A Randomization Technique for Non-Orthogonal Space-Time Block Codes

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Abstract

In this paper we propose a transmission concept that improves the performance of high rate non-orthogonal space-time block codes. Orthogonal space-time codes have well known rate limitations [9], [7]. If the symbol rate is increased beyond those limits either code orthogonality [5] or the effective diversity gain is necessarily compromised. In the presence of channel coding the performance of non-orthogonal space-time codes is further degraded by "block-interference" inherent in the code construction. In this paper we present a general approach in which the non-orthogonality is randomized with a sequence of pseudo-random unitary transformations.

I. Introduction

The third generation WCDMA system, currently being defined in 3GPP[12], 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. However, there are cases where the feedback signal cannot be used for this purpose. For example, common channels typically need to be transmitted throughout the cell. In addition, in some cases the feedback signal is not sufficiently reliable or is for some other reason uncorrelated with the downlink channel. The open-loop mode is used in these cases in order to improve system performance. The currently adopted open-loop concepts apply antenna hopping and the two dimensional full rate space-time code[1], known as Space-Time Transmit Diversity (STTD) in 3GPP.

The closed-loop modes can be, in principle, augmented rather straightforwardly to the cases where there are three or more transmit elements in the base station. The simplest solution is to provide additional feedback signals for the additional antenna elements. However, with open-loop concepts these extensions are not so straightforward. Space-time block codes with symbol rate 1 exist only for up to two transmit antennas. If a full rate space-time code is not used the transmission concept has to increase the rate of channel coding, in order to maintain a given overall coding rate. In order to avoid the rate limitation several concepts have been devised which increase the symbol rate but reduce the diversity gain of the system. As an example, we can combine two well known concepts, STTD and Orthogonal Transmit Diversity (OTD)[15]. This solution obtain effectively the same diversity order as STTD alone, but a performance gain can be realized in the presence of channel coding and interleaving.

Related open-loop transmit diversity techniques apply various linear or non-linear preprocessing techniques to combat the fading channel. For example, linear pulse shaping (FIR filtering) techniques were proposed in [11] to provide transmit diversity without bandwidth expansion in single and multi-antenna systems. A related linear filtering approach has been subsequently advocated in [6]. The framework in [6] subsumes also the antenna hopping (also called time-division-transmit-diversity (TSTD) in 3GPP[13]), frequency offset based solutions [4], [2], and OTD relaed code-domain solutions [10] as special cases.

The major limitation of orthogonal full-diversity, full rate space-time block codes (STBC) is that they exist only when there are 2 antenna elements in the base station. Whereas the previous solutions, summarized above, compromise the diversity gain, a different solution was proposed in [5]. In [5] code orthogonality was sacrificed in order to device full rate space-time block codes for $M > 2$ transmit antennas. In this paper we follow this approach and propose an extension, which improves performance in the presence of channel coding (with or without channel interleaving). This is achieved by converting a block-interference channel into one where the code correlations are randomized.

II. Open-Loop Diversity

The most well known open-loop techniques include delay-diversity[11] and frequency-offset diversity[4]. 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)[15] 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], [9], [3] 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 [5]. 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.

A. 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

$$C(S_1,S_2) \;=\; \left[\begin{array}{cc} S_1 & S_2 \\ -S_2^* & S_1^* \end{array}\right] . \tag{1}$$

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

$$\mathbf{r} = \left[\begin{array}{c} S_1\alpha_1 + S_2\alpha_2 \\ S_1^*\alpha_2 - S_2^*\alpha_1 \end{array}\right] \;+\; \text{noise} \;. \tag{2}$$

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

$$H(\alpha_1,\alpha_2) = \left[\begin{array}{cc} \alpha_1 & \alpha_2 \\ \alpha_2^* & -\alpha_1^* \end{array}\right] . \tag{3}$$

B. Three or Four Transmit Antennas

B.1 Orthogonal Designs

For three and four Tx antennas, a full diversity space-time block code was proposed in [9]. 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 [7]

$$C(S_1,S_2,S_3) = \left[\begin{array}{cccc} S_1 & S_2 & S_3 & 0 \\ -S_2^* & S_1^* & 0 & -S_3 \\ -S_3^* & 0 & S_1^* & S_2 \\ 0 & S_3^* & -S_2^* & S_1 \end{array}\right] . \tag{4}$$

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

B.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

$$C_{ABBA}(S_1,S_2,S_2,S_4) = \left[\begin{array}{cc} C(S_1,S_2) & C(S_3,S_4) \\ C(S_3,S_4) & C(S_1,S_2) \end{array}\right] \tag{5}$$

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

$$H_{ABBA}(\alpha_1,\alpha_2,\alpha_2,\alpha_4) = \left[\begin{array}{cc} H(\alpha_1,\alpha_2) & H(\alpha_3,\alpha_4) \\ H(\alpha_3,\alpha_4) & H(\alpha_1,\alpha_2) \end{array}\right] . \tag{6}$$

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

$$H_{ABBA}^H H_{ABBA} = \left[\begin{array}{cccc} a & 0 & b & 0 \\ 0 & a & 0 & b \\ b & 0 & a & 0 \\ 0 & b & 0 & a \end{array}\right] , \tag{7}$$

[1]The name "ABBA" stems from the block structure where two Alamouti codes A and B are as building blocks, see [5] for details.

where

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

and

$$a = \sum |\alpha_i|^2. \qquad (9)$$

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

Randomized ABBA (RABBA): In a block fading channel the correlation coefficient (b) is constant leading to "block-interference channel". Clearly, such interference can not be randomized by interleaving, and hence in general in slowly fading channels coded BER can suffer. In order to provide interference diversity we propose to randomize the correlation between different space-time coded blocks. 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. Then the correlation coefficient takes the value

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

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] In general antenna gains may be changed as well. If g_m is the gain for antenna m, the correlation coefficient is given by

$$b_t = 2\,\mathrm{Re}\,[\exp(j\theta_t)g_1\alpha_1 g_3\alpha_3^* + \exp(j\theta_t)g_2\alpha_{24}\alpha_4^*]. \quad (11)$$

However, this change compromises the diversity gain. If $g_1 = g_2 = 0$ we get the two antenna Alamouti code. If only $g_3 = 0$ we get three antenna transmission with different interference statistics, and so on. Figure 1 shows the cumulative distribution of the normalized correlation coefficient b/a in a case where the channels are circular complex Gaussian. It is seen that the correlation properties are slightly better with three antennas (i.e. when $g_3 = 0$ with legend $M = 3$) than with the full four antenna case (with legend $M = 4$). In a stationary channel, without randomization, the channel decoder following ABBA, is faced with one realization of said

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

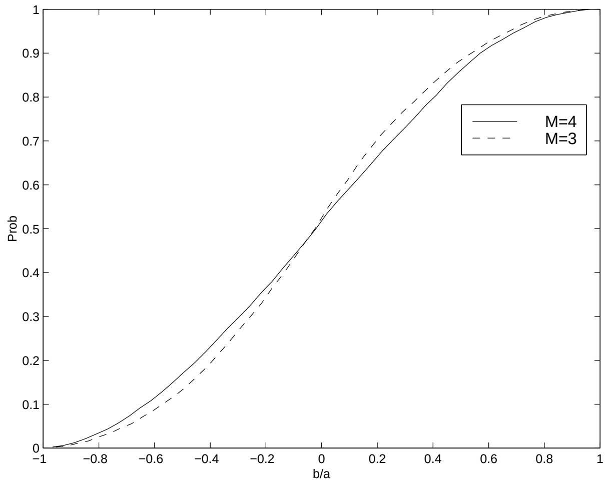

Fig. 1. Cumulative distribution of normalized correlation values b/a for randomized ABBA with three ($M = 3$) and four ($M = 4$) transmit antennas.

distribution. In contrast, the randomization produces multiple samples from said distribution within one encoding block.

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. 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, $\tilde{C} = UCV$. If the code is orthogonal, these transformations do not change the performance. For a non-orthogonal code, however, an unitary transformation changes the correlations, as seen above. By using a pseudo-random sequence of unitary transformations, any non-orthogonal space-time code can be improved in slowly fading channels. Due to the simple form of the ABBA non-orthogonality (7), the unitary transformations for RABBA are of the simple form described above.

C. *Performance with an outer code*

We consider rate 1/3 Turbo coded transmission with 318 bit frame size and random interleaving. The channel is block Rayleigh fading and the Turbo code is concatenated with a four TX antenna transmission using either ABBA or RABBA. The simulation assumptions are summarized in Table 1.

We assume perfect power control such that the received signal power a is fixed for all comparisons. The non-orthogonality b varies according to whether randomization is used or not, and obviously it depends on

channel	Block Rayleigh fading over frame
modulation	BPSK spreading, BPSK symbols
encoding	rate 1/3 PCCC, with generators 7_8 and 5_8
Turbo interleaving	318(+2 tail) bits. random interleaver
Power control	Perfect (i.e., fixed a)
Randomization	Random phase for each transmit antenna for RABBA

TABLE I
SIMULATION ASSUMPTIONS

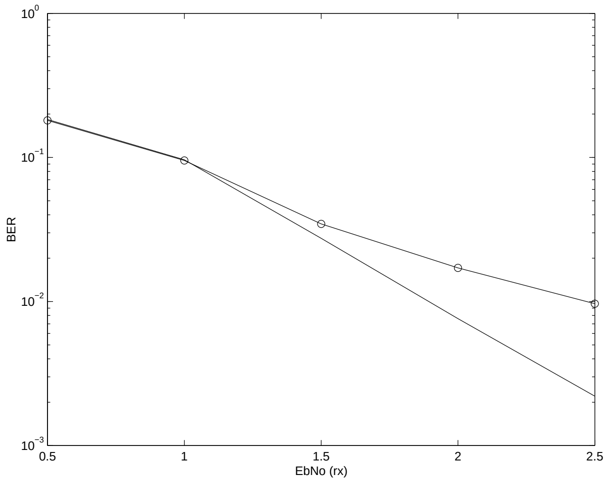

Fig. 2. Bit–error rates of Turbo coded ABBA (-o-) and RABBA (-) in a block fading channel. There are 6 iterations in Turbo decoding.

the actual channel realization. It is clear that randomization does not help when there is no channel coding in the system, and therefore we do not elaborate the performance at symbol level. The performance of Turbo coded transmission is given in Fig. 2. The randomized code uses only phase rotations and therefore has the same received power as the ABBA code. From Fig. 2 we can see that the performance of RABBA does not saturate whereas that of ABBA does. Thus we have ergodized the inherently non-ergodic channel. No attempt was made to optimize the randomization (the phase-hopping sequence). In some cases it may be desirable to consciously reduce the diversity gain as well (with parameters g_1 and g_2). Then the concept can continuously switch between a limited diversity system for which simple decoding suffices (as in OTD or TSTD) and a full diversity full rate system (e.g. ABBA) requiring a slightly more involved receiver.

III. CONCLUSION

We have proposed a randomization scheme for non-orthogonal space-time block codes. The concept was shown to provide significant gains in the presence of a concatenated encoding concept, where the inner coder is a non-orthogonal space-time code and the outer code is a Turbo code. The proposed general approach, combined e.g. with the ABBA code[5], provides an attractive avenue for increasing data rates in future systems.

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