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Title	An enhanced closed-loop MIMO design for OFDM/OFDMA-PHY
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Re:	Contribution to the IEEE P802.16e working group
Abstract	This document proposes a simple and novel closed-loop transmit precoding scheme to improve the bit-error rate performance of OFDM/OFDMA-PHY in IEEE 802.16e. The proposed scheme requires a feedback of only two bits per OFDM tone for the entire duration of a frame. The feedback rate can even be reduced to one bit per OFDM tone by sacrificing the performance gain. Simulation results are provided to illustrate the performance gain of the proposed closed-loop technique over the existing open-loop operation framework.
Purpose	Adoption
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An enhanced closed-loop MIMO design for OFDM/OFDMA-PHY

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1. Introduction

The current IEEE 802.16-2004 standard [1] and its IEEE 802.16e-D4 amendment [2] suggest open-loop MIMO operation. This mode of operation assumes no knowledge, whatsoever, of the communication channel at the transmitter. In this contribution, we propose a simple closed-loop MIMO transmission methodology, where the transmitted symbols are precoded using a finite set of pre-defined unitary rotation matrices. This set of matrices is known both to the receiver and to the transmitter. Given the received data, the receiver determines the optimum rotation matrix for each OFDM tone that will result in best performance. It will then transmit *only* the index of the optimum rotation matrix to the transmitter, where it is reconstructed and used to precode the transmitted symbols. With a very few number of rotation matrices in a basis set, the amount of feedback involved in such a scheme is much less than if the full set of channel coefficients are sent back from the receiver to the transmitter.

Using numerical simulations, we will show that significant performance gain is achieved from the proposed closed-loop operation over the default open-loop case. We also illustrate the performance/feedback-rate tradeoff and suggest possible options in easing this tradeoff.

2. MIMO Setup

Consider a MIMO OFDM setup with P transmit antennas and Q receive antennas. The Q-dimensional baseband received signal vector $\mathbf{r} = \left[r_1, r_2, \ldots, r_Q\right]^T$ can be written as

$$\mathbf{r} = \sum_{p=1}^{P} \mathbf{h}_p s_p + \mathbf{w} = \mathbf{Hs} + \mathbf{w},$$

where $\mathbf{h}_i = \left[h_{1i}, h_{2i}, \ldots, h_{Qi}\right]^T$ is a Q-dimensional vector containing channel coefficients from ith transmitter to Q receivers, $\mathbf{H} = \left[\mathbf{h}_1, \mathbf{h}_2, \ldots, \mathbf{h}_P\right]$ is the $Q \times P$ channel matrix, $\mathbf{s} = [s_1, s_2, \ldots, s_P]^T$ is the P-dimensional transmit signal vector, and $\mathbf{w} = \left[w_1, w_2, \ldots, w_Q\right]^T$ is the Q-dimensional vector of zero-mean noise with variance σ^2. The received signal can be processed by using either the optimal maximum-likelihood method or a sub-optimal method like zero-forcing or linear minimum mean squared error processing.

Note that the vector $\mathbf{s}$ is represented by

$$\mathbf{s} = \mathbf{Vd},$$

where $\mathbf{d} = [d_1, d_2, \ldots, d_P]^T$ is the P-dimensional vector of symbols to be transmitted and $\mathbf{V}$ is the $P \times P$ precoding rotation matrix. The reason of introducing this notation is to bring in the flexibility of treating closed-loop and open-loop options within the same framework. Note that for the open loop case, $\mathbf{V}$ is the $P \times P$ identity matrix. The effective (rotated) channel matrix is, therefore, denoted by

$$\mathbf{H}^r = \mathbf{HV}.$$

3. Closed-Loop MIMO

In this contribution, we will consider a two transmit antennas and two receive antennas case; i.e., $P = Q = 2$. Extension to $P > 2$ and $Q > 2$ is straightforward.

It is known that if perfect channel state information is available at the transmitter, then one can precode the transmitted symbols with the eigenvectors $\mathbf{V}$ of the matrix $\mathbf{H}^H\mathbf{H}$, where $(\cdot)^H$ denotes conjugate transposition. In this case, we can perfectly separate the transmitted symbols at the receiver, thereby achieving capacity. However, the transmittal of channel state information from receiver to the transmitter is prohibitively expensive. The cost of feedback is even higher in an OFDM system, where a different eigenvector is associated with each tone.

An alternative to sending the complete channel state information is to define a finite set of N unitary rotation matrices, which is known to both the transmitter and the receiver. Based on a metric that improves post-processed SNR, the receiver determines a rotation matrix from the set for each OFDM tone. The index of this matrix is then sent to the transmitter via a feedback path, where the matrix is reconstructed and used to precode the transmitted symbols. This operation requires only $\log_2 N$ bits to be fed back from the transmitter to the receiver per OFDM tone. For example, if the set has eight rotation matrices, then three bits per tone need to be sent back.

Let us define a set of N 2×2 rotation matrices denoted by $\mathbf{V}$

$$\mathbf{V}_{N_1 n_2 + n_1} = \begin{bmatrix} e^{j\phi_{n_2}} \cos\theta_{n_1} & -e^{j\phi_{n_2}} \sin\theta_{n_1} \\ \sin\theta_{n_1} & \cos\theta_{n_1} \end{bmatrix},$$

where

$$\phi_{n_2} = \frac{2\pi n_2}{N_2}, n_2 = 0,1,\ldots,N_2 - 1$$

$$\theta_{n_1} = \frac{\pi n_1}{2N_1}, n_1 = 0,1,\ldots,N_1 - 1$$

and $N = N_1 N_2$.

The proposed closed-loop transmission scheme is illustrated in Figure 1. Note that for each tone, the index of the rotation matrix is sent from the receiver to the transmitter only once per frame. This is assuming that the channel stays static over the frame duration.

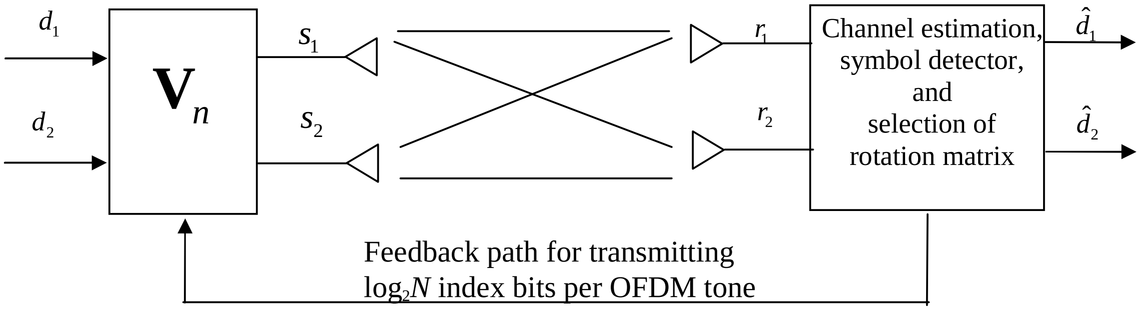

Figure 1: Proposed closed-loop transmission scheme for a two-input two-output system.

3.1. Selection of Rotation Matrix

The selection of rotation matrix depends on the type of receiver employed to recover the transmitted source symbols. In this contribution, we will consider the iterative minimum-mean squared error (IMMSE) receiver, which detects the transmitted symbols in the order of decreasing post-processed SNR; i.e., the most "reliable" symbols are detected first and removed from the received signal followed by estimating symbols of decreasing reliability.

The MMSE post-processed SNR of the two received symbol streams is given by

$$\mathrm{SNR}_i = \mathbf{h}_i^H \left(\mathbf{h}_j \mathbf{h}_j^H + \sigma^2 \mathbf{I}\right)^{-1} \mathbf{h}_i, \quad i, j = 2; i \neq j,$$

where $\mathbf{h}_i$ is the ith column of the channel matrix $\mathbf{H}$ and $\mathbf{I}$ is the 2×2 identity matrix. Note that the above SNR value is computed for the open-loop transmission.

In order to pick the best rotation matrix for each tone in the OFDM symbol, we compute the post-processed SNR for each rotation matrix in the basis set. If we define the rotated channel matrix as

$$\mathbf{H}_n^r = \mathbf{H}\mathbf{V}_n, \quad n = 0, 1, \ldots, N-1,$$

then the post-processed SNR for each case is given by

$$\mathrm{SNR}_{n,i}^r = \mathbf{h}_{n,i}^{r\ H} \left(\mathbf{h}_{n,j}^r \mathbf{h}_{n,j}^{r\ H} + \sigma^2 \mathbf{I}\right)^{-1} \mathbf{h}_{n,i}^r, \quad i, j = 2; i \neq j; n = 0, \ldots, N-1.$$

Of the two received streams, we pick up the smaller of the two SNR values and maximize it over all possibilities of the rotation matrices. Mathematically, the selection of rotation matrix can be stated as

$$\mathbf{V}_n^{\mathrm{opt}} = \arg\max_n \left(\min_i \left(\mathrm{SNR}_{n,i}^r\right)\right).$$

In other words, the above operation guarantees the maximization of the minimum post-processed SNR over all the possible choices.

4. Simulation Results

To verify the potential of the proposed closed-loop method, we carried out numerical simulations for a 2×2 baseband MIMO OFDM system employing IMMSE receiver. The symbols were QPSK modulated and the transmission took place via three-path Rayleigh fading channels. We considered 102 data tones in the OFDM symbol, which employed 128-point IFFT/FFT at the transmitter/receiver. Different sets of basis rotation matrices were considered by choosing discrete values of N_1 and N_2 as shown in Table 1.

Table 1: Sets of rotation matrices employed in closed-loop transmission.

Set	N_1	N_2	N	Feedback bits
1	2	1	2	1
2	4	1	4	2
3	4	2	8	3
4	8	1	8	3
5	16	1	16	4
6	2	2	4	2
7	2	4	8	3

Figure 2 compares the open loop transmission against the closed-loop schemes employing rotation matrix sets 1-5 of Table 1. Note that the closed-loop feedback with 2, 3, and 4 bits result in similar performance, where the gain over open-loop performance is around 5 dB at the raw bit error rate of 10^{-3}. The single-bit feedback case of Set 1 results in around 3 dB gain.

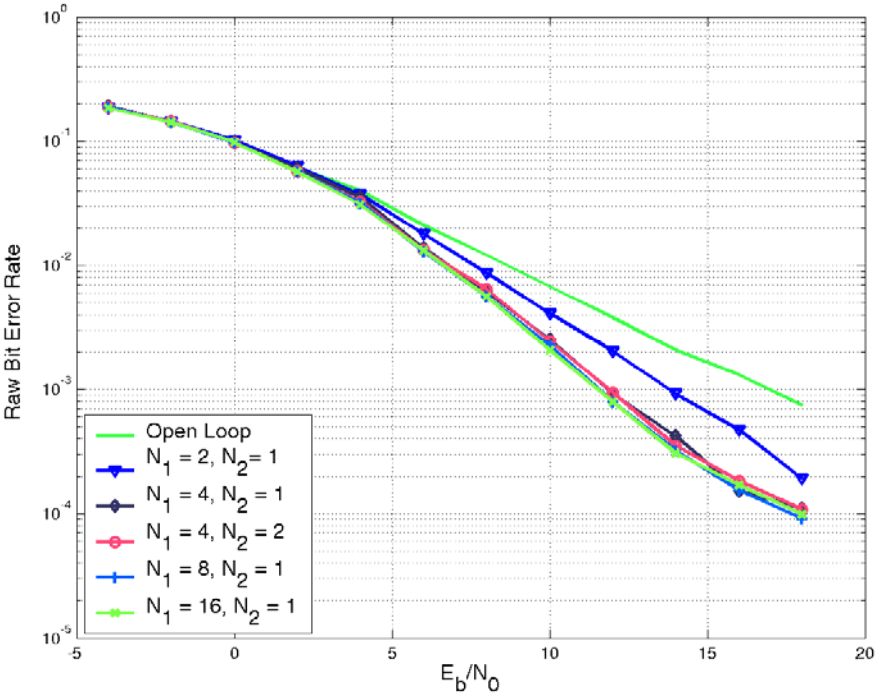

Figure 2: Performance of open-loop transmission scheme against the closed-loop scheme for Sets 1-5 of rotation matrices.

Figure 3 compares open-loop transmission against the two-bit and three-bit feedback governed by Sets 6 and 7 of Table 1. For completeness, the single-bit feedback and the two-bits feedback results from Figure 2 are also plotted. These results show that increasing the value of N_2 does not help in any performance gain. Most of the gain is achieved by increasing the values of N_1.

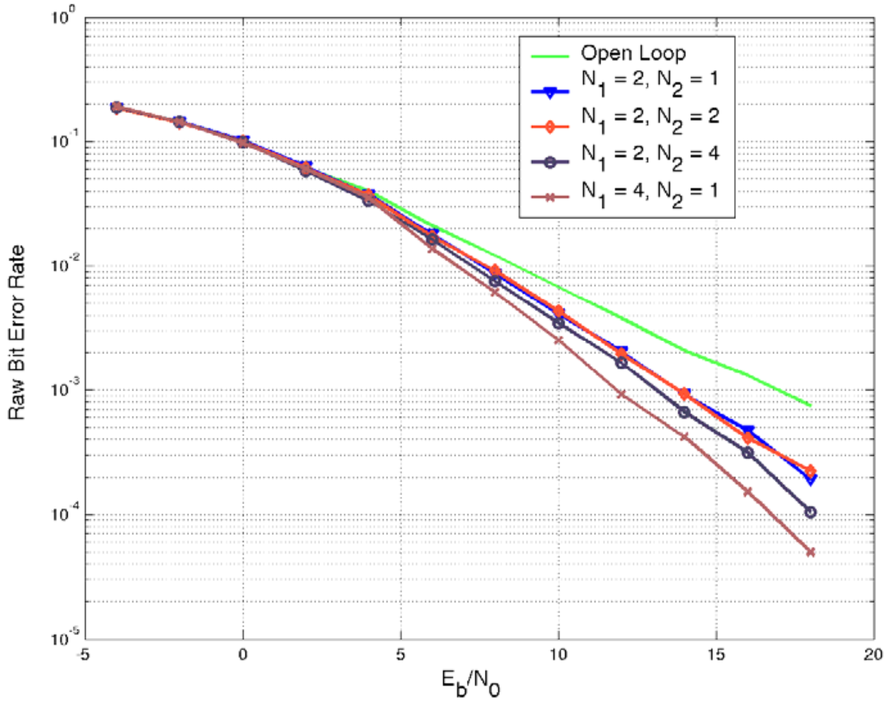

Figure 3: Performance of open-loop transmission scheme against the closed-loop scheme for Sets 6 and 7 of rotation matrices.

Table 2 lists the performance improvement of each closed-loop option over the open-loop case at the raw bit error rates of 10^{-2} and 10^{-3}. It is clear that the $(N_1, N_2) = (4,1)$ option requiring two bits of feedback per OFDM tone gives the best tradeoff between performance and the feedback rate. There is a slight performance improvement for the $(N_1, N_2) = (4,2)$ case, but it requires an additional bit to be fed back to the transmitter. On the other hand, performance can be sacrificed by saving a bit and resorting to single-bit feedback in the $(N_1, N_2) = (2,1)$ case.

Table 2: Performance improvement of closed-loop options over the open-loop case.

Set of rotation matrices	**Performance gain in dB over open loop at raw bit error rate of** 10^{-2}	**Performance gain in dB over open loop at raw bit error rate of** 10^{-3}
1; $(N_1, N_2) = (2,1)$	1.04	3.16
2; $(N_1, N_2) = (4,1)$	1.87	5.11
3; $(N_1, N_2) = (4,2)$	1.88	5.07
4; $(N_1, N_2) = (8,1)$	2.04	5.39
5; $(N_1, N_2) = (16,1)$	2.01	5.42
6; $(N_1, N_2) = (2,2)$	0.95	3.16
7; $(N_1, N_2) = (2,4)$	1.39	3.84

5. Proposed Text Changes

To be determined by the IEEE 802.16e working group.

6. References

1. *Draft IEEE Standard for Local and Metropolitan Area Networks Part 16: Air Interface for Fixed Broadband Wireless Access Systems*, IEEE P802.16-REVd/D5-2004, May 2004.
2. *Draft IEEE Standard for Local and Metropolitan Area Networks Part 16: Air Interface for Fixed Broadband Wireless Access Systems - Amendment for Physical and Medium Access Control Layers for Combined Fixed and Mobile Operation in Licensed Bands*, IEEE P802.16e/D4, August 2004.