Performance of Convolutionally-Coded MIMO Systems with Antenna Selection

Walaa Hamouda and Ali Ghrayeb

Abstract: **In this work, we study the performance of a serial concatenated scheme comprising a convolutional code (CC) and an orthogonal space-time block code (STBC) separated by an interleaver. Specifically, we derive performance bounds for this concatenated scheme, clearly quantify the impact of using a CC in conjunction with a STBC, and compare that to using a STBC code only. Furthermore, we examine the impact of performing antenna selection at the receiver on the diversity order and coding gain of the system. In performing antenna selection, we adopt a selection criterion that is based on maximizing the instantaneous signal-to-noise ratio (SNR) at the receiver. That is, we select a subset of the available receive antennas that maximizes the received SNR. Two channel models are considered in this study: Fast fading and quasi-static fading. For both cases, our analyses show that substantial coding gains can be achieved, which is confirmed through Monte-Carlo simulations. We demonstrate that the spatial diversity is maintained for all cases, whereas the coding gain deteriorates by no more than $10\log_{10}(M/L)$ dB, all relative to the full complexity multiple-input multiple-output (MIMO) system.**

Index Terms: **Antenna selection, convolutional codes, flat fast-fading channels, multiple-input multiple-output (MIMO), space-time block codes (STBC), space-time trellis codes (STTC).**

I. INTRODUCTION

Much work has been published recently on the use of antenna diversity for achieving reliable communication over wireless links. These works include the early work by Guey *et al.* [1] in which signal design techniques that exploit the diversity provided by employing multiple antennas at the transmitter were considered. Then in 1998, Tarokh *et al.* [2] introduced a new class of codes (referred to as *space-time trellis codes* (*STTC*)) suitable for systems equipped with multiple transmit antennas. In their paper, they develop design guidelines for space-time codes over Rayleigh and Rician channels. They show that the performance of space-time codes depends primarily on the number of transmit and receive antennas employed in the system, in addition to the underlying code. The performance of space-time codes (over fading channels) is typically characterized by two parameters: The coding and diversity gains.

In 1998, Alamouti [3] introduced a very simple, and yet efficient, scheme which involves using two transmit antennas at the base station (BS) and one receive antenna at the other end of the down-link. A simple decoding algorithm was introduced for this scheme, which can be extended for arbitrary number of receive antennas. Motivated by the simplicity of the Alamouti scheme, Tarokh *et al.* [4] generalized that scheme to an arbitrary number of transmit antennas, resulting in the so-called *space-time block codes* (STBCs). For the same number of transmit and receive antennas, both STTC and STBC normally achieve the same spatial diversity. However, despite the low complexity they offer, STBCs do not provide any coding gain, unlike the case for STTCs. Therefore, STBCs may need to be combined with an outer channel coding scheme in order to provide such coding gains.

To this end, a few papers have appeared recently in the literature in which various coding schemes concatenated with STBC were considered, including [5]–[10] among others. The coding scheme that was studied in most of these works involves concatenating a STBC with a channel code such as a turbo code, trellis code, convolutional code, and block code, where the channel code in this case serves as an outer code. It was observed in these works that a substantial coding gain can be achieved. In some cases, it was demonstrated that a STBC used in conjunction with an outer channel code can be superior, in terms of performance, to a STTC at even a lower complexity [5]. However, in all these works, the conclusions were based on Monte-Carlo simulations and no rigorous analysis was performed.

Another aspect of space-time codes that has been of interest lately is the complexity associated with employing multiple antennas at the transmitter and/or receiver. (This applies to both STBC and STTC.) The complexity stems from the fact that a separate RF chain is required for every employed antenna, which results in a significant increase in the implementation cost. In addition, the physical limitation of some wireless devices, such as mobile phones, prohibits using many RF chains. In an effort to overcome these problems, while utilizing the advantages of using multiple antennas, several papers (e.g., [11] and [12] and references therein) have recently addressed the notion of *antenna selection*. The idea behind antenna selection is to use only a subset of the transmit and/or receive antennas in multiple-input multiple-output (MIMO) systems. With this, the number of RF chains required now becomes equal to the number of selected antennas, which can lead to a dramatic cut down in cost and physical size of MIMO systems.

In [11], Molisch *et al.* studied the effect of antenna selection from a channel capacity perspective. It was shown that only a very little loss in capacity is suffered when the *receiver* uses a good subset of the available receive antennas. In [13], the authors studied the impact of antenna selection at the receiver on the diversity order and coding gain provided by the underlying space-time code. It was shown that, for full-rank STTC

Manuscript received January 29, 2004; approved for publication by Kyung-whoon Cheun, Division II Editor, September 6, 2004.

The authors are with the Department of Electrical and Computer Engineering, Concordia University, Montreal, Quebec, H3G 1M8, Canada, email: {hamouda, aghrayeb}@ece.concordia.ca.

This research was supported in part by Natural Sciences and Engineering Research Council (NSERC) of Canada Grants N008861 and N00858 and P-FQRNT/NATEQ Grant F00482.

codes and quasi-static fading channels, the diversity order of the underlying STTC code is maintained, whereas the coding gain deteriorates by a value upper bounded by $10\log_{10}(M/L)$ dB where M is the number of available receive antennas and L is the number of selected antennas. A more comprehensive analysis of the setting considered in [13] is presented in [12] along with code construction with antenna selection. The authors in [14] considered antenna selection for STTCs over fast fading channels. It was shown that the diversity order deteriorates with antenna selection and it becomes a function of the number of selected antennas and *not* the number of available antennas. The implication of this result is that employing more receive antennas while maintaining the same number of selected antennas unchanged will only provide additional coding gain.

Recent works on STBCs with and without antenna selection can be found in [15]–[17]. In [15], a simple decoding algorithm for the full-complexity (i.e., no antenna selection) STBC was proposed. In [16] and [17], MIMO systems with receive antenna selection were analyzed but no concatenated code was used. In this paper, we first study the performance of the coding scheme that comprises a convolutional code and a STBC based on orthogonal designs [4] concatenated in a serial fashion and separated by an interleaver. In particular, we derive analytical bounds for the probability of error performance for this coding scheme. We quantify the effect of the CC and STBC on the overall performance. We also examine the performance of this concatenated system in the face of antenna selection at the receiver. In this study, we consider two fading channels: Fast fading and quasi-static fading. For both cases, we show that considerable coding gains are possible to achieve when employing a CC in conjunction with a STBC. In addition, with antenna selection, we demonstrate that the spatial diversity is maintained for all cases, whereas the coding gain deteriorates by no more than $10\log_{10}(M/L)$ dB, all relative to the full complexity MIMO system.

We remark that concatenating a STBC with an outer channel code such as a CC code may result in reducing the spectral efficiency due to the added redundancy. In such cases, the combined concatenation scheme is not full rate. This is unlike the case for STTCs where such codes are normally full rate. However, this problem can be rectified by using a trellis-coded modulation (TCM) code as an outer code. In this case, the redundancy is compensated for by expanding the constellation size of the transmitted signal. As for complexity, if we were to compare the complexity of a combined outer channel code/STBC with a STTC, for the same number of code states, both schemes will roughly have the same complexity. However, the former scheme is more flexible in the sense is that it is easy to design full rate codes for any number of transmit antennas and any number of code states. This is not an easy task for STTCs (see [2] as an example). In addition, a MIMO channel employing a STBC, after combining at the receiver, may be viewed as a single-input single-output (SISO) system. As such, channel coding schemes developed for SISO systems can be applied to MIMO systems in a straightforward manner. Again, this is not possible for MIMO systems employing STTCs.

The rest of the paper is organized as follows. In Section II, we present the system model. Performance analysis for the full-complexity system is presented in Section III. In Section IV, we present performance bounds and simulation results for the full-complexity system. We also include in that section simulation results for the coded system with antenna selection at the receiver for various scenarios. Finally, Section V concludes the paper.

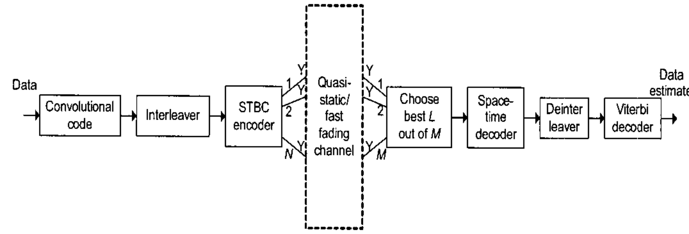

Fig. 1. Block diagram CC-STBC system with antenna selection.

II. SYSTEM MODEL

The system under consideration is shown in Fig. 1, which models a wireless communication system that employs N antennas at the transmitter side and M antennas at the receiver side. As shown in the figure, the incoming data is encoded by a convolutional code, interleaved, and then encoded by the space-time block encoder. The output of the space-time block encoder is then transmitted from the N transmit antennas. Blocks that involve modulation, demodulation, etc. have been suppressed from the figure due to their irrelevance in the analysis.

Without loss of generality, and for the purpose of this study, we consider the case of two transmit and M receive antennas where the STBC introduced in [3] is used. In this case, the received signal r_t^j at antenna j, after demodulation, matched-filtering, and sampling, is given at time t by

$$r_1^j = h_{j1}b_1 + h_{j2}b_2 + w_1^j \tag{1}$$

and at time $t+T$ by

$$r_2^j = -h_{j1}b_2^* + h_{j2}b_1 + w_2^j \tag{2}$$

where $*$ denotes complex conjugate, b_1 and b_2 are the two signals transmitted simultaneously from antennas 1 and 2 at two consecutive transmission periods; the noise w_t^j at time t is modeled as independent samples of a zero-mean complex Gaussian random variable with variance $\sigma^2 = N_0/2$ per dimension. The coefficients $h_{ji} = \alpha_{ji}e^{j\theta_{ji}}$ model the fading between the i-th transmit and j-th receive antennas and are assumed to be complex Gaussian random variables with variance 0.5 per dimension.

In this study, we consider two channel models. The first one is a quasi-static flat fading channel, i.e., the fading coefficients h_{ji} for $i = 1, 2, \cdots, N$ and $j = 1, 2, \cdots, M$ are constant during a frame and vary from one frame to another, and the subchannels fade independently. The second is a fast fading channel in which case the fading coefficients h_{ji} for $i = 1, 2, \cdots, N$ and $j = 1, 2, \cdots, M$ are constant over a block of symbols of length N within a frame and vary independently from one block to another (within the same frame). This assumption is valid only when perfect interleaving is assumed. Furthermore, the underlying space-time block code is assumed to have full rank.

Using maximum likelihood (ML) detection, and assuming binary-phase-shift-keying (BPSK) transmission, the soft estimate of the transmitted data bits are given by [3]

$$\begin{aligned}\widehat{b}_1 &= \Re\left\{\sum_{j=1}^{M} h_{j1}^* r_1^j + h_{j2} r_2^{j*}\right\} \\ &= \sum_{i=1}^{N=2}\sum_{j=1}^{M} \alpha_{ji}^2 b_1 + \Re\left\{\sum_{j=1}^{M} h_{j1}^* w_1^j\right\} + \Re\left\{\sum_{j=1}^{M} h_{j2} w_2^{j*}\right\} \\ &= \sum_{i=1}^{N=2}\sum_{j=1}^{M} \alpha_{ji}^2 b_1 + \sum_{j=1}^{M} \Re(h_{j1}^*)\Re(w_1^j) + \Re(h_{j2})\Re(w_2^{j*}) \\ &\quad - \Im(h_{j1}^*)\Im(w_1^j) - \Im(h_{j2})\Im(w_2^{j*}),\end{aligned} \tag{3}$$

$$\begin{aligned}\widehat{b}_2 &= \Re\left\{\sum_{j=1}^{M} h_{j2}^* r_1^j - h_{j1} r_2^{j*}\right\} \\ &= \sum_{i=1}^{N=2}\sum_{j=1}^{M} \alpha_{ji}^2 b_2 + \sum_{j=1}^{M} \Re(h_{j2}^*)\Re(w_1^j) - \Re(h_{j1})\Re(w_2^{j*}) \\ &\quad - \Im(h_{j2}^*)\Im(w_1^j) + \Im(h_{j1})\Im(w_2^{j*})\end{aligned} \tag{4}$$

where $\Re$ and $\Im$ denote the real and imaginary parts operations, respectively. Note that in (3) and (4), we assume that the receiver has perfect knowledge of the channel fading coefficients.

III. PERFORMANCE ANALYSIS

In this section, we evaluate the upper bound for the bit error rate (BER) of the space-time convolutionally coded system over flat fading channels with ideal channel interleaving. This can easily be justified if the channel is fast fading, where small interleavers can be adequate to provide independent fading statistics from one bit to another. By ideal interleaving, we mean that an independent fading variable exists for every two consecutive transmitted bits. Note that the BER upper bound is based on the Viterbi decoding algorithm with infinite quantization levels.

Considering a window of d bits, the conditional pairwise error probability is given by [18]

$$P(d \mid \overline{\alpha}) = P\left\{\sum_{n=1}^{d} \widehat{b}_n \geq 0\right\} \tag{5}$$

where the vector $\overline{\alpha} = [\alpha_{11,1}, \cdots, \alpha_{ji,n}, \cdots, \alpha_{NM,d}]$, and the summation in (5) is taken over the incorrect path of d bits assuming the all zero path has been transmitted. Note that in (5) we assume a perfect interleaving process where the fading coefficients are independent from one-bit-to-another. Using (15) and (20) in [15], the pairwise error probability in (5) can be written as

$$P(d \mid \overline{\alpha}) = Q\left(\sqrt{\sum_{n=1}^{d}\sum_{i=1}^{N}\sum_{j=1}^{M} \frac{E\alpha_{ji,n}^2}{2\sigma^2}}\right) \tag{6}$$

where E is the average energy per coded bit, and is related to the uncoded bit energy through $R_c E_b$ where R_c is the code rate. Now, assuming independent fading coefficients among different antennas and from bit-to-another, the pairwise error probability is given by

$$P(d \mid \overline{\alpha}) = Q\left(\sqrt{\sum_{k=1}^{NMd} \frac{E\alpha_k^2}{2\sigma^2}}\right). \tag{7}$$

Using the upper bound for the probability of bit error given in [18], we have

$$P_b < (1/m) \sum_{d=d_{free}}^{\infty} \beta_d P(d) \tag{8}$$

where the terms β_d represent the coefficients of the derivative of the CC transfer function and $P(d)$ is the pairwise error probability given in (7).

Note that the fading coefficients are assumed independent resulting in a total diversity order equal to NMd where d corresponds to the time diversity delivered by the convolutional code with ideal channel interleaving, and NM corresponds to total spatial diversity given by the space-time block code.

Now, the α_k^2 terms in (7) represent a chi-square distribution with $2NMd$ degrees of freedom. Averaging of (7) over the chi-square distribution [19], gives the probability of error as

$$P(d) = [\frac{1}{2}(1-\gamma)]^{NMd} \sum_{n=0}^{NMd-1} \binom{NMd-1+n}{n} [\frac{1}{2}(1+\gamma)]^n \tag{9}$$

where

$$\gamma = \sqrt{\frac{SINR_{av}}{SINR_{av}+1}} \tag{10}$$

and

$$SINR_{av} = (E/2\sigma^2)E(\alpha^2) \tag{11}$$

is the average signal-to-noise plus interference ratio per coded bit, and $E\{\cdot\}$ denotes statistical expectation. Having obtained the pairwise probability of error, it is now easy to find the probability of bit error upper bound in (8). Note that the generalization of this bound to quasi-static channels is straightforward, given that a sufficiently large interleaver is used to obtain independent fading variables within the transmitted data block. Note that the probability of bit error in (7) is similar to the maximal-ratio combining receiver (MRC) with a diversity order equal to NMd. This is not surprising since channel coding is some form of time diversity with diversity order equal to the minimum Hamming distance of the used code.

For the case where antenna selection is used at the receiver side, an upper bound as in [13] can be used to roughly estimate the BER for the CC-STBC system. In this case, the pairwise error probability is upper bounded by

$$\begin{aligned}P(d) &\leq [\frac{1}{2}(1-\frac{L}{M}\gamma)]^{NMd} \\ &\quad \times \sum_{n=0}^{NMd-1} \binom{NMd-1+n}{n} [\frac{1}{2}(1+\frac{L}{M}\gamma)]^n.\end{aligned} \tag{12}$$

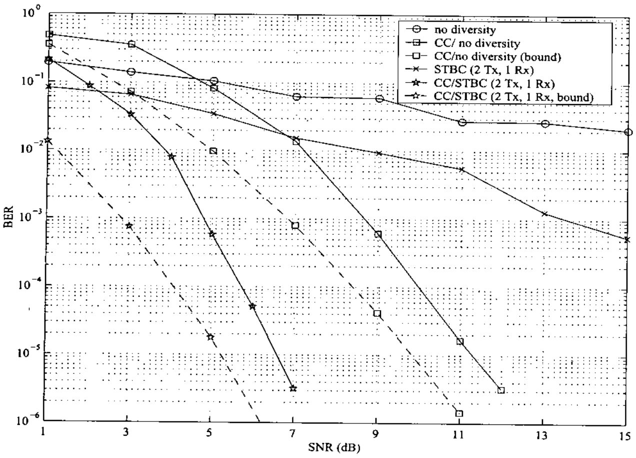

Fig. 2. Performance bounds for the convolutionally-coded space-time system over flat fast-fading channels with ideal channel interleaving.

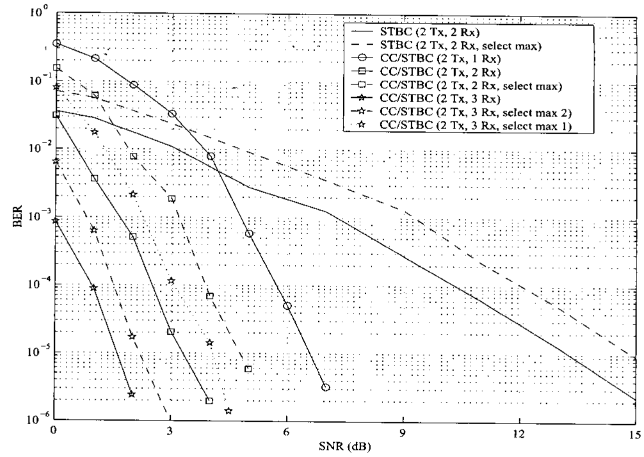

Fig. 3. BER performance of STBC with and without SD-CC, and employing antenna selection. The channel is fast-fading with ideal channel interleaving.

Note that the factor $(\frac{L}{M})$ represents the coding gain loss due to antenna selection. For the case when $L = M$, the system achieves its maximum coding gain at full complexity (i.e., no antenna selection). In the following section, we present simulation results that confirm the validity of this bound.

IV. SIMULATION RESULTS

In the following simulation results, we consider a space-time system with ideal channel interleaving. In our study, we also consider the performance of the space-time coded system over quasi-static flat-fading channels, where we compare it with the results obtained for the fast fading case. The remaining system parameters used in our simulations are as follows.

- Binary-phase shift-keying (BPSK) transmission.
- Convolutional coding with rate $R = 1/2$ and a constraint length $L = 7$.
- The space-time block code used is based on Alamouti's code [3].
- The channel is modeled as a fast fading one, or else mentioned.

A. BER Upper Bound

Since it is difficult to obtain an exact expression for the CC generating function at large constraint lengths, we only consider the first five, distinct, Hamming distances and their coefficients to evaluate the BER in (8). Note that at low BERs, the trellis paths with the least Hamming distances will constitute the major error events effecting the overall system performance.

Fig. 2 shows the BER performance of the CC system with and without space-time block coding. Also shown for comparison reasons is the performance of the Alamouti space-time code with two transmit and one receive antennas, along with the BER upper bound for the CC system. An important observation on these results is seen from the large coding gain achieved when using soft-decision (SD)-CC with STBC. The large diversity order delivered by the CC space-time system (seen from the slope of the BER curve) is mainly due to the perfect interleaving assumption. The effect of nonideal interleaving will be considered later when we discuss block versus fast fading results. Moving on to the BER upper bound derived in Section III, one can see that the bound is in a good agreement with simulation results. Note that the BER bounds become more tight as the SNR increases and as such, a use of these bounds becomes essential where computer simulations are impractical at low BER levels. For instance, the SNR tolerance incurred using such a bound is shown to be approximately 1.5 dB at a BER of 10^{-5}.

It is worth mentioning that the error bound we considered assumes a system with infinite quantization whereas the simulated results are based on an 8-level quantization scheme, which is usually used in practice. Note that, our comparison is similar to the one in the classical paper [20] for the AWGN channel case.

B. Antenna Selection

As discussed earlier, the use of maximum SNR antenna selection can reduce the number of RF chains at the receiver side of a MIMO system while maintaining the same diversity order. In what follows, we denote the number of antenna selected by the letter L. Here, we examine the BER performance of both the STBC system and convolutionally-coded one when antenna selection is employed at the receiver side. The results of this investigation are shown in Fig. 3 for the system BER, and in Fig. 4 for the frame error rate (FER) with a frame of size 130 symbols, both for the fast-fading channel. In these results, we fix the number of transmit antennas, N, to two elements, and consider a receiver with $M = 2$ and 3 antenna elements. We also include the $N = 2$ and $M = 1$ case for comparison purposes. From these results, some important observations are

- for both STBC and CC-STBC, the use of antenna selection only affects the system's coding gain while the total diversity order is maintained. This result is quite clear from the slope of the BER curves with and without antenna selection. A similar observation was reported for STTC's over quasi-static flat-fading channels [13].
- In the $N = 2$ and $M = 2$ with CC-STBC, the antenna selection provides a coding gain of approximately 2 dB higher than the corresponding $N = 2$ and $M = 1$ case. Note that

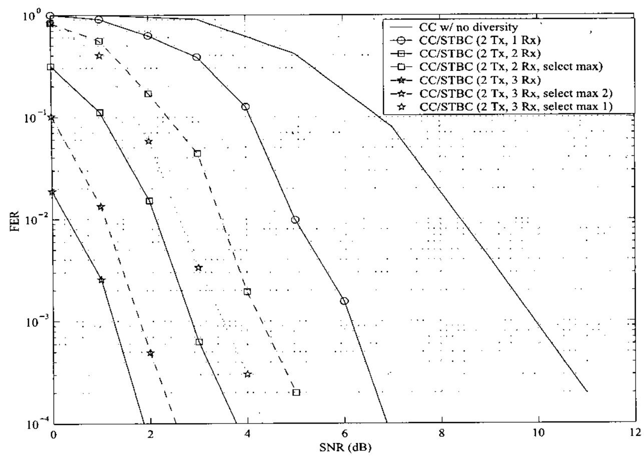

Fig. 4. FER performance of STBC with and without SD-CC, and employing antenna selection. The channel is fast-fading with ideal channel interleaving.

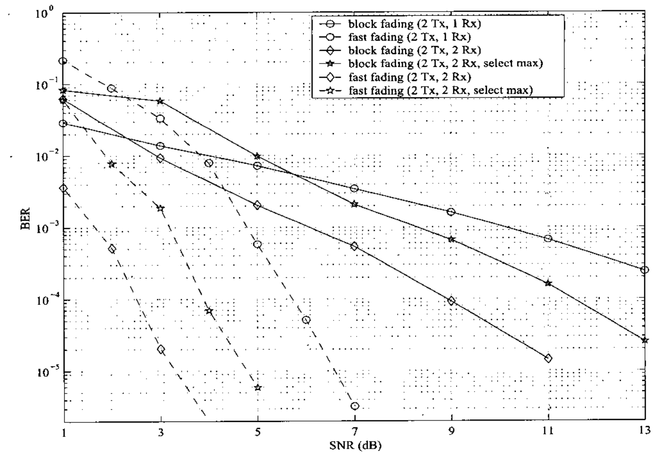

Fig. 5. BER performance of the SD-CC/STBC with antenna selection. Quasi-static fading versus fast-fading.

the loss incurred due to antenna selection is in the range of 1.5 dB. This SNR loss is almost the same as for the STBC alone (with the same number of antennas).

- For the $N = 2$ and $M = 3$ scenario, we can see that the $L = 1$ case results in a coding gain reduction of approximately 2.5 dB relative to the full diversity case ($L = 3$, no antenna selection). Note that the $L = 1$ case offers a larger coding gain than the $N = 2$, $M = 2$ case with antenna selection. Also for $L = 2$, one can see that the SNR reduction from the full diversity case is very small (approximately 0.5 dB).
- The BER results for the antenna selection case are in a good agreement with the bound given in (12). We have also noted that the error bound in (12) becomes loose as the number of selected antennas decreases relative to the total number of receive antennas.

C. *Antenna Selection for Quasi-Static Fading Versus Fast Fading*

Having examined the performance of the convolutionally-coded space-time system over fast fading channels with ideal interleaving, it is of interest to examine its performance on block fading channels. In the following simulation results, we consider a block fading channel where the channel fading is considered constant over a frame of length 130 symbols. To simplify the comparison, we only focus on the $N = 2$ and $M = 2$ system when we discuss the effect of antenna selection on the receiver BER performance.

In Fig. 5, we compare the performance of the CC-STBC system in fast fading with that over block fading channels. As seen from these results, the fast fading channel provides much larger diversity order than the block fading case for the same space diversity order (same number of transmit and receive antennas). This large diversity order is due to the time diversity delivered by the channel interleaving process which dominates the overall system diversity. One important remark on antenna selection is that regardless of the channel model, the diversity order is maintained and only a reduction in the SNR gain is incurred.

V. CONCLUSIONS

In this paper, we analyzed the performance of the serial concatenation of convolutional coding with space-time block coding. We obtained an error bound for the space-time coded system with ideal channel interleaving. Our results indicated that these error bounds are in a good agreement with the exact BER performance especially at low BER levels where error bounds become more significant. We have also shown that the use of antenna selection at the receiver side only effects the SNR coding gain, but not the overall diversity order. This phenomena was evident for both the fast and block flat fading channel models. Moreover, we have shown that the receiver performance is affected significantly by channel interleaving. In that, a comparison between the quasi-static and fast fading channels was conducted where it was shown that the time diversity order dominates the overall system diversity. Furthermore, we have noted that the use of antenna selection results in almost the same SNR reduction regardless of the channel model used. This coding gain loss due to antenna selection was shown to be upper bounded by $10\log_{10}(M/L)$ dB. In comparing the performance of STTCs with the concatenated CC-STBC, for the case when antenna selection is used, we observed that the diversity order is maintained for the latter as opposed to the former where the diversity order is known to deteriorate with antenna selection.

ACKNOWLEDGMENT

The authors would like to thank the anonymous reviewers for their helpful comments and suggestions that helped to improve the presentation of this manuscript.

REFERENCES

[1] J. C. Guey, M. P. Fitz, M. R. Bell, and W. Y. Kuo, "Signal design for transmitter diversity wireless communication systems over rayleigh fading channels," in *Proc. IEEE VTC'96*, vol. 1, 1996, pp. 136–140.

[2] V. Tarokh, N. Seshadri, and A. R. Calderbank, "Space-time codes for high data rate wireless communication: Performance criterion and code construction," *IEEE Trans. Inform. Theory*, vol. 44, pp. 744–765, Mar. 1998.

[3] S. M. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE J. Select. Areas Commun.*, vol. 16, no. 8, pp. 1451–1458, Oct. 1998.

[4] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, "Space-time block codes from orthogonal designs," *IEEE Trans. Inform. Theory*, vol. 45, no. 5, pp. 1456–1467, July 1999.
[5] S. Sandhu, R. Heath, and A. Paulraj, "Space-time block codes versus space-time trellis codes," in *Proc. IEEE ICC 2001*, vol. 4, June 2001, pp. 1132–1136.
[6] S. M. Alamouti, V. Tarokh, and P. Poon, "Trellis-coded modulation and transmit diversity: Design criteria and performance evaluation," in *Proc. ICUCP'98*, 1998.
[7] J. C. Guey, "Concatenated coding for transmit diversity systems," in *Proc. IEEE VTC'99*, vol. 5, 1999, pp. 2500–2504.
[8] S. Baro, G. Bauch, and A. Hansmann, "Improved codes for space-time trellis-coded modulation," *IEEE Commun. Lett.*, vol. 4, no. 1, pp. 20–22, Jan. 2000.
[9] X. Lin and R. S. Blum, "Improved space-time codes using serial concatenation," *IEEE Commun. Lett.*, vol. 4, no. 7, pp. 221–223, July 2000.
[10] Y. Liu, M. P. Fitz, and O. Y. Takeshita, "Full rate space-time turbo codes," *IEEE J. Select. Areas Commun.*, vol. 19, no. 5, pp. 969–980, May 2001.
[11] A. F. Molisch, M. Z. Win, and J. H. Winters, "Capacity of MIMO systems with antenna selection," in *Proc. IEEE ICC 2001*, vol. 2, June 2001, pp. 570–574.
[12] I. Bahceci, T. M. Duman, and Y. Altunbasak, "Antenna selection for multiple-antenna transmission systems: Performance analysis and code construction," *IEEE Trans. Inform. Theory*, to be published.
[13] A. Ghrayeb and T. M. Duman, "Performance analysis of MIMO systems with antenna selection over quasi-static fading channels," *IEEE Trans. Veh. Technol.*, vol. 52, no. 2, pp. 281–288, Mar. 2003.
[14] A. Ghrayeb, A. Sanei, and Y. Shayan, "Space-time trellis codes with antenna selection in fast fading," *IEE Electron. Lett.*, vol. 40, no. 10, pp. 613–614, May 2004.
[15] X. Li, T. Luo, and C. Yin, "Asquaring method to simplify the decoding of orthogonal space-time block codes," *IEEE Trans. Commun.*, vol. 49, pp. 1700–1703, Oct. 2001.
[16] A. Gorokhov, D. Gore, and A. Paulraj, "Receive antenna selection for MIMO spatial multiplexing: Theory and algorithms," *IEEE Trans. Signal Processing*, vol. 51, pp. 2796–2807, Nov. 2003.
[17] S. Kim and E. Kim, "Optimum receive antenna selection minimizing error probability," in *Proc. WCNC 2003*, pp. 441–447.
[18] A. Viterbi and J. Omura, *Principles of Digital Communication and Coding*, McGraw-Hill Publishing, 1979.
[19] J. Proakis, *Digital Communications*, McGraw-Hill Publishing, 1995.
[20] J. Heller and I. Jacobs, "Viterbi decoding for satellite and space communication," *IEEE Trans. Commun.*, pp. 835–848, Oct. 1971.

Walaa Hamouda received his B.Sc. degree in 1992 in Electrical Engineering from Ain Shams University, Cairo, Egypt and his M.Sc. and Ph.D. degrees from Queen's University, Kingston, Ontario, Canada, in 1998 and 2002, respectively, all in Electrical Engineering. During his graduate studies, he was awarded the Ontario Graduate Scholarships and Queen's Graduate Fellowship. From 1994 to 1995, he joined Siemens, Cairo, Egypt, in the Telecommunications Division, where he focused on the design of telecommunication cables and fiber optic transmission systems. Since July 2002, he has been appointed as an Assistant Professor with the Department of Electrical and Computer Engineering, Concordia University, Montreal, Quebec, Canada. He has served in the technical committees/chaired sessions of several IEEE conferences including IEEE IPCCC 2003, IEEE International Conference on Information & Communication Technologies, and VTC 2001–2003. His current research interests are in wireless and mobile communications, smart antenna techniques, channel coding, and space-time coding.

Ali Ghrayeb received the Ph.D. degree in electrical engineering from the University of Arizona, Tucson, AZ, in May 2000. From 2000 to 2002, he was an Assistant Professor in the Electrical Engineering Department at the American University of Sharjah, UAE. Since August 2002, he has been with the Department of Electrical and Computer Engineering, Concordia University, Montreal, Canada, where he is an Assistant Professor. His research interests include digital and wireless communications, channel coding, turbo codes, space-time codes, and signal processing and coding for data transmission and storage. He has published over 40 refereed technical papers in the above research areas. He has served/is serving on the Technical Program Committee of several IEEE conferences, including VTC 2003/2004, ICC 2004/2005, and PIMRC 2003/2004. He co-instructed technical tutorials on coding for MIMO systems at IEEE Globecom 2003, WCNC 2004, and PIMRC 2004. He is serving as Associate Editor for the Wiley Wireless Communications and Mobile Computing Journal.