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Closed-Loop Extended Orthogonal Space Frequency Block Coding Techniques for OFDM Based Broadband Wireless Access Systems

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Abstract—A simple extended orthogonal space-frequency coded multiple input single output (MISO) orthogonal frequency division multiplexing (OFDM) transmitter diversity technique for wireless communications over frequency selective fading channels is presented. The proposed technique utilizes OFDM to transform frequency selective fading channels into multiple flat fading sub-channels on which space-frequency coding is applied. A four-branch transmitter diversity system is implemented without bandwidth expansion and with only one receive antenna. The associated simulations verify that the four-branch transmitter diversity scheme achieves a significant improvement in average bit-error rate (BER) performance. The proposed scheme also outperforms the previously reported scheme due to *Yu, Keroueden, and Yuan* with only single phase feedback, and that improvement is retained with quantized feedback. Since the angle feedback is on a per tone basis, the feedback information would be too large for any practical OFDM system. However, we adopt a method which exploits the correlation among the feedback terms for the subcarriers, i.e. a group based quantization technique to reduce the feedback overhead significantly, rendering this scheme attractive to broadband wireless access systems. The performance improvement of convolutionally concatenated space-frequency block coding (CCSBC) schemes is also investigated.

Index Terms– Closed-loop (EO-SFBCs), Phase rotation, array gain, diversity gain, coding gain.

I. INTRODUCTION

Spatial diversity combined with OFDM is an effective technique for mitigating detrimental effects in broadband wireless multipath fading channels. A key element of OFDM is the utilization of a large number of independent harmonically spaced sub-carriers which are formed in a computationally efficient manner with the fast Fourier transform (FFT). The use of multiple antennas for diversity can enhance channel capacity, making MISO a very attractive practical system. Conventionally, multiple antenna systems have been employed at the receiver side. This increase of receiver hardware can be a major drawback, particularly for portable receivers where physical size and cost are restricted. Transmit diversity has therefore received increased interest, typically for the downlink, as it can achieve diversity gain without increasing the size and complexity of the portable receiver.

Research on adapting several closed-loop methods for STBCs has been proposed to attain full code rate and full diversity. In [1] and [2] the phases of the signals transmitted from certain antennas are rotated in a prescribed way in order to make the code orthogonal based upon the information fed back from the receiver, thereby increasing the diversity gain. Consequently, these techniques are often only effective over slowly-varying flat fading channels.

Space-time coded OFDM (ST-OFDM) systems [3][4], have been proposed for frequency selective fading channels. In [4], it was shown that OFDM modulation with cyclic prefix can be used to transform frequency selective fading channels into multiple flat fading channels, so that orthogonal space-time transmitter diversity can be applied, even for channels with large delay spread. Another approach for transmission over MISO channels using OFDM is to replace the "time" dimension with the "frequency" dimension. The result is called space-frequency coded OFDM (SF-OFDM) transmitter diversity, which has also been suggested in [3].

In this paper, we propose closed-loop space-frequency block coding (SFBC) algorithms for OFDM to achieve full transmit diversity in terms of transmit antennas and array gain, and demonstrate that one bit feedback per subcarrier is adequate to obtain satisfactory performance. In particular, we develop a new scheme to maximize the signal to noise ratio (SNR) improvement as compared to previously reported work in [2] and [5]. For reference, quasi-orthogonal space-frequency coded OFDM (QO-SFBC) has also been considered [1]. Simulation results show that the average bit error rate performance of the proposed scheme outperforms previous schemes even when the scheme is quantized and when the fading channel is frequency-selective. Moreover, by exploiting feedback correlation among subcarriers, a group based quantization technique is proposed to reduce the feedback overhead significantly, while maintaing satisfactory performance, making this scheme very attractive to broadband wireless access such as WLANs and WMANs such as IEEE 802.11a [6], IEEE 802.16a [7]. In addition, the performance improvement is also investigated when the proposed scheme is combined with convolutional codes, so as to exploit coding gain. Other coding schemes such as turbo-like techniques are not considered due to their larger complexity.

The organization of this paper is as follows. In Section II we describe the closed-loop EO-SFBC for OFDM. In Section III, the concatenation of the closed-loop method
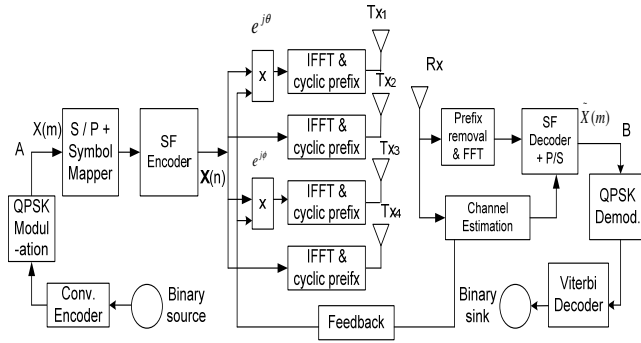
Fig. 1. Baseband representation of the proposed closed-loop space-frequency MISO-OFDM transmitter diversity system.

with convolutional codes (CCSBC) is explained. Simulation results are presented in Section IV and finally some concluding remarks are provided in Section V.

II. CLOSED-LOOP EO-SFBC FOR OFDM

The proposed EO-SFBC scheme for the enhancement of diversity with four transmit antennas for an OFDM system is shown in Fig.1. We consider the following 2×4 EO-SFBC code matrix similar to the code in [2], where a method was proposed to construct full rate SF codes from full-diversity ST codes [8] via a repetition mapping,

$$
\mathbf{C} = \left[\begin{array}{cccc} X_0(n) & X_0(n) & X_1(n) & X_1(n) \\ -X_1^*(n) & -X_1^*(n) & X_0^*(n) & X_0^*(n) \end{array} \right] \quad (1)
$$

where the symbol in the i-th row and j-th column is transmitted through the j-th transmit antennas on the i-th frequency tone during the block instant n.

By taking the complex conjugate of the second row for convenience, the equivalent received signal vector for one receive antenna can be obtained as $\mathbf{R}(n) = [R_1, R_2^*(n)]^T$ and the equivalent noise vector becomes $\mathbf{Z}(n) = [Z_0(n), Z_1(n)]^T$. The result is the matrix equation $\mathbf{R}(n) = \mathbf{H}(n)\mathbf{X}(n) + \mathbf{Z}(n)$, with $\mathbf{X}(n) = [X_0(n), X_1(n)]^T$, and the matrix $\mathbf{H}(n)$ defined as

$$
\mathbf{H}(n) = \left[\begin{array}{cc} \Lambda_0(n) + \Lambda_1(n) & \Lambda_2(n) + \Lambda_3(n) \\ \Lambda_2^*(n) + \Lambda_3^*(n) & -\Lambda_0^*(n) - \Lambda_1^*(n) \end{array} \right] \quad (2)
$$

At the receiver, the matched filtering is performed by premultiplying by $\mathbf{H}^H(n)$ in each subcarrier, as follows:

$$
\begin{aligned}
\mathbf{H}^H \mathbf{R}(n) &= \mathbf{H}^H(n)\mathbf{H}(n)\mathbf{X}(n) + \mathbf{H}^H(n)\mathbf{Z}(n) \\
\tilde{\mathbf{R}}(n) &= \mathbf{\Delta}(n)\mathbf{X}(n) + \tilde{\mathbf{Z}}(n) \quad (3)
\end{aligned}
$$

where $\tilde{(\cdot)}$ denotes a quantity preprocessed by $\mathbf{H}(n)^H$. It can be shown that as this an orthogonal block code, all the off-diagonal terms of $\mathbf{\Delta} = \mathbf{H}^H(n)\mathbf{H}(n)$ will be zero. It is thus reasonable to expect the proposed EO-SFBC for OFDM transmit diversity system to achieve full diversity. However, the factor $\beta(n)$ as shown in equation (4) may reduce the performance of the scheme. In order to achieve maximum performance, i.e. full diversity and array gain, we propose a feedback scheme to modify

the transmitted signals from certain antennas as shown in Fig. 1 by rotating with an appropriate phase angle to ensure that the $\beta(n)$ term is maximized during the transmission period.

$$
\mathbf{\Delta}(n) = \left[\begin{array}{cc} \alpha(n) + \beta(n) & 0 \\ 0 & \alpha(n) + \beta(n) \end{array} \right] \quad (4)
$$

where $\alpha(n) = \sum_{i=0}^{3} |\Lambda_i(n)|^2$ and the factor $\beta(n) = 2Re\{(\Lambda_0(n)\Lambda_1^*(n) + \Lambda_2(n)\Lambda_3^*(n))\}$. The operator $|\cdot|^2$ denotes the modulus squared of a complex number and $Re\{\cdot\}$ its real part.

A. Phase-Rotation

Assume that the symbols transmitted from the first and the third antennas in the n-th subcarrier are rotated by phasors $e^{j\theta}$ and $e^{j\phi}$ respectively. It is apparent that this does not change the transmitted power. Since the phase rotation on the transmitted symbols is effectively equivalent to rotating the phases of the corresponding channel coefficients, then the β term can be written as:

$$
\grave{\beta}(n) = 2Re\{(\Lambda_0(n)\Lambda_1^*(n)e^{j\theta} + \Lambda_2(n)\Lambda_3^*(n)e^{j\phi})\} \quad (5)
$$

In this case, by rotating with appropriate phase angles to ensure that $\beta(n)$ is maximized, and correspondingly the signal-to-noise ratio (SNR), therefore θ and ϕ are determined as:

$$
\begin{aligned}
\theta &= -angle(\Lambda_0(n)\Lambda_1^*(n)) \\
\phi &= -angle(\Lambda_2(n)\Lambda_3^*(n)) \quad (6)
\end{aligned}
$$

where $angle(\cdot)$ denotes the phase angles, in radians, for each complex element.

B. Common Phase-Rotation

If $\theta = \phi$, a common phasor $e^{j\theta}$ can be used to rotate the transmitted symbols from the first and third antennas and the rotation angle is selected from a range between 0 and 2π. The new $\grave{\beta}$ term can be written as:

$$
\grave{\beta}(n) = 2Re\{(\Lambda_0(n)\Lambda_1^*(n) + \Lambda_2(n)\Lambda_3^*(n))e^{j\theta}\} \quad (7)
$$

In this case, the transmitter needs to have knowledge of a single phase. Therefore, θ is determined as

$$
\theta = -angle(\Lambda_0(n)\Lambda_1^*(n) + \Lambda_2(n)\Lambda_3^*(n)) \quad (8)
$$

However, the gain of this scheme would generally be less.

C. Quantization

Due to practical limitations, the number of feedback bits required from the receiver to the transmitter should be kept as small as possible. In the sequel, we provide a method to reduce the number of feedback bits while retaining satisfactory forward link performance. Feeding back the exact value of the phase angle with, for example, fixed or floating point resolution requires very large feedback overhead. In a practical application this may not be possible due to the very limited feedback bandwidth.

Therefore, the phase angles should be quantized, and then these levels are fed back to the transmitter. Suppose, for each phase angle, if we have two bit feedback, then we can feedback only four phase level angles such that the phase angles are from the set of $\{\Theta, \Phi\} \in \Omega = [0, \pi/2, \pi \ or \ 3\pi/2]$ then for the first antenna phase adjustment, the discrete feedback information corresponding to the phases may be selected according to

$$\Theta = \arg \max_{\theta \in \Omega} Re\Big\{\big(\Lambda_0(n)\Lambda_1^*(n)\big)e^{j\theta}\Big\} \qquad (9)$$

Similarly, for the third antenna phase adjustment, the phases may be selected according to

$$\Phi = \arg \max_{\phi \in \Omega} Re\Big\{\big(\Lambda_2(n)\Lambda_3^*(n)\big)e^{j\phi}\Big\} \qquad (10)$$

In this case the particular selection giving the largest values of (9) and (10) may be preferable, as it would provide the largest array gain and achieve maximum diversity advantage. This idea can also easily be applied to (8). We now make an observation that when the phase angle is not quantized and when both the first and third antenna signals are rotated using the phase angles, this scheme can be considered as a combined beamformer and SFBC [11], where the pairs of first and second antennas and third and fourth antennas are used as beamformers. Moreover, when the phase angles are quantized to only two levels $(0 \ or \ \pi)$, this scheme is reduced to the scheme proposed in [2]. Hence, the proposed scheme is expected to perform between the scheme in [2] and combined beamformer and SFBC.

D. Feedback Reduction Via Sub-channel Correlations

For frequency division duplex (FDD) based OFDM, however, we require at least N bits feedback for the phase rotation method. This imposes too much of an overhead constraint on the uplink channel to convey very large amount of feedback information. However, for OFDM based WLANs and WMANs (terminals are likely to remain fixed), the channel variations are small as compared to mobile channels in UMTS, hence phase angles can be fedback less frequently. Nevertheless, techniques that could potentially reduce the amount of feedback will yield significant benefits to the broadband wireless access systems. One possibility to reduce feedback overhead is to exploit the strong correlation in the feedback sequence among the subcarriers [9].

For an arbitrary frequency selective channel of length two, we computed the phase feedback required for a 64 point OFDM symbol and depicted in Fig.2. A two level quantized phase $-\pi/4$ and $\pi/4$ is also shown in the same figure. We observe that the required phase feedback is a highly correlated waveform in frequency. We exploit this to perform significant reduction in feedback overheads.

III. CONCATENATION WITH CONVOLUTIONAL CODES

In wireless applications, it is favorable to have an outer error-control coding to correct errors that remain after inner codes. In this section, concatenation of the proposed
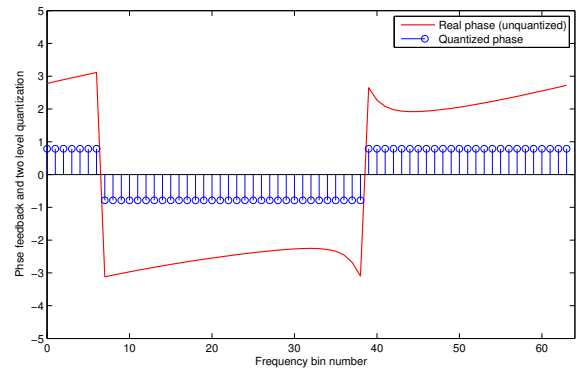

Fig. 2. Quantized and un-quantized phase angles for a 64-point OFDM symbol

scheme with convolutional codes [13] is investigated, due to their low complexity and their practical applicability such as in IEEE 802 11/16, as in Fig.1. It is worth noting in channel with bursty errors across frequencies, an interleaver could also be added, however, due to the channel model used in this work this is not included.

Consider that a binary data sequence $s[f]$, $f \in \{1, \cdots, L_c\}$ is to be transmitted. First, it is encoded by the binary convolutional encoder. The output samples of convolutional encoder denoted $c[l]$, $l \in \{1, \cdots, N_c\}$ are mapped onto signal points taken from a QPSK constellation, and the resulting symbols are transmitted according to the EO-SFBC, which is described in Section 2. At the receiver, it is assumed that the CSI is perfectly known. Since the proposed closed-loop EO-SFBCs are decoded using linear processing, the soft values of the symbols of an EO-SFBC codeword can be easily taken from outputs of the matched filter, given in (2). The operation of the convolutional decoder (Viterbi decoder) can be found in many sources (e.g.,[13]), therefore, it is not going to be explained here in detail.

IV. SIMULATION RESULTS

In this section, we evaluate the error performance of the proposed schemes in quasi-static frequency selective channels. The fading is constant within a frame and changes independently from one frame to another. For the closed-loop system, we have simulated the BER against SNR using QPSK symbols. Each frame consists of 10000 symbols in our simulation. In Fig.3, we provided simulation results comparing the performance of the proposed closed-loop full-rate EO-SFBC for four transmit and one receive antennas. The proposed EO-SFBC with phase-rotation feedback obtains better performance than the previous scheme [5], the full rate closed-loop QO-SFBC [9] and the open-loop EO-SFBC respectively. As shown in Fig.3, when the BER is 10^{-3}, it can yield 1.3 dB gain over the previous scheme [5], which demonstrates the proposed closed-loop EO-SFBC can get the conventional diversity gain equal to the number of transmit antennas and more additional array gain (feedback gain) at the same time. Furthermore, the performance of the closed-loop QO-SFBC with perfect CSI is also depicted, which does not
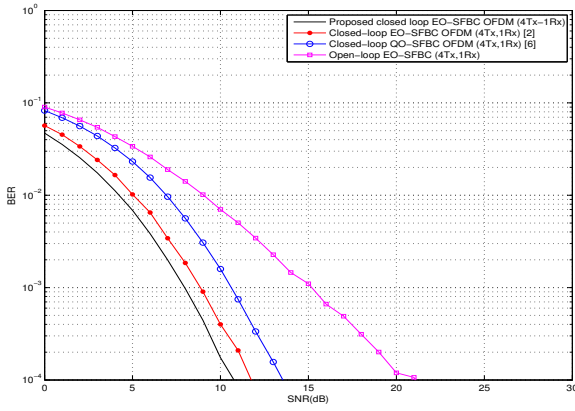
Fig. 3. Average BER performance comparison of the proposed phase rotation scheme with different SFBCs in a 4×1 MISO system.

Fig. 4. Average BER performance with quantized and un-quantized phase angles, for 4×1 system.

benefit from the array gain of the other schemes. The performance of the proposed scheme provides approximately 3 dB and 7.5 dB of gain at BER of 10^{-3} as compared to QO-SFBC and open-loop EO-SFBC respectively.

The simulation result of a practical scenario of a quantization method is depicted in Fig.4. In addition to this, the un-quantized feedback for the proposed scheme is also depicted. From the figure, simulation results indicate that the performance of the quantized scheme is very close to the performance of the un-quantized scheme, and still significantly better than that of the previously reported closed loop scheme [5]. For the phase rotation method, we quantized the required phase angles into four levels [0, $\pi/2$, π, $3\pi/2$] so that only two bits per subcarrier were required for feedback.

As a tradeoff, we assigned K number of consecutive subcarriers into a group and proposed to feedback one quantized phase angle for each group instead of feeding back the phase angle for each subcarrier. The phase angle required for each group is determined based on the majority of phase angles within that group. In this way, the 64 bit feedback required for one OFDM symbol is reduced to only $M = 64/K$ bits. A result is also shown in Fig.4 for $M = 4$. Compared to an un-quantized feedback scheme, where a 64 floating point numbers are used to represent the feedback angles, the quantization with four-bits degrades the BER performance at 10^{-3} by only 1.0 dB, but still outperforms closed-loop QO-SFBC and open-loop EO-SFBC by approximately 1.0 dB and 5.0 dB respectively.

Although our scheme provides a diversity gain and array gain, an outer channel code can be concatenated to achieve further coding gain. For the final set of simulations, in Fig.5 we provide performance results when the proposed methods are concatenated with convolutional codes, which is referred to as CCSBC. For this concatenated wireless system, the overall data rate is given by
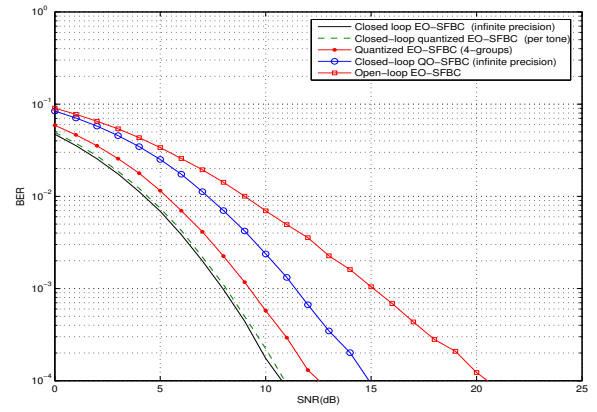
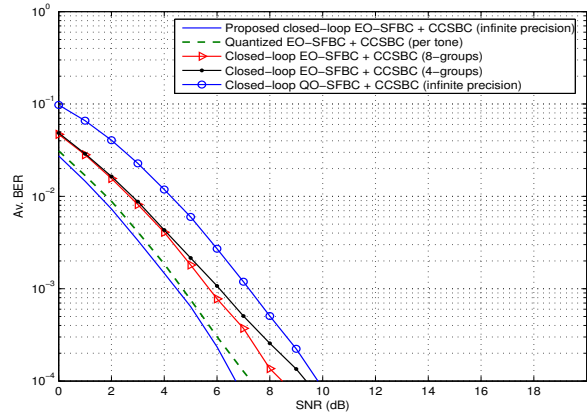$$r = k \, log_2(m) \qquad bits/sec \qquad (11)$$

Fig. 5. Average BER performance comparison based on adding outer convolutional code with grouping of feedback terms based quantization, with $M = 4$ and 8.

where k is the code rate of convolutional codes, and m is the dimension of the modulation scheme. In our simulations, we have used a QPSK (i.e. m=4) signal constellation with Gray mapping and a rate $1/2$ convolutional code (i.e. $k = 1/2$) in full rate closed-loop EO-SFBC systems to achieve the data rate of 1 bits/sec. As depicted in Fig.5, for four transmit antennas, when BER=10^{-3}, CCSBC concatenated with closed-loop EO-SFBC can get 3 dB from that concatenated with the QO-SFBC code.

V. CONCLUSIONS

In this paper, we described an extended orthogonal space-frequency coded OFDM scheme for providing high data-rate wireless communication over frequency selective MISO fading channels. We presented simulation results for a QPSK space-frequency coded OFDM system and compared its performance to the previously reported space-frequency coded OFDM scheme of [5]. We have exploited the feedback correlation among subcarriers to reduce the feedback overheads significantly while

maintaining satisfactory diversity performance. Furthermore, it is worth noting that the channel matrix of the EOSFBC is orthogonal, which is different from that of the QOSFBC. The proposed closed-loop EO-SFBC scheme with CCSBC can outperform the previous schemes by 4 dB at BER of 10^{-3}. This is because in schemes such as CL-QOSFBC there is only diversity gain and no array gain, but in the proposed CL-EOSFBC there is both diversity and array gains. We remark that at each frequency bin that with four rtansmit antennas the maximum diversity for a combined link would be 4, i.e N_t. It has been shown in [14] that with the use of linear complex field coding across frequency bins it is possible to obtain maximum diversity of $N_t \times (L + 1)$, this issue is left as future work.

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