RATE ADAPTIVE SPACE-TIME MODULATION TECHNIQUES FOR COMBATING COCHANNEL INTERFERENCE

Qing Yan and Rick S. Blum

Department of Electrical Engineering and Computer Science
Lehigh University, Bethlehem, PA 18015

ABSTRACT

Space-time coding is a highly effective approach for combating fading in wireless communications and improving the capacity of wireless networks. However, a recent paper has shown that cochannel interference can degrade performance significantly in cellular systems. Here we design and demonstrate the interference suppression capability of low rate space-time codes. Optimal 1 b/s/Hz 2-space-time trellis codes with various number of states over Z_4 and GF(4) are obtained through search. We also propose rate adaptive space-time modulation which can increase the overall throughput. The effectiveness of this proposed method is demonstrated by using 2-space-time codes in an orthogonal frequency division multiplexing (OFDM) system with 2 transmit and 2 receive antennas.

1. INTRODUCTION

Space-time coding has been shown to be very effective for improving the capacity of wireless networks. In view of this, much attention has been focused on high-rate space-time codes [1, 2, 3, 4]. Recently, it has been pointed out that cochannel interference can degrade performance significantly [5] when space-time codes are used in cellular systems. Moreover, in [2], space-time coding has been shown to be very desirable for achieving high peak data rates among the various transmitter diversity techniques, but it may result in much higher retransmission probability for typical mobile environments when compared to other techniques that possess interference suppression capabilities. The reasons are 1) the capacity for channels with interference is small while the space-time coding scheme still attempts to deliver large amounts of information with the same power, 2) no interference suppression is performed.

Accordingly, in this paper, we demonstrate that this problem can be partly overcome by using low rate space-time codes when cochannel interference is present. Further, we propose rate adaptive space-time modulation which takes advantage of both low-rate and high-rate space-time codes to increase overall throughput.

The paper is organized as follows. In Section 2, we briefly review the design criteria for space-time codes and give some optimum codes for rapid fading and quasi-static fading, respectively. Trellis codes over rings and finite fields are considered. In Section 3, the performance of these optimum codes is examined, in the presense of interference, through simulation for an orthogonal frequency division multiplexing (OFDM) system example. In Section 4, we propose rate selection methods.

2. OPTIMUM SPACE-TIME TRELLIS CODES

Space-time trellis code design has attracted a lot of interest. The design criteria proposed in [1] can be used to find asymptotically optimum codes. Most of the codes found so far are of the maximum rate for the highest diversity gain achievable ($n_T n_R$) with n_T transmit and n_R receive antennas. Such codes achieve a good trade off between diversity and data rate assuming the communication channel has relatively high signal-to-noise ratio (SNR) and high signal-to-interference ratio (SIR).

Consider the problem of designing space-time codes for interference suppression. Space-time codes with rates lower than those usually studied are of interest, since these codes provide more powerful error correction capability and tend to perform well for low SNRs or SIRs. According to the criteria in [1], in quasi-static fading cases, we need to maximize the diversity gain g_d and coding gain g_c, while in rapid fading cases, we need to maximize the length of the shortest error event path, g_d, and the minimum product of branch distances, pd_{min}, along the shortest error event path. Since in each case we can find many codes that provide the same value of each metric, we compute the number of codeword pairs that provide the best set of values of all the metrics and try to find codes that minimize this number.

We use the systematic approach [4] with minor modifications to search for the 1 b/s/Hz optimum 2-space-time trellis codes for rapid fading and quasi-static fading cases. In Table 1 and 2 we list the optimum 1 b/s/Hz 2-space-time

This paper is based on work supported by National Science Foundation under Grant No. MIP-9703730

q	g_c^2	#pairs	G^T
2	16	4	$\begin{pmatrix} 2 & 0 \\ 0 & 2 \end{pmatrix}$
4	48	16	$\begin{pmatrix} 2 & 2 & 0 \\ 2 & 0 & 2 \end{pmatrix}$
8	80	32	$\begin{pmatrix} 2 & 2 & 1 & 0 \\ 2 & 0 & 2 & 2 \end{pmatrix}$
16	128	128	$\begin{pmatrix} 2 & 2 & 1 & 2 & 0 \\ 0 & 2 & 2 & 0 & 2 \end{pmatrix}$

Table 1. Optimum q-state 1 b/s/Hz QPSK 2-space-time codes over Z_4 for quasi-static fading.

q	g_c^2	#pairs	G
2	16	4	$\begin{pmatrix} 1+\alpha & 0 \\ 0 & 1+\alpha \end{pmatrix}$
4	48	16	$\begin{pmatrix} 1+\alpha & 1+\alpha \\ 1+\alpha & 0 \\ 0 & 1+\alpha \end{pmatrix}$
8	84	32	$\begin{pmatrix} \alpha & 1 \\ 1+\alpha & \alpha \\ \alpha & 1+\alpha \\ 1 & \alpha \end{pmatrix}$
16	132	32	$\begin{pmatrix} 1+\alpha & 1+\alpha \\ \alpha & 1 \\ 1+\alpha & \alpha \\ \alpha & 1+\alpha \\ 1 & \alpha \end{pmatrix}$

Table 2. Optimum q-state 1 b/s/Hz QPSK 2-space-time codes over GF(4) for quasi-static fading.

codes for quasi-static fading cases over Z_4 and $GF(4)$, respectively, using the notation G of [4]. Here α denotes a primitive element of $GF(4)$. For the Z_4 codes, the output symbol z is mapped into $e^{j\frac{\pi}{2}z}$, while the $GF(4)$ codes use Gray mapping. It is interesting to find that for some number of states, the best code over $GF(4)$ are slightly better than that over Z_4. We have made similar calculations for the 2 b/s/Hz cases for quasi-static fading. In this case the best codes over $GF(4)$ give exactly the same coding gain as the best Z_4 codes from [4]. Similarly, we provide optimum 1 b/s/Hz 2-space-time codes for rapid fading cases in Table 3 and 4 for Z_4 and $GF(4)$, and here again we observe that the performance measures $(g_d^2, pd_{min}^2, \#pairs)$ for Z_4 and $GF(4)$ are exactly the same for the best codes.

As demonstrated in [1], for a system using quaternary phase-shift keying (QPSK) modulation, the coding rate is upper bounded by 2 b/s/Hz to achieve a diversity of $n_T n_R$. Optimum codes for quasi-static fading with this rate can be

q	g_d^2	pd_{min}^2	#pairs	G^T
2	2	64	4	$\begin{pmatrix} 2 & 2 \\ 2 & 2 \end{pmatrix}$
4	3	384	16	$\begin{pmatrix} 2 & 1 & 2 \\ 2 & 2 & 2 \end{pmatrix}$
8	4	2304	64	$\begin{pmatrix} 2 & 1 & 2 & 1 \\ 2 & 2 & 2 & 2 \end{pmatrix}$
16	5	13824	256	$\begin{pmatrix} 2 & 2 & 1 & 2 & 1 \\ 2 & 1 & 2 & 2 & 2 \end{pmatrix}$

Table 3. Optimum q-state 1 b/s/Hz QPSK 2-space-time codes over Z_4 for rapid fading.

q	g_d^2	pd_{min}^2	#pairs	G
2	2	64	4	$\begin{pmatrix} 1+\alpha & 1+\alpha \\ 1+\alpha & 1+\alpha \end{pmatrix}$
4	3	384	16	$\begin{pmatrix} 1+\alpha & 1+\alpha \\ 1 & 1+\alpha \\ 1+\alpha & 1+\alpha \end{pmatrix}$
8	4	2304	64	$\begin{pmatrix} 1+\alpha & 1+\alpha \\ 1 & 1+\alpha \\ 1+\alpha & 1+\alpha \\ 1 & 1+\alpha \end{pmatrix}$
16	5	13824	256	$\begin{pmatrix} 1+\alpha & 1+\alpha \\ 1 & 1+\alpha \\ 1+\alpha & 1+\alpha \\ \alpha & 1+\alpha \\ 1 & 1+\alpha \end{pmatrix}$

Table 4. Optimum q-state 1 b/s/Hz QPSK 2-space-time codes over GF(4) for rapid fading.

obtained from [4]. As we intend to use the 16-state code for comparison in later sections, the code from [4] is quoted here

$$G = \begin{pmatrix} 0 & 2 & 1 & 1 & 2 & 0 \\ 2 & 2 & 1 & 2 & 0 & 2 \end{pmatrix}^T. \tag{1}$$

Using the ideas from [4], a search for the optimum 16-state code for rapid fading found

$$G = \begin{pmatrix} 0 & 2 & 2 & 0 & 1 & 0 \\ 2 & 2 & 1 & 2 & 1 & 2 \end{pmatrix}^T \tag{2}$$

with $g_d = 3$, $pd_{min} = \sqrt{96}$ and $\#pairs = 1024$.

3. SPACE-TIME CODES WITH OFDM UNDER INTERFERENCE

While the design criteria from [1] are aimed at flat-fading channels, combining space-time coding and OFDM has

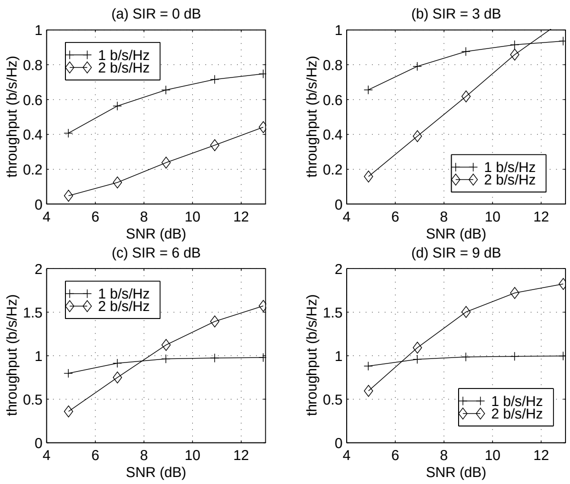

Fig. 1. Throughput comparison of 16-state rate 1 b/s/Hz and rate 2 b/s/Hz 2-space-time codes under interference.

been shown [2, 3] to be a promising method for frequency-selective channels. In [3], a 4 b/s/Hz space-time trellis code is designed for a 4 transmit and 4 receive antenna OFDM system using QPSK modulation. Here, we study the performance of codes with different rates for OFDM systems with interference. For the system description and simulation, we refer to [2, 3]. In our simulation, we use the hilly-terrain (HT) channel model and assume 256 OFDM tones, 2 transmit and 2 receive antennas.

In [3], the performance of space-time codes for quasi-static and rapid fading with rate 2 b/s/Hz are shown to be very close. This is also observed for rate 1 b/s/Hz codes and specific results are omitted here. In the following, we consider only the 16-state code in Table 4 and the code in (1). These codes provided the best performance. In Fig. 1 we show the throughput of the two coding schemes under certain levels of interference, using the 1 b/s/Hz code and the 2 b/s/Hz code. From Fig. 1, codes with different rates can perform quite differently. First of all, they generally provide different throughput. For high SIRs (Fig. 1(c) and (d)), the 2 b/s/Hz scheme provides larger throughput, while for SIR less than about 3 dB, using 1 b/s/Hz is almost always better (Fig. 1(a) and (b)). Also, they generally provide different error rate. This is significant for services that require specified levels of quality. Obviously, the overall performance of the ST-OFDM system can be improved by varying the coding rate according to the channel status. Next we will focus on this issue.

4. RATE ADAPTIVE SPACE-TIME MODULATION

Consider the case where automatic retransmission request (ARQ) is employed to request retransmission when a word is received in error. Allowing retransmission will require additional resources (because it requires feedback) and cause delay. To characterize all of these, we assume unit cost for transmission and a cost of c_r for retransmission. Typically, we have $c_r \geq 1$. For simplicity, we do not consider the issue of undetected errors explicitly and we assume ideal feedback (perfect feedback channel).

Assume the rate $R(SNR = s_1, SIR = s_2)$ is chosen from a set T, according to the level of SNR and SIR, which can be estimated and tracked. For a given level of SNR and SIR, the average cost of correctly sending one word with coding rate $R(s_1, s_2)$, taking into account the retransmissions, can be written as

$$\begin{aligned} c(s_1, s_2) &= 1 + c_r \sum_{i=1}^{\infty} (f(R(s_1, s_2), s_1, s_2))^i \\ &= 1 + c_r \frac{f(R(s_1, s_2), s_1, s_2)}{1 - f(R(s_1, s_2), s_1, s_2)} \end{aligned} \quad (3)$$

where $f(R(s_1, s_2), s_1, s_2)$ denotes word error rate (WER), and the average number of transmissions needed to send one word correctly is

$$\sum_{i=0}^{\infty} (f(R(s_1, s_2), s_1, s_2))^i = \frac{1}{1 - f(R(s_1, s_2), s_1, s_2)}. \quad (4)$$

Assuming $SNR = s_1$ and $SIR = s_2$, the amount of information correctly transmitted in one transmission, $i_1(s_1, s_2)$, is proportional to $R(s_1, s_2)$ divided by (4). Similarly the average cost for this transmission is (3) divided by (4), which we call $c_1(s_1, s_2)$. Our performance measure is $\frac{c_1(s_1, s_2)}{i_1(s_1, s_2)}$. We acknowledge this is an instantaneous or short-term average cost. For users having long-term connections, an average cost over a long period may be more suitable. The rate selection that minimizes $\frac{c_1(s_1, s_2)}{i_1(s_1, s_2)}$ is

$$R_s(s_1, s_2) = \arg\min_{r \in T} \frac{1 + c_r \frac{f(r, s_1, s_2)}{1 - f(r, s_1, s_2)}}{r}. \quad (5)$$

To generally obtain this solution, we need to perform extensive simulations to calculate the values of $f(r, s_1, s_2)$ on a grid, and then use (5) to determine the rate.

As a special case, let $c_r = 1$, which means no extra cost is assumed for retransmission. From (5) we get

$$R(s_1, s_2)|_{c_r = 1} = \arg\min_{r} \{ \frac{1}{r(1 - f(r, s_1, s_2))} \} \quad (6)$$

This is equivalent to maximizing the throughput. Next, we examine the effectiveness of this scheme by simulation. For simplicity, we assume the decoder has ideal channel state information (CSI) for the desired signal and for the interference as well. The CSI for interference is used for pre-whitening the received signal prior to the Viterbi decoder.

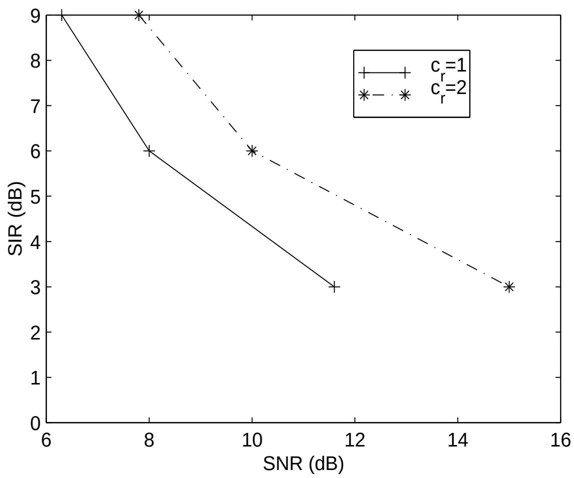

Fig. 2. Rate selection for a given level of SIR and SNR.

For a given level of SIR and SNR, the appropriate rate can be determined by using the results in Fig.1. Roughly, we need to read the crossing points from Fig.1 and obtain a rate selection curve as shown in Fig.2 with solid line. We use rate 1 b/s/Hz for the region below this curve and 2 b/s/Hz for the rest. The dashed line in Fig.2 for $c_r = 2$.

We model the desired signal and interference as independent Rayleigh fading signals. We assume the power level of both the desired signal and interference are known to the transmitter. We used the 16-state 2 b/s/Hz code from (1) to model the interference, but other codes gave very similar results. The SNR is assumed to be uniformly distributed between 5 dB and 13 dB, and the SIR is uniformly distributed between 1 dB and 9 dB. Using a fixed coding rate of 1 b/s/Hz, the throughput we obtain in our simulation is 0.90 b/s/Hz with WER=10.0%. Using a fixed coding rate of 2 b/s/Hz, the throughput is 0.95 b/s/Hz with WER=52.5%. With rate adaptation, we get 1.08 b/s/Hz throughput with WER=23.0%. Compared with the fixed rate approach, the throughput is improved by more than 10% over fixed rate 2 b/s/Hz and 20% over fixed rate 1 b/s/Hz. Note that the high WER for the 2 b/s/Hz case could lead to a large number of retransmissions. This would ultimately make this approach unacceptable. This makes the approach with rate adaptation even more attractive.

In the above example, the retransmission rate is not considered as we only try to maximize the throughput. To maintain a given level of quality of service (QoS), a certain low retransmission probability is preferred. This means a low WER is required. One approach is to employ (5) subject to a constraint on the WER conditioned on (s_1, s_2). Obviously, this is much more stringent than using a constraint on unconditional WER, and for certain low $SNRs$ and $SIRs$, there might be no appropriate rate $r \in T$ that can meet this constraint. In this case, we have no choice but use the lowest rate in T. Another approach is to use (5) to search for a rate selection by adjusting the value of c_r, since we can expect lower unconditional WER upon increasing the value of c_r. For example, in Fig. 2, the curve for $c_r = 2$ is above that for $c_r = 1$, consequently, more of the SNR-SIR space is devoted to rate 1 b/s/Hz and the WER will be lower. In general, the value of c_r will be determined by the required retransmission rate.

5. CONCLUSION

We studied the use of low rate space-time trellis codes for communication with cochannel interference. Simulation results show that this is an efficient approach for dealing with interference. Rate adaptation based on cost is discussed and evaluated, based on an example OFDM system.

6. ACKNOWLEDGMENT

The authors would like to thank Ye (Geoffrey) Li for providing programs used to generate simulation results.

7. REFERENCES

[1] V. Tarokh, N. Seshadri, and A. R. Calderbank, “Space-time codes for high data rate wireless communication: Performance criteria and code construction,” *IEEE Trans. Inform. Theory*, Mar. 1998, pp. 744-764.

[2] Y. (Geoffrey) Li, J. C. Chuang and N. R. Sollenberger, “Transmitter diversity for OFDM systems and its impact on high-rate data wireless networks,” *IEEE Trans. J. Select. Areas Commun.*, vol. 17, no. 7, July 1999.

[3] R. S. Blum, Y. (Geoffrey) Li, J. H. Winters and Q. Yan, “Improved Techniques for 4 transmit and 4 receive antenna MIMO-OFDM for wireless communications,” *IEEE Trans. Commun.*, submitted.

[4] Q. Yan and R. S. Blum, “Optimum space-time convolutional codes,” *Wireless Communications and Networking Conference*, 2000.

[5] S. Catreux, L. J. Greenstein, and P. F. Dressen, “Simulation results for an interference-limited multiple-input multiple-output cellular System”, *IEEE Communication Letters*, Dec. 2000.