC-SFBC has better overall performance than conventional SFBC. It also slightly outperforms STBC at high vehicular speeds (by 0.3 dB at 324 kmph).

Conclusion: We have introduced a new type of SFBC, which avoids the implementation-related limitations of STBC and the PAPR degradation of conventional SFBC when combined with SC-FDMA. Avoidance of PAPR degradation is achieved with the new SFBC, because it preserves the SC-like envelope of SC-FDMA signals. As a consequence, this new technique leads to better overall performance than conventional SFBC. Furthermore, in addition to its higher flexibility than STBC, it leads to superior performance at high vehicular speeds.

References

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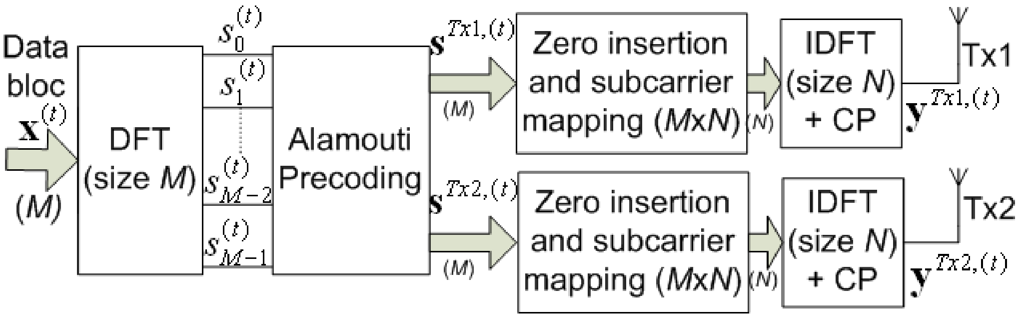
Figure captions:

Fig. 1 Block diagram of a SC-FDMA transmitter (M out of N allocated subcarriers, two transmit antennas).

Fig. 2 SC-SFBC mapping, example for M=8, p=4.

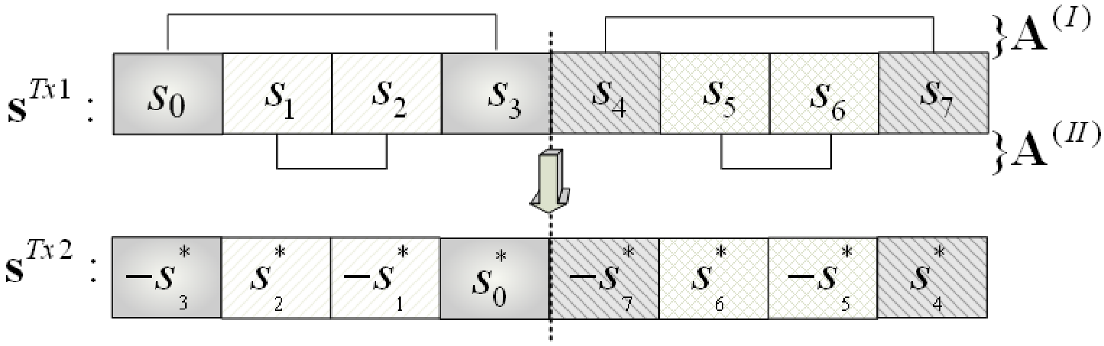
Fig. 3 Bit Error Rate (BER) performance at different vehicular speeds: 60 localized subcarriers, 1/2 convolutionally coded Quadrature Phase Shift Keying, Minimum Mean Square Error decoding with perfect channel estimation, two receive antennas.

Figure 1



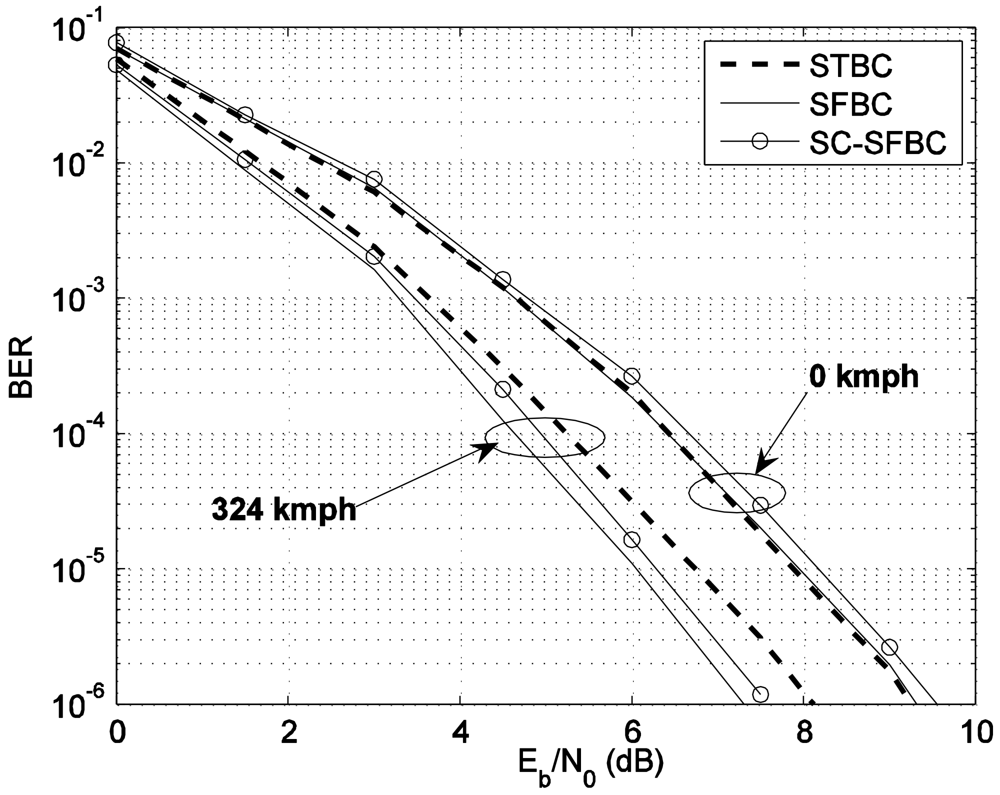
Data
bloc
$\mathbf{x}^{(t)}$
(M)
DFT
(size M)
$s_0^{(t)}$
$s_1^{(t)}$
$s_{M-2}^{(t)}$
$s_{M-1}^{(t)}$
Alamouti
Precoding
$\mathbf{s}^{Tx1,(t)}$
(M)
$\mathbf{s}^{Tx2,(t)}$
(M)
Zero insertion
and subcarrier
mapping (MxN)
(N)
IDFT
(size N)
+ CP
$\mathbf{y}^{Tx1,(t)}$
Tx1
Zero insertion
and subcarrier
mapping (MxN)
(N)
IDFT
(size N)
+ CP
$\mathbf{y}^{Tx2,(t)}$
Tx2

Figure 2



$\mathbf{s}^{Tx1}$:
s_0
s_1
s_2
s_3
s_4
s_5
s_6
s_7
$\}\mathbf{A}^{(I)}$
$\}\mathbf{A}^{(II)}$
$\mathbf{s}^{Tx2}$:
$-s_3^*$
s_2^*
$-s_1^*$
s_0^*
$-s_7^*$
s_6^*
$-s_5^*$
s_4^*

Figure 3


10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
BER
0
2
4
6
8
10
Eb/N0 (dB)
STBC
SFBC
SC-SFBC
0 kmph
324 kmph