A Space-Time Coding Concept for a Multi-Element Transmitter

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Abstract — In this paper we propose a transmission concept that combines phase hopping and space-time coding to enable efficient multi-antenna transmission. The proposed space-time code can be considered as a *non-orthogonal* construction, a sibling of the ABBA code proposed in [7]. The transmission concept proposed here has the advantage that is can be utilized on top of the Alamouti code, essentially without any complexity increase in the terminal demodulator or decoder.

1 Introduction

The third generation WCDMA system, currently being defined in 3GPP has two transmit diversity modes. The closed-loop mode applies terminal-to-base feedback in an attempt to maximize the received signal-to-noise ratio. The closed-loop techniques give remarkable gains with multiple transmit antennas if the feedback signal is highly correlated with the actual downlink channel.

Various open-loop transmit diversity techniques that apply linear or non-linear preprocessing techniques to combat the fading channel have been proposed recently, see e.g. [13] and [8]. The framework in [8] subsumes also the antenna hopping (also called time-division-transmit-diversity (TSTD) in 3GPP[15]), and some frequency offset based solutions [5, 3], and OTD related code-domain solutions [12] as special cases.

The currently adopted open-loop concept applies the two dimensional full rate space-time code[1], known as Space-Time Transmit Diversity (STTD) in 3GPP. However, it is well known that space-time block codes with symbol rate 1 exist only for up to two transmit antennas, see e.g. [9]. When extending the number of transmit antennas beyond two a number of tradeoffs arise, when keeping the overall coding rate fixed. In order to avoid rate matching problems it is highly desirable to construct a rate 1 space-time modulator. One possibility is to adopt a sub-optimal concept that combines STTD and Orthogonal Transmit Diversity (OTD)[17], or some other code multiplexing approach[2]. This are effectively solutions that achieves only order to diversity, and the concepts are very sensitive to interleaver design.

Another family of solutions is to maintain full diversity and full rate, but at the expense of code orthogonality. Such codes and related transmssion concepts were proposed in [7, 6]. These codes perform well but require a more complex receiver (effectively a joint detector) in order to squeeze out the full potential of the code construction. In this paper we follow a slightly different approach and propose a code construction, which improves performance in the presence of channel coding (with or without channel interleaving) and which yields significant gains with a simple receiver.

2 Open-Loop Diversity

The most well known open-loop techniques include delay-diversity[13] and frequency-offset diversity[5]. In certain cases these can be used as add-on features, without a need to change the system specification. In CDMA systems one could also achieve full diversity by allocating multiple channelization codes to a given user and transmitting the information in parallel from M antennas. This, however, would affect the system operation, as the number of orthogonal codes is limited. Orthogonal Transmit Diversity (OTD)[17] applies the same basic concept with the exception that different substreams are transmitted from different antennas using M-time longer orthogonal codes. This does not provide full diversity, and may cause significant interleaver design problems.

Space-time block codes[1, 11, 4] provide a number of interesting solutions when designing systems that are required to achieve full diversity. In order to realize the gains fully most of the the proposed approaches require sufficiently uncorrelated channel coefficients and that these coefficients can be easily estimated sufficiently well in the receiver. With imperfect channel knowledge the orthogonal space-time block codes are only quasi-orthogonal. However, the diversity gain obtained by space-time block codes is mostly needed in slowly fading channels, which can be typically estimated rather accurately. Hence, the imperfection due to channel mismatch often causes only a small loss in performance. On the other hand, when the number of transmit elements is increased a number of trade-offs arise. Namely, one has to balance between simple decoding (code orthogonality), code rate, and the diversity gain. It is likely that in future systems the data rate cannot be compromised and therefore a non-orthogonal full rate space-time code was proposed in [7]. This construction, and in fact any non-orthogonal space-time block code of arbitrary rate, can be combined with a randomization technique which further improves the performance in the presence of channel coding.

2.1 Alamouti code (STTD)

The Alamouti code[1] (a.k.a in 3GPP as space–time transmit diversity, STTD), has symbol rate 1, and it operates as follows. Two complex modulation symbols S_1, S_2 are transmitted from two antennas during two symbol intervals, with the code matrix

$$C(S_1, S_2) \;=\; \begin{bmatrix} S_1 & S_2 \\ -S_2^* & S_1^* \end{bmatrix} . \tag{1}$$

In an one-tap channel with coefficient α_1 and α_2, the received symbol vector (assuming one Rx antenna for simplicity) is

$$\mathbf{r} = \begin{bmatrix} S_1\alpha_1 + S_2\alpha_2 \\ S_1^*\alpha_2 - S_2^*\alpha_1 \end{bmatrix} \;+\; \text{noise} . \tag{2}$$

It is well known that this construction is orthogonal and that the decoding matrix is given by

$$H(\alpha_1, \alpha_2) = \begin{bmatrix} \alpha_1 & \alpha_2 \\ \alpha_2^* & -\alpha_1^* \end{bmatrix} . \tag{3}$$

2.2 Three or Four Transmit Antennas

2.2.1 Orthogonal Designs For three and four Tx antennas, a full diversity space-time block code was proposed in [11]. The proposed code has rate 3/4. Moreover, it is problematic due to its severe power-imbalance; the power transmitted from a given antenna fluctuates between different symbol intervals. Another code, with the same properties (in terms of performance) was proposed in [9]

$$C(S_1, S_2, S_3) = \begin{bmatrix} S_1 & S_2 & S_3 & 0 \\ -S_2^* & S_1^* & 0 & -S_3 \\ -S_3^* & 0 & S_1^* & S_2 \\ 0 & S_3^* & -S_2^* & S_1 \end{bmatrix} . \tag{4}$$

where the peak to average power ratio is slightly smaller[9]. Nevertheless, the code rate remains at 3/4.

2.2.2 Non-orthogonal designs Non-orthogonal designs compromise code orthogonality in order to achieve increase the code rate. An example for a rate 1 design is given below.

ABBA: The Alamouti code defined for two Tx antennas is used as a building block of the ABBA[1] code defined for 3 or 4 transmit antennas as follows

$$C_{ABBA}(S_1, S_2, S_2, S_4) = \begin{bmatrix} C(S_1, S_2) & C(S_3, S_4) \\ C(S_3, S_4) & C(S_1, S_2) \end{bmatrix} \tag{5}$$

The space-time matched filter for the Alamouti code is given in equation (3) and for ABBA the decoding matrix is

$$H_{ABBA}(\alpha_1, \alpha_2, \alpha_2, \alpha_4) = \begin{bmatrix} H(\alpha_1, \alpha_2) & H(\alpha_3, \alpha_4) \\ H(\alpha_3, \alpha_4) & H(\alpha_1, \alpha_2) \end{bmatrix} . \tag{6}$$

The non-orthogonality of this particular space-time code manifests itself as correlation coefficient b in the correlation matrix

$$H_{ABBA}^H H_{ABBA} = \begin{bmatrix} a & 0 & b & 0 \\ 0 & a & 0 & b \\ b & 0 & a & 0 \\ 0 & b & 0 & a \end{bmatrix} , \tag{7}$$

where

$$b = 2\,\mathrm{Re}\,[\alpha_1\alpha_3^* + \alpha_2\alpha_4^*] \tag{8}$$

and

$$a = \sum |\alpha_i|^2 . \tag{9}$$

where α_i is the complex channel channel coefficient between antenna i the the receiving antenna.

Randomized ABBA (RABBA): Randomization can be used to improve ABBA in slowly fading channels where the correlation coefficient b remains effectively constant over a coding block. In order to provide (self-)interference diversity we proposed a method to randomize the correlation between different space-time coded blocks[6], which is summarized below. In some cases proper randomization may even enable us to dispose of channel interleaving, and thereby to reduce the transmission delay.

One approach to achieve randomization is to weight at least one antenna output by a constant amplitude (complex) signal, changing pseudo-randomly after each ABBA block. The pseudo-random sequence would be known to the receiver, who could thus use e.g. common channels for channel estimation. For example, the coefficient $\exp(j\theta_t)$ can be applied to two ABBA rows (e.g. rows 3 and 4), and the coefficient is changed after each ABBA block. In addition gain g_m (possibly time-varying) can be applied for antenna m. Then the correlation coefficient takes the value

$$b_t = 2\,\mathrm{Re}\,[\exp(j\theta_t)g_1\alpha_1 g_3\alpha_3^* + \exp(j\theta_t)g_2\alpha_2 g_4\alpha_4^*] . \tag{10}$$

Typically, we like to keep all gains equal, in order to maximize diversity. However, it can be seen that with unequal gains the correlations are reduced and therefore a simpler

[1]The name "ABBA" stems from the block structure where two Alamouti codes A and B are as building blocks, see [7] for details.

decoder may suffice. In fact, if for example $g_1 = g_2 = 0$ we obtain the two antenna Alamouti code. If only $g_3 = 0$ we get three antenna transmission with different interference statistics, and so on. With the phase evenly distributed, this clearly randomizes the interference coefficient without changing the effective correlation averaged over time and without sacrificing the diversity gain. [2]

The scheme described above can be considered as a special case of a generic scheme in which the performance of an arbitrary space-time code is improved by ergodizing the channel[6]. Indeed, any space-time code can be described in terms of a $T \times N$ code-matrix C of the form (1,4), transmitting some symbol from N antennas during T symbol intervals. Unitary transformations can be applied on the matrix from both sides, $\tilde{C} = UCV$. For a non-orthogonal code unitary transformations change the correlations, as seen above. Due to the simple form of the ABBA non-orthogonality (7), the unitary transformations for RABBA are of the simple form described above.

2.3 Phase hopping STTD ("Trombi")

Yet another "non-orthogonal" design can be constructed e.g. as follows

$$C_{tr}(S_1, S_2, S_2, S_4) = \begin{bmatrix} C(S_1, S_2) & \exp(j\theta_t)C(S_1, S_2) \\ C(S_3, S_4) & \exp(j\theta_{t-1})C(S_3, S_4) \end{bmatrix} \quad (11)$$

where $\{\theta_t\}$ is a phase hopping sequence. In this construction we have two identical copies of the Alamouti code (or some other orthogonal space-time code) and the are summed together with pseudo-random phases. In general, of course, there can be a different phase hopping patterns in different antennas. We call code constructions of this type "Trombi" in the following.

In the Trombi construction the terminal sees a linear combination of the channels. In the following we assume that there are two different phase hopping patters, each randomizing one branch of the STTD code. Then, the effective received channels for two successive symbols (at the input the STTD decoder after signal combining) are given by

$$\tilde{\alpha}_1 = \alpha_1 + \exp(j\theta_1)\alpha_2, \quad (12)$$

$$\tilde{\alpha}_2 = \alpha_3 + \exp(j\theta_2)\alpha_4, \quad (13)$$

and these can be used in the STTD decoder in place of the actual channel coefficients. Preferably the phase hopping coefficients are defined jointly so that $\exp(j\theta_1) = -\exp(j\theta_2)$, since this will induce no performance loss in AWGN channel. However, if the channels are uncorrelated arbitrary hopping patterns are equally good (e.g. the one given above). One can for example use hopping patterns from an $8 - PSK$ constellation.

The Trombi code can be applied either so that the terminal measures only the effective channels (in which no change to 3G specification is needed) or by enabling channel estimation for each of the constituent channels $\alpha_1, \alpha_2, \alpha_3, \alpha_4$ (e.g. by using common pilot channels) from which effective channels can be derived, together with the known hopping patterns. In the latter case the dedicated hopping pattern can be arbitrary, since the channel estimation performance need not be compromized. We note in passing that this concept can be combined easily with the current closed-loop modes, where the "hopping pattern" is optimzed with terminal to base feedback.

[2] In highly correlated channels it may be sensible to use a different weight for antennas 3 and 4.

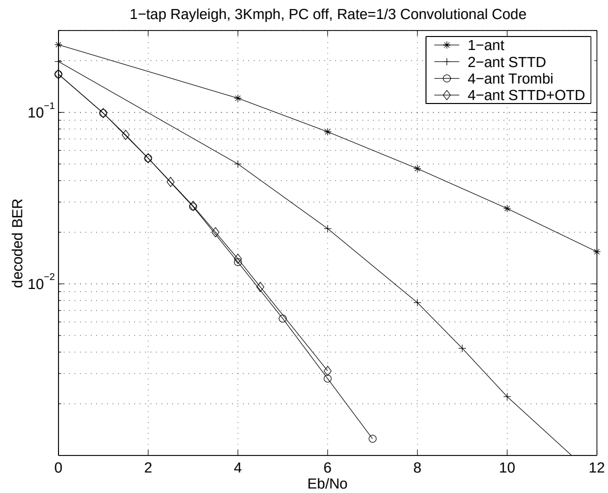

Figure 1: Performance of single antenna transmission, STTD (with 2 tx antennas) STTD-OTD transmission, and Trombi transmission, in a single path Rayleigh fading channel at $3km/h$.

3 Performance

We consider rate 1/3 convolutional coded transmission in a Rayleigh fading channel. The signal is transmitted QPSK modulated using either single transmit antenna, STTD (two transmit antennas), Combined OTD and STTD[17] (with improved interleaving), or Trombi. The performance of the different open-loop concepts are given in Fig. 1 and Fig. 2. The simulation assumptions are summarized in Table 1.

channel	Rayleigh fading, single path
modulation	QPSK
encoding	rate 1/3 CC
interleaving	Block (two interleavers for OTD)
Power control	Off
Randomization	300 Hz Phase hopping sequence for Trombi

Table 1: Simulation Assumptions

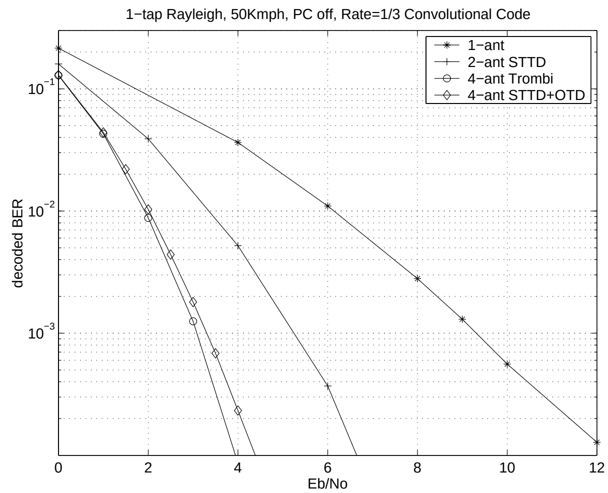

Figure 2: Performance of single antenna transmission, STTD (with 2 tx antennas) STTD-OTD transmission, and Trombi transmission, in a single path Rayleigh fading channel at $50 km/h$.

We note that the performance of Combined STTD+OTD is significantly worse if the WCDMA interleaver is used, in place of two separate interleavers applied here for the OTD branches.

4 Conclusion

In this paper we have discussed multi-antenna transmission concepts that are currently being considered for the WCDMA system. The open-loop concept proposed in the paper (Trombi) can be used effectively with the current STTD decoder, with only marginal changes to the system description (if any). The performance gain with the proposed four antenna transmission concepts, when compared to two antenna transmission (STTD) is considerable.

References

[1] 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, October, 1998.

[2] K.Ban, M. Katayama, W. Stark, T. Tamamoto and A. Ogawa, "Convolutionally coded DS/CDMA system using multi-antenna transmission," in *Proc. IEEE Globecom '97*, Phoenix, Arizona, Nov. 1997.

[3] W. -L. Kuo and M. P. Fitz, "Design and analysis of transmitter diversity using intentional frequency offset for wireless communications," *IEEE Trans. Vehic. Tech.*, Vol. 46, no. 4, pp. 871-881, November, 1997.

[4] J.-L. Guey, M. P. Fitz, M. R. Bell and Y. Kuo, "Signal design for transmitter diversity wireless communication systems over Rayleigh fading channels," to appear in *IEEE Trans. Comm.*.

[5] A. Hiroike, F. Adachi and N. Nakajima, "Combined effects of phase sweeping transmitter diversity and channel coding," *IEEE Trans. Vehic. Tech.,* Vol. 41, No. 2, pp. 170-176, May 1992.

[6] A. Hottinen and O. Tirkkonen, " A randomization technique for non-orthogonal space-time codes," in *Proc. IEEE VTC*, Rhodes, Greece, May 2001.

[7] O. Tirkkonen, A. Boariu and A. Hottinen, "Minimal orthogonality space-time block code for 3+ Tx antennas," *Proc. IEEE Int. Symp. Spr. Spect. Tech. Appl. (ISSSTA)*, New Jersey, USA, September 2000.

[8] A. Narula, M. Trott and G. Wornell, "Information-theoretic analysis of multiple-antenna transmission diversity," in *Proc. Int. Symp. Inform. Th. Appl.*, Canada, Sept. 1996.

[9] O. Tirkkonen and A. Hottinen, "Complex space-time block codes for four tx antennas," in *Proc. IEEE Globecom*, San Francisco, CA., November, 2000

[10] V. Tarokh, A. Naguib, N. Seshadri and A. R. Calderbank, "Space-time codes for high data rate wireless communications: performance criteria," in *Proc. IEEE Int. Conf. Commun.*, Montreal, Canada, June 1997.

[11] V. Tarokh, H. Jafarkhani and A. R. Calderbank, "Space-time clock coding for wireless communications: theory of generalized orthogonal designs,"*IEEE Trans. Inf. Th.*, 1999.

[12] V. Weerackody, "Diversity for the direct-sequence spread spectrum system using multiple transmit antennas," in *Proc. IEEE Int. Conf. Comm.*, Geneva, Switzerland, 1993.

[13] A. Wittneben, "A new bandwidth efficient transmit antenna modulation diversity scheme for linear digital modulation," in *Proc. IEEE Int. Conf. Commun.*, pp. 1630-1634, Geneva, Switzerland, 1993.

[14] Samsung Electronics, "Proposal for Downlink Time Switched Transmission Diversity," Contribution to ETSI SMG2 L1, Bocholt, Germany, May 18-20, 1998.

[15] Nokia, "Downlink Transmit Diversity," Contribution to ETSI SMG2 L1, Bocholt, Germany, May 18-20, 1998.

[16] Motorola, "Orthogonal Transmit Diversity for Direct Spread CDMA," Contribution to ETSI SMG2, Stockholm, Sweden, September 15-17, 1997.