PRECODED STBC-VBLAST FOR MIMO WIRELESS COMMUNICATION SYSTEMS

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ABSTRACT

A degradation in the bit error rate (BER) performance of the vertical Bell-Labs layered space-time (VBLAST) MIMO system is often due to its low minimum diversity and decoder's error propagation. To remedy this problem, a hybrid scheme that integrates orthogonal space time block codes (STBC) into the lower layers of a VBLAST system was recently introduced. However, if channel state information is available at the transmitter, this hybrid system does not necessarily outperform a *precoded* VBLAST. This, in turn, motivates our work in this paper, namely the joint design of a precoder and its corresponding decoder for the VBLAST-STBC hybrid system. We consider the two scenarios of a flat and frequency selective fading channels and derive complete analytical solutions for both cases. Our simulation results indicate that the BER performance of the proposed precoded hybrid system is better than all of the other schemes.

***Index Terms*—** MIMO Communication Systems, Space-Time Block Codes, Vertical Bell-Labs Layered Space-Time, Precoding, STBC, VBLAST

1. INTRODUCTION

Contemporary multi-input multi-output (MIMO) communication systems use multiple transmit antennas to increase channel capacity and/or diversity gain over single transmit antenna systems in high speed wireless applications [1]. The vertical Bell-labs layered space-time scheme is one of the recently proposed MIMO systems designed to achieve this performance improvement [2]. At the transmitter, each antenna sends its own independently coded symbol, while at the receiver a spatial domain generalized decision feedback equalizer is employed. The symbols are decoded on an individual basis, starting from the symbol with the minimum estimation error variance (for more details, see [1]). Once this symbol is decoded, its interference with the other symbols is removed by appropriately subtracting it from the received signal. The decoder then proceeds to decode the remaining symbols in a similar fashion. This process of successive interference cancellation can however cause performance degradation because of potential decoding error propagation. To mitigate error propagation by increasing the diversities of the lower VBLAST layers, a new scheme which combines orthogonal space-time block codes [3] with VBLAST, namely the STBC-VBLAST has been recently introduced [4]. Although it is shown in [4] that the minimum diversity of the hybrid system is generally larger than that of other VBLAST systems, the authors consider the specific case where channel state information (CSI) is only present at the receiver. However, in a slowly varying communication environment such as indoor wireless local area networks (WLAN), the CSI can be also available at the transmitter via feedback or through the reciprocal principle when time division duplex (TDD) is used. In these situations, a VBLAST jointly *optimal* precoder and decoder can substantially improve the BER performance. In fact, our simulation results given in Section 5, clearly demonstrate that with channel state information at the transmitter (CSIT), the hybrid system is not guaranteed to outperform an *optimal precoded* VBLAST. This particular observation has motivated the work presented in this paper, namely the design of a precoder and its corresponding decoder (equalizer) for the hybrid STBC-VBLAST system. We note that precoder designs for the individual sub-systems have been studied by a number of researchers. For example, the design of precoding matrices for the standard VBLAST system using the so-called geometric mean decomposition (GMD) was suggested recently in [5] and [6], and extension of these results for frequency selective fading channels can be found in [7]. A desirable feature of the GMD approach is the ability to decompose the MIMO channel into a set of parallel sub-channels that have *identical* mean square errors (MSE) (equivalently BER). Thus, the GMD precoder can be viewed as an attractive alternative to the standard technique of decomposing the channel into a set of parallel sub-channels using the singular value decomposition (SVD) and then applying a bit loading algorithm as a practical implementation of water filling. The GMD improvement is due to the discrete nature of bit loading which degrades the overall BER performance. Similarly, the design of precoders for STBC has been investigated by a number of researchers (see for example [8, 9, 10] to name a few). Nevertheless, the joint precoder/decoder design for the hybrid system does not exist in the literature and is therefore proposed here. It should be clear from the previous exposition that the problem can be approached in a number of ways and a variety of different solutions can be obtained depending on the underlying assumptions and design criterions. In this paper, we seek a suboptimal but efficient transceiver rather than an optimal complex one. In specific, the contribution of this paper is three folds: first, we consider the case of a flat fading channel and derive an efficient procedure to design a precoder and decoder for the STBC-VBLAST system. We emphasize at this point that although part of our approach is inspired by some of the above work, the results derived here for the hybrid system are *not* a simple concatenation of the precoder solutions of the individual sub-systems. In fact, most of the STBC precoder designs assume either partial knowledge of CSIT [8] or knowledge of the transmit antenna fading correlations [9, 10] and are therefore not directly applicable to our problem. The structure of the hybrid system constrains the precoder/decoder design, which in turn requires the development of a new mathematical approach as we discuss in detail in the rest of the paper. Second, we extend these results to the frequency selective fading channel case. An attractive feature of the proposed design process in this case is that it exhibits the same computational complexity and system latency as in flat fading. Finally, our simulation results indicate that the precoded hybrid system outperforms the precoded VBLAST as well as the unprecoded schemes.

2. TRANSMITTER FOR PRECODED STBC-VBLAST

We study a MIMO system with n_T transmit antennas and n_R receive antennas. Although our results extend readily to any number of STBC layers, we consider here a single STBC layer for simplicity purpose. The transmitter for the precoded STBC-VBLAST system is depicted in Fig. 1. where the STBC operates over n_S transmit antennas and m symbol intervals.

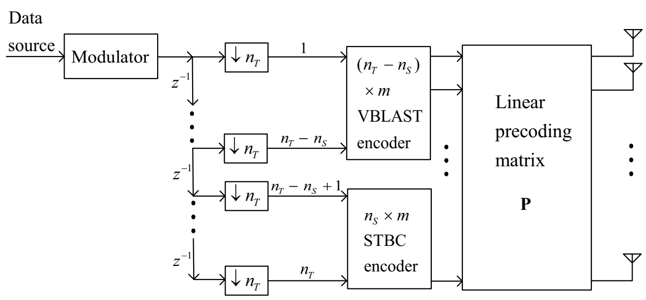

Fig. 1. Precoded STBC-VBLAST transmitter

It is assumed that the channel does not change within one STBC interval. Over that interval, the transmitted block of symbols before the linear precoder are in the following form

$$\mathbf{S} = \begin{bmatrix} \mathbf{S}_V \\ \mathbf{S}_S \end{bmatrix}$$

where $\mathbf{S}_V$ is the $(n_T - n_S) \times m$ VBLAST codeword and $\mathbf{S}_S$ is the $n_S \times m$ STBC codeword. If the data rate of the original STBC is r_S, then, the data rate of the hybrid system is $n_T - n_S + r_S$, which is lower than the VBLAST case but much higher than the STBC one.

Finding the linear precoder. Ideally, we would like to decode $\mathbf{S}_V$ and $\mathbf{S}_S$ *independently* from each other. However, the signals transmitted from the n_T antennas propagate via flat fading channels and interfere with each other at the receiver. The $n_R \times m$ matrix $\mathbf{X}$ of received symbols is a linear combination of $\mathbf{S}_V$ and $\mathbf{S}_S$ and, these codewords can not, in general, be separated at the receiver. We will show however that, by carefully selecting the linear precoder $\mathbf{P}$, we can retrieve the STBC and VBLAST codewords in a *consecutive* and *decoupled* manner. To do this, we start by enforcing a block diagonal structure on the precoder as follows

$$\mathbf{P} = \begin{bmatrix} \mathbf{P}_V & \mathbf{0} \\ \mathbf{0} & \mathbf{P}_S \end{bmatrix}$$

where $\mathbf{P}_V$ is an $(n_T - n_S) \times (n_T - n_S)$ precoding matrix for $\mathbf{S}_V$, and $\mathbf{P}_S$ is an $n_S \times n_S$ precoding matrix for $\mathbf{S}_S$. We emphasize that the block diagonal structure of $\mathbf{P}$ by itself does not decouple the two MIMO sub-systems. Indeed, the matrix $\mathbf{X}$ of received symbols given by

$$\begin{aligned} \mathbf{X} &= \begin{bmatrix} \mathbf{H}_V & \mathbf{H}_S \end{bmatrix} \begin{bmatrix} \mathbf{P}_V & \mathbf{0} \\ \mathbf{0} & \mathbf{P}_S \end{bmatrix} \begin{bmatrix} \mathbf{S}_V \\ \mathbf{S}_S \end{bmatrix} + \mathbf{W} \\ &= \mathbf{H}_V \mathbf{P}_V \mathbf{S}_V + \mathbf{H}_S \mathbf{P}_S \mathbf{S}_S + \mathbf{W} \end{aligned} \quad (1)$$

where $[\mathbf{H}_V \ \mathbf{H}_S]$ denotes the $n_R \times n_T$ channel information matrix, and $\mathbf{W}$ denotes $n_R \times m$ matrix of additive noise with i.i.d. complex Gaussian random variables elements, is still a linear combination of $\mathbf{S}_V$ and $\mathbf{S}_S$. To maximize the channel capacity and decode the STBC and VBLAST codewords independently, we propose to compute $\mathbf{P}_V$ and $\mathbf{P}_S$ as follows

1. We first determine $\mathbf{P}_V$ by applying the geometric mean decomposition (GMD) to the augmented channel matrix

$$\begin{bmatrix} \mathbf{H}_V \\ \sqrt{\alpha} \mathbf{I}_{n_T - n_S} \end{bmatrix} = \mathbf{Q}_V \mathbf{R}_V \mathbf{P}_V^* \quad (2)$$

where $\mathbf{Q}_V$ is an $(n_R + n_T - n_S) \times (n_T - n_S)$ semi-unitary matrix, $\mathbf{R}_V$ is an $(n_T - n_S) \times (n_T - n_S)$ upper-triangular matrix with equal diagonal elements and α^{-1} is the SNR. The above choice of $\mathbf{P}_V$ makes the mean squared error (MSE) of each element of $\mathbf{S}_V$ identical and similar to [5], we can show that this approach insures that error propagation in the VBLAST portion of the hybrid system is *minimized*. We note that an additional precoder that performs optimal power loading for VBLAST can be designed independently at this step. Nevertheless and similar to [7], we will only focus on the design of the GMD precoder in this paper.

2. We then obtain $\mathbf{P}_S$ by applying a reduced QR decomposition to the *new channel matrix*

$$\begin{bmatrix} \mathbf{H}_V \mathbf{P}_V & \mathbf{H}_S \end{bmatrix} = \mathbf{Q} \begin{bmatrix} \mathbf{R}_{VV} & \mathbf{R}_{VS} \\ \mathbf{0} & \mathbf{R}_{SS} \end{bmatrix} \quad (3)$$

where $\mathbf{Q}$ is an $n_R \times n_T$ unitary matrix, $\mathbf{R}_{VV}$ is an $(n_T - n_S) \times (n_T - n_S)$ upper-triangular matrix representing the effective channel for $\mathbf{S}_V$, $\mathbf{R}_{VS}$ is an $(n_T - n_S) \times n_S$ matrix representing the interference introduced by $\mathbf{S}_S$ to $\mathbf{S}_V$, and $\mathbf{R}_{SS}$ is an $n_S \times n_S$ upper-triangular matrix representing the effective channel for $\mathbf{S}_S$. Let $\mathbf{\Lambda} = \mathbf{P}_S \mathbf{P}_S^*$. To maximize the MIMO channel capacity, we need to solve [3]

$$\mathbf{\Lambda} = \arg \max_{Tr(\mathbf{\Lambda}) \leq n_S} \log \det(\mathbf{I} + \alpha^{-1} \mathbf{R}_{SS} \mathbf{\Lambda} \mathbf{R}_{SS}^*) \quad (4)$$

where $Tr(\cdot)$ denotes the trace of a matrix. Hence, $\mathbf{\Lambda}$ can be computed via the well-known water filling algorithm. Let $\mathbf{J}$ denote the n_S-dimensional reversal matrix defined as

$$\mathbf{J} = \begin{bmatrix} 0 & 0 & \cdots & 1 \\ 0 & \cdots & 1 & 0 \\ \vdots & \vdots & \vdots & \vdots \\ 1 & 0 & \cdots & 0 \end{bmatrix}$$

and $\mathbf{L}$ denote the Cholesky factor of $\mathbf{J}\,\mathbf{\Lambda}\,\mathbf{J}$, we have

$$\begin{aligned} & \mathbf{\Lambda} = \mathbf{P}_S \mathbf{P}_S^* \\ \Longrightarrow\ & \mathbf{J}\,\mathbf{\Lambda}\,\mathbf{J} = (\mathbf{J}\,\mathbf{P}_S\,\mathbf{J})(\mathbf{J}\,\mathbf{P}_S\,\mathbf{J})^* \\ \Longrightarrow\ & \mathbf{P}_S = \mathbf{J}\,\mathbf{L}\,\mathbf{J} \end{aligned} \quad (5)$$

We note that the precoder $\mathbf{P}_S$ in (5) and the precoded effective channel $\mathbf{R}_{SS}\,\mathbf{P}_S$ are upper-triangular matrices with positive diagonal elements. This fact plays a *key role* in the construction of the hybrid system decoder as we discuss next.

3. RECEIVER FOR PRECODED STBC-VBLAST

To derive the decoding algorithm for the precoded hybrid system, we assume that $n_R \geq n_T$ and that the $n_R \times n_T$ channel information matrix $\mathbf{H} = [\mathbf{H}_V \ \mathbf{H}_S]$ is of full rank, i.e., rank of $\mathbf{H} = n_T$. Note that if $\mathbf{H}$ is of full rank, then,

$$\begin{bmatrix} \mathbf{H}_V \mathbf{P}_V & \mathbf{H}_S \end{bmatrix} = \begin{bmatrix} \mathbf{H}_V & \mathbf{H}_S \end{bmatrix} \begin{bmatrix} \mathbf{P}_V & \mathbf{0} \\ \mathbf{0} & \mathbf{I} \end{bmatrix}$$

is also of full rank. The following theorem will be useful.

Theorem 1. [11] Any $M \times N$ matrix $\mathbf{A}$ ($M \geq N$) of full rank has a *unique* reduced QR decomposition $\mathbf{A} = \mathbf{QR}$ where the diagonal elements of $\mathbf{R}$ are positive numbers.

We are now ready to describe the decoding algorithm.

1. To decode $\mathbf{S}_S$, we start with the following claim

Theorem 2. Consider a reduced QR decomposition of the effective channel $\mathbf{HP}$, that is, let $\mathbf{HP} = \mathbf{Q}_1\mathbf{R_1}$. Then, $\mathbf{Q}_1 = \mathbf{Q}$ of (3) and

$$\mathbf{R_1} = \begin{bmatrix} \mathbf{R}_{VV} & \mathbf{R}_{VS} \\ \mathbf{0} & \mathbf{R}_{SS} \end{bmatrix} \begin{bmatrix} \mathbf{I} & \mathbf{0} \\ \mathbf{0} & \mathbf{P}_S \end{bmatrix}$$

Proof. We first note that

$$\begin{bmatrix} \mathbf{H}_V\mathbf{P}_V & \mathbf{H}_S\mathbf{P}_S \end{bmatrix} = [\mathbf{H}_V\mathbf{P}_V \ \mathbf{H}_S] \begin{bmatrix} \mathbf{I} & \mathbf{0} \\ \mathbf{0} & \mathbf{P}_S \end{bmatrix} = \mathbf{Q}_1\mathbf{R}_1$$
$$\Longrightarrow [\mathbf{H}_V\mathbf{P}_V \ \mathbf{H}_S] = \mathbf{Q}_1\mathbf{R}_1 \begin{bmatrix} \mathbf{I} & \mathbf{0} \\ \mathbf{0} & \mathbf{P}_S \end{bmatrix}^{-1} \tag{6}$$

Since the inverse of an upper triangular matrix is also upper triangular, the result follows immediately from the uniqueness of the reduced QR decomposition of $[\mathbf{H}_V\mathbf{P}_V \ \mathbf{H}_S]$. $\nabla\nabla\nabla$

We again emphasize that the above exposition is only feasible due to the special structure of $\mathbf{P}_S$. It follows that

$$\begin{aligned} \begin{bmatrix} \mathbf{H}_V\mathbf{P}_V & \mathbf{H}_S\mathbf{P}_S \end{bmatrix} &= \mathbf{Q} \begin{bmatrix} \mathbf{R}_{VV} & \mathbf{R}_{VS}\mathbf{P}_S \\ \mathbf{0} & \mathbf{R}_{SS}\mathbf{P}_S \end{bmatrix} \\ \Longrightarrow \mathbf{Q}^*\mathbf{X} &= \begin{bmatrix} \mathbf{R}_{VV} & \mathbf{R}_{VS}\mathbf{P}_S \\ \mathbf{0} & \mathbf{R}_{SS}\mathbf{P}_S \end{bmatrix} \begin{bmatrix} \mathbf{S}_V \\ \mathbf{S}_S \end{bmatrix} + \mathbf{Q}^*\mathbf{W} \end{aligned} \tag{7}$$

Since $\mathbf{Q}$ is unitary, the statistical properties of the additive noise remain unchanged. Define

$$\mathbf{Q}^*\mathbf{X} = \begin{bmatrix} \mathbf{X}_{VS} \\ \mathbf{X}_S \end{bmatrix},$$

where $\mathbf{X}_{VS}$ and $\mathbf{X}_S$ are of size $(n_T - n_S) \times m$ and $n_S \times m$, respectively. Let $\{s_1, s_2, \ldots, s_{m \cdot r_S}\}$ be the set of symbols that form $\mathbf{S}_S$, the STBC maximum likelihood detection is then

$$\begin{aligned} \{s_1, \ldots, s_{m\cdot r_S}\} = &\ \arg\min \|\mathbf{X}_S - \mathbf{R}_{SS}\mathbf{P}_S\mathbf{S}_S\|_F \\ &\ s.t. \ \{s_1, s_2, \ldots, s_{m\cdot r_S}\} \in \mathbf{C}^{m\cdot r_S} \end{aligned} \tag{8}$$

where $\|\cdot\|_F$ denotes the Frobenius norm of a matrix and $\mathbf{C}$ denotes the constellation set of the underlying modulation scheme. When linear orthogonal STBC are used, we can express $\mathbf{S}_S$ as

$$\mathbf{S}_S = \sum_{n=1}^{m\cdot r_S} (Re(s_n) \cdot \mathbf{A}_n + iIm(s_n) \cdot \mathbf{B}_n)$$

where $Re(\cdot)$, $Im(\cdot)$ denote respectively the real and imaginary parts of a complex symbol, and $\mathbf{A}_n$, $\mathbf{B}_n$ denote fixed $n_T \times m$ code matrices. In this case, (8) can be further simplified into the following $m \cdot r_S$ independent tests

$$\begin{aligned} s_n = &\arg\min_{s_n \in \mathbf{C}} \\ &\left| s_n - \frac{Re(Tr(\mathbf{X}_S^*\mathbf{R}_{SS}\mathbf{P}_S\mathbf{A}_n)) - iIm(Tr(\mathbf{X}_S^*\mathbf{R}_{SS}\mathbf{P}_S\mathbf{B}_n))}{\|\mathbf{R}_{SS}\mathbf{P}_S\|_F^2} \right|^2, \\ &n = 1, 2, \ldots, m \cdot r_S \end{aligned} \tag{9}$$

and (9) can then be used to efficiently decode $\mathbf{S}_S$.

2. After we decode $\mathbf{S}_S$, we can subtract its contribution from $\mathbf{X}$ and obtain a new matrix $\mathbf{X}_V$ as follows

$$\mathbf{X}_V = \mathbf{X} - \mathbf{H}_S\mathbf{P}_S\mathbf{S}_S = \mathbf{H}_V\mathbf{P}_V\mathbf{S}_V + \mathbf{W} \tag{10}$$

Note that $\mathbf{X}_V$ is a function of $\mathbf{S}_V$ only.

3. Finally, we decode $\mathbf{S}_V$ by rewriting (10) in the following vector form

$$\mathbf{x}_V^j = \mathbf{H}_V\mathbf{P}_V\mathbf{s}_V^j + \mathbf{w}^j, \ j = 1, 2, \ldots, m$$

where $\mathbf{x}_V^j$, $\mathbf{s}_V^j$, $\mathbf{w}^j$ are the received signals, transmitted signals and noise at the j^{th} time slot. Let $s_V^{j,1}, s_V^{j,2}, \ldots, s_V^{j,n_T-n_S}$ denote the $n_T - n_S$ symbols in $\mathbf{s}_V^j$. These symbols are detected using the standard VBLAST decoding algorithm [5], [6].

4. PRECODED STBC-VBLAST FOR FREQUENCY SELECTIVE FADING MIMO CHANNELS

For ISI channels, a MIMO system is typically modelled as

$$\mathbf{X}(t) = \sum_{l=0}^{L} \mathbf{H}(l)\mathbf{S}(t-l) + \mathbf{W}(t),$$

where $\mathbf{X}(t)$ and $\mathbf{S}(t)$ are the received and transmitted block of symbols at the t^{th} STBC interval, $\mathbf{W}(t)$ is the additive noise, and $\mathbf{H}(z) = \sum_{l=0}^{L} \mathbf{H}(l)z^{-l}$ is the channel polynomial matrix. Assuming that $\mathbf{H}(z)$ remains fixed for at least $N_0 + L$ time intervals, we propose to use a MIMO-OFDM scheme with a cyclic prefix of length L and an FFT of length N_0 to combat frequency selective fading. Under these assumptions and for one transmitted OFDM frame, we can write

$$\begin{bmatrix} \mathbf{X}(0) \\ \mathbf{X}(1) \\ \vdots \\ \mathbf{X}(N_0-1) \end{bmatrix} = \begin{bmatrix} \widetilde{\mathbf{H}}(0) & & & \\ & \widetilde{\mathbf{H}}(1) & & \\ & & \ddots & \\ & & & \widetilde{\mathbf{H}}(N_0-1) \end{bmatrix} \cdot \begin{bmatrix} \mathbf{S}(0) \\ \mathbf{S}(1) \\ \vdots \\ \mathbf{S}(N_0-1) \end{bmatrix} + \begin{bmatrix} \widetilde{\mathbf{W}}(0) \\ \widetilde{\mathbf{W}}(1) \\ \vdots \\ \widetilde{\mathbf{W}}(N_0-1) \end{bmatrix} \tag{11}$$

where

$$\widetilde{\mathbf{H}}(k) = \sum_{l=0}^{L} \mathbf{H}(l)e^{-i\frac{2\pi kl}{N_0}}, \quad \widetilde{\mathbf{W}}(k) = \frac{1}{\sqrt{N_0}} \sum_{l=0}^{N_0-1} \mathbf{W}(l)e^{-i\frac{2\pi kl}{N_0}}$$

From (11), we process each transmit block separately and apply at the transmitter the precoder of Section 2 before the inverse FFT. Similarly, we use at the receiver the decoder of Section 3 after processing the received symbols by the FFT. Note that since we process each block separately, the computation of the geometric mean and/or the QR factorization of the large channel matrix is completely avoided. In fact, if some form of parallel processing is available at the transmitter and receiver, the above scheme has *exactly* the same computational complexity and system latency as the flat fading case. This computational efficiency is however achieved at the expense of a sacrifice in BER performance since the above approach is sub-optimal.

5. SIMULATION RESULTS

We compare the BER performances of four MIMO systems, namely, (1) the precoded STBC-V-BLAST introduced in this paper, (2) the unprecoded STBC-VBLAST of [4], (3) the precoded VBLAST of [5] and [6], and (4) the unprecoded VBLAST. 8PSK modulation and standard orthogonal space-time block codes from [3] are used in all of our simulations. For the flat fading case, we assume Rayleigh block fading channels. The MIMO channel parameters are $n_T = 6$ and $n_R = 6$. The space-time block codes parameters are $n_S = 4$, $m = 4$, and $r_S = 3/4$. The resulting BER curves are shown in Fig. 2. For the frequency selective fading case, the ISI MIMO channel matrix $\mathbf{H}(z)$ has order 15. Cyclic prefix and FFT of length 15 and 64 are respectively used. The parameters in this case are $n_T = 5, n_R = 5$, $n_S = 3$, $m = 4$ and $r_S = 3/4$. The BER results are illustrated in Fig. 3. From Fig. 2 and 3, we observe that when the CSI is available at the transmitter, the precoded VBLAST outperforms the unprecoded STBC-VBLAST at large SNR. In these situations, we can exploit the CSIT to design a precoder/decoder for the STBC-VBLAST system. The specific solution derived in this paper produces the best BER performance among the four schemes. The BER performance gain is however achieved at the expense of higher encoding and decoding complexity compared to the unprecoded STBC-VBLAST, and at the expense of a lower data rate compared to the precoded VBLAST. The new MIMO system is therefore a very appealing choice when such tradeoffs are deemed acceptable.

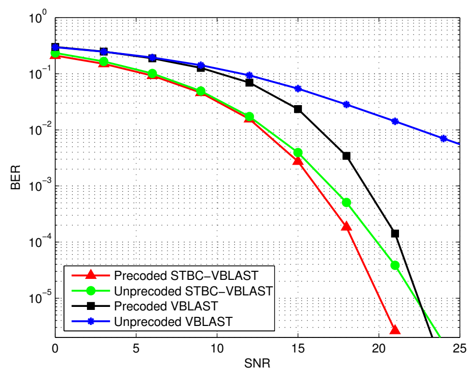

Fig. 2. BER performances for flat fading MIMO channels

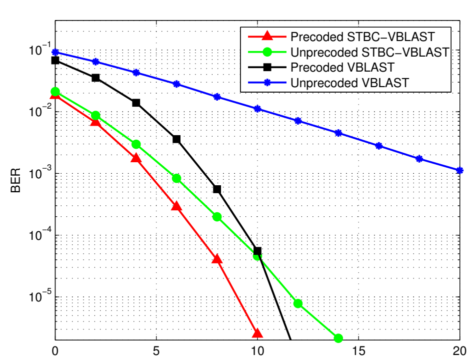

Fig. 3. BER performances for ISI MIMO channels

6. CONCLUDING REMARKS

Two main approaches have been proposed in the literature to exploit the potential of MIMO communication systems. One is the space time coding method that improves BER by increasing the diversity gain while the other is spatial multiplexing (e.g. VBLAST) which focusses on maximizing the channel throughput. Recently, a hybrid STBC-VBLAST system has been proposed to reap the benefits of both methods. Although the hybrid system has better BER performance than the standard VBLAST, it does not necessarily outperform a precoded VBLAST system. Motivated by this observation, we have therefore presented an efficient procedure for the joint design of a precoder and decoder for the hybrid system. Our exposition here is more exploratory than comprehensive and many potential research issues can be investigated. For example, our design process is clearly sub-optimal since we explicitly enforced a block diagonal structure on the precoder. Can we design a precoder and decoder if we remove this constraint ? what is the optimal precoder in this case and how much improvement in BER performance can we obtain ? These are open questions at this point in time. Another important research problem is the design of the hybrid system transceiver with *partial* CSIT or knowledge of the transmit antenna fading correlations, conditions that are typically more suitable for utilizing STBC.

7. REFERENCES

[1] G. J. Foschini and M. J. Gans, "On limits of wireless communications in a fading environment when using multiple antennas," *Wireless Personal Communication*, pp. 311–335, March 1998.

[2] P. W. Wolniansky, G. J. Foschini, G. D. Golden, and R. A. Valenzela, "V-BLAST: An architecture for realizing very high data rates over the rich scattering channel," *Proc. ISSE*, pp. 295–300, September 1998.

[3] E. G. Larsson and P. Stoica, *Space-Time Block Coding for Wireless Communications*, Cambridge University Press, 2005.

[4] T. Mao and M. Motani, "STBC-VBLAST for MIMO wireless communication systems," *Proc. ICC*, pp. 2266–2270, May 2005.

[5] Y. Jiang, J. Li, and W. W. Hager, "Joint transceiver design for MIMO communications using geometric mean decomposition," *IEEE Tr. on Signal Processing*, pp. 3791–3803, October 2005.

[6] J. K. Zhang, A. Kavcic, and K. M. Wong, "Equal-diagonal QR decomposition and its application to precoder design for successive-cancellation detection," *IEEE Tr. on Information Theory*, pp. 154–172, January 2005.

[7] C. Y. Chen and P. P. Vaidyanathan, "Precoded V-BLAST for ISI MIMO channels," *Proc. ISCAS*, May 2006.

[8] P. Jongren, M. Skoglund, and B. Ottersen, "Combining beamforming and orthogonal space-time block codes," *IEEE Tr. on Information Theory*, pp. 611–627, March 2002.

[9] H. Sampath and A. Paulraj, "Linear precoding for space-time coded systems with known fading correlations," *IEEE Communication letters*, pp. 239–241, June 2002.

[10] A. Hjorungnes, J. Akhtar, and D. Gesbert, "Precoding for space-time block codes in (non-)kronecker correlated MIMO channels," *Proc. Eusipco*, September 2004.

[11] L. N. Trefethen and D. Bau, *Numerical Linear Algebra*, SIAM, 1997.