ROBUST PRECODING FOR SPACE TIME BLOCK CODES AND SPATIAL MULTIPLEXING HYBRID SYSTEM

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ABSTRACT

This paper proposes a robust precoding for the space time block codes (STBC) and spatial multiplexing (SM) hybrid system. The overall precoding is disassembled into independent precoder optimization of different STBC groups by decomposing the overall channel matrix into several independent virtual channel matrices, this method will considerably reduce the amount of the required feedback information. Also, the precoder optimization is based on a new derived SER bound and considers the uncertainty of the channel feedback. Simulation results demonstrate the performance of the proposed technique.

Index Terms—Precoding, space time block codes, spatial multiplexing, robust, channel feedback

1. INTRODUCTION

Multiple input multiple output (MIMO) wireless communications system is capable of considerably increasing the capacity. Recently, diversity technique such as space-time block codes (STBC) and spatial multiplexing (SM) technique such as BLAST have been studied extensively, and STBC and SM hybrid system has attracted much attention too [1][2][3]. In order to preserve the STBC structure of each group, a QR group receiver using successive group interference cancellation (SGIC) is proposed in [3].

Transmit designs adapted to the intended propagation channels are capable of improving both performance and data rate of communications links. The previous work has considered how side channel knowledge at the transmitter is utilized in conjunction with certain spatial multiplexing or space time codes. From the perspective of the form of the obtained channel knowledge, several precoding techniques have been proposed based on knowledge of full channel state information at the transmitter [4], first-order statistics [5][6], or the second-order statistics of the channel [7].

Most of early works focus on the precoding techniques for spatial multiplexing system or space time coded system alternatively, while in this paper we study the precoding issue of STBC and SM hybrid system. Considering the complexity and the facilitation of per stream rate control, we process each STBC signal with independent linear precoding matrix which is designed based on a feedback virtual channel state information (V-CSI). If SGIC is applied at the receiver, the V-CSI of each STBC group is easily obtained by QR decomposition of actual CSI of the hybrid system, through which the needed feedback information for precoding is considerably reduced. In practice, the feedback information is usually distorted by estimation error, delay error, and quantization error if vector quantization method is applied. In this paper, we will remodel the channel knowledge at the transmitter using the obtained imperfect feedback channels, thereby improving the robustness of precoding technique. Also, the proposed precoding will use the SER criterion.

2. SYSTEM MODEL

We consider a point to point hybrid wireless communications system equipped with N transmit antennas and M receive antennas, which combines Space Time Block Codes and Spatial Multiplexing. The flat block fading model is considered. A block diagram describing the proposed system is shown in Fig.1. Space time block coding is first performed on each independent stream and the encoded signal matrix is denoted as $\mathbf{S}_g$, each $\mathbf{S}_g$ is then multiplied by a precoding matrix $\mathbf{W}_g \in \mathbb{C}^{2\times 2}$ and sent out using a group of selected transmit antennas. Due to the good property of Alamouti structure, only 2×2 STBC is employed in this paper and the number of the transmit antennas in each group is two. Also the total number of transmit antennas is assumed to be even. If the technique of adaptive antenna grouping (AAG) [8] is applied, each precoded STBC selects appropriate transmit antennas according to a feedback index. The allocation of specific transmit antennas for each precoded STBC is actually determined at the receiver using the estimated channel state information, which aims to optimizing the performance of earlier detected STBC group and is performed in a recursive way. Once an optimal antenna grouping is obtained, its index in a set of predefined allocation patterns, i.e. an antenna grouping codebook is fed back to the transmitter. Readers please refer to [8] for detail derivation. The baseband receive signal for the proposed system is given by

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$$\tilde{\mathbf{Y}} = \mathbf{HWS} + \tilde{\mathbf{V}} \quad (1)$$

where $\mathbf{H}$ denotes $M \times N$ channel matrix and its entry is distributed according to $\mathcal{CN}(0,1)$; $\mathbf{S} \triangleq [\mathbf{S}_1^T,...,\mathbf{S}_G^T]^T$; $\mathbf{W} = diag(\mathbf{W}_1,...,\mathbf{W}_G)$, $G \triangleq N/2$ denotes the overall precoding matrix, and $\tilde{\mathbf{V}}$ is the noise matrix whose entries are i.i.d complex Gaussian random variables with zero mean and variance of $2\sigma_v^2$.

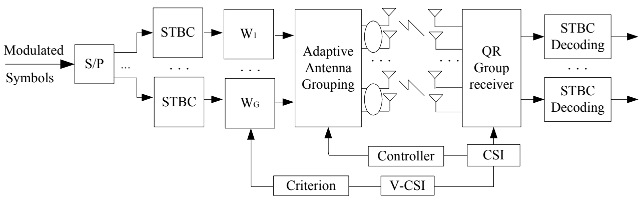

Fig.1. Block diagram of the proposed precoded STBC and SM hybrid system.

3. ROBUST PRECODING

In order to preserve the good property of orthogonal STBC, our goal is to decouple the optimization problems of the precoding matrices associated with different groups. To this end, the virtual channel state information for each STBC group is first derived based on the specific receiver, the precoding matrix $\mathbf{W}_g$ is then optimized independently using its individual V-CSI.

3.1 V-CSI based on QR decomposition

It's demonstrated in [3] that QR group receiver and successive group interference cancellation will achieve the same diversity order as the STBC system. Based on this receiver structure, the virtual channel state information will be easily derived, which will be described as follows.

For simplicity we assume $N = M$, and the channel matrix $\mathbf{H}$ is QR decomposed as $\mathbf{H} = \mathbf{QR}$, where $\mathbf{Q}$ is a unitary matrix and $\mathbf{R}$ is an upper triangular matrix. After left-multiplying the receive signal of (1) by $\mathbf{Q}^H$ it yields

$$\mathbf{Y} = \mathbf{RWS} + \mathbf{V} \quad (2)$$

Since $\mathbf{R}$ is an upper triangular matrix, it can be expressed as

$$\mathbf{R} = \begin{bmatrix} \mathbf{R}_{11} & \mathbf{R}_{12} & \dots & \mathbf{R}_{1G} \\ \mathbf{0} & \mathbf{R}_{22} & \dots & \mathbf{R}_{2G} \\ \vdots & \vdots & & \vdots \\ \mathbf{0} & & \dots & \mathbf{R}_{GG} \end{bmatrix} \quad (3)$$

where $\mathbf{R}_{ij}$ is a 2×2 submatrix. If we rewrite $\mathbf{Y}$ and $\mathbf{V}$ as

$$\mathbf{Y} = [\mathbf{Y}_1^T,...,\mathbf{Y}_G^T]^T, \ \mathbf{V} = [\mathbf{V}_1^T,...,\mathbf{V}_G^T]^T, \quad (4)$$

where $\mathbf{Y}_g, \mathbf{V}_g$ are 2×2 matrices, then we have

$$\mathbf{Y}_g = \mathbf{R}_{gg}\tilde{\mathbf{S}}_g + \sum_{k=g+1}^{G} \mathbf{R}_{gk}\tilde{\mathbf{S}}_k + \mathbf{V}_g, \ g = 1,..,G \quad (5)$$

where $\tilde{\mathbf{S}}_g \triangleq \mathbf{W}_g\mathbf{S}_g$. It is observed that the last group $\mathbf{Y}_G$ is interference free from other groups, and $\mathbf{R}_{GG}$ constitutes the virtual channel matrix of the transmitted signal $\tilde{\mathbf{S}}_G$, so this STBC group will be first estimated. Once $\tilde{\mathbf{S}}_G$ is estimated, its impact is subtracted from the next block $\mathbf{Y}_{G-1}$ and $\tilde{\mathbf{S}}_{G-1}$ is processed. This procedure, termed as successive group interference cancellation, is repeated until all the transmitted groups are processed. If we assume no error propagation, it is obvious from (5) that $\mathbf{R}_{gg}$ constitutes the V-CSI for the transmitted group $\tilde{\mathbf{S}}_g$. Then the STBC and SM hybrid system will be decomposed into G independent sub-systems whose transmit-receive relationship is expressed as

$$\mathbf{Y}_g = \mathbf{R}_{gg}\tilde{\mathbf{S}}_g + \mathbf{V}_g, \ g = 1,...,G \quad (6)$$

Therefore, the precoding matrix for each sub-system will be optimized independently, and only the V-CSI's need to be fed back from the receiver. Compared with the direct feedback of the channel matrix $\mathbf{H}$, the required feedback information is considerably reduced because the V-CSI's only includes the upper triangular submatrices $\{\mathbf{R}_{gg}\}$.

3.2 Robust precoding design

In this part our goal is to optimize the precoding matrices $\{\mathbf{W}_g\}$ respectively. When full or partial channel knowledge is known at the transmitter, transmit design can be derived based on different criteria, such as capacity criteria, post processing SNR etc. In this paper, the optimal precoding matrices will be derived based on SER criterion. Moreover, we consider the case of imperfect V-CSI, namely, the feedback V-CSI is distorted by estimation error, and we adopt the following model

$$\mathbf{R}_{gg} = \hat{\mathbf{R}}_{gg} + \mathbf{E}_{gg}, \ g = 1,...,G \quad (7)$$

where $\hat{\mathbf{R}}_{gg}$ is the obtained V-CSI at the transmitter, and $\mathbf{E}_g$ is an upper triangular matrix with upper triangular entries randomly distributed according to $\mathcal{CN}(0,\sigma_{e,g}^2)$, the variance $\sigma_{e,g}^2$ indicates the uncertainty of the obtained V-CSI.

For each sub-system, without loss of generality, we adopt the form of 2-D beamformer precoding combined with Alamouti coding [6], and the transmitted space-time matrix is expressed in detail as

$$\tilde{\mathbf{S}}_g = \mathbf{W}_g\mathbf{S}_g = \left[\mathbf{w}_{1,g}, \mathbf{w}_{2,g}\right] \begin{bmatrix} \sqrt{\delta_{1,g}}, & 0 \\ 0, & \sqrt{\delta_{2,g}} \end{bmatrix} \begin{bmatrix} s_{1,g}, & -s_{2,g}^* \\ s_{2,g}, & s_{1,g}^* \end{bmatrix} \quad (8)$$

where $\mathbf{w}_{1,g}, \mathbf{w}_{2,g}$ are the two basis-beam vectors, and $\delta_{1,g}$, $\delta_{2,g}$ are the corresponding power allocation parameters, with $0 \le \delta_{1,g}, \delta_{2,g} \le 1$ and $\delta_{1,g} + \delta_{2,g} = 1$. In the two time intervals the two columns of $\tilde{\mathbf{S}}_g$ is transmitted on the selected two antennas simultaneously.

Using the fast decoding technique for Alamouti codes, each information symbol is equivalent to pass through a scalar channel with input and output relationship expressed as

$$z_{i,g} = h_{e,g} s_{i,g} + \hat{v}_{i,g}, i = 1,2 \quad (9)$$

where the equivalent channel is

$$h_{e,g} \triangleq [\delta_{1,g} \| \mathbf{R}_{gg}\mathbf{w}_{1,g} \|_F^2 + \delta_{2,g} \| \mathbf{R}_{gg}\mathbf{w}_{2,g} \|_F^2]^{1/2}. \quad (10)$$

$\hat{v}_{i,g}$ is Gaussian noise with zero mean and variance $2\sigma_v^2$. Hence, the output SNR of each information symbol is

$$\gamma_g = h_{e,g}^2 \frac{E\{|s_{i,g}|^2\}}{2\sigma_v^2} = (\delta_{1,g} \| \mathbf{R}_{gg}\mathbf{w}_{1,g} \|_F^2 + \delta_{2,g} \| \mathbf{R}_{gg}\mathbf{w}_{2,g} \|_F^2) \frac{E\{|s_{i,g}|^2\}}{2\sigma_v^2} \quad (11)$$

Then we rewrite (11) as

$$\gamma_g = \sum_{u=1}^{2}\sum_{v=1}^{2} \gamma_{g,u,v}$$
$$\gamma_{g,u,v} \triangleq \delta_{u,g} \, |[\mathbf{R}_{gg}\mathbf{w}_{u,g}]_v|^2 \frac{E\{|s_{i,g}|^2\}}{2\sigma_v^2}. \quad (12)$$

where $[\cdot]_v$ denotes the vth element of the argument vector. Thus the output SNR in (11) is equivalent to the MRC output for 4 independent channels, with $\gamma_{g,u,v}$ denoting the (u,v) subchannel's SNR. Notice that the subchannel fading coefficient $|[\mathbf{R}_{gg}\mathbf{w}_{u,g}]_v|$ is Ricean distributed, and the quality of the subchannel is indicated by two important factors [6]. The first is the Ricean factor

$$\kappa_{g,u,v} \triangleq \frac{|[\hat{\mathbf{R}}_{gg}\mathbf{w}_{u,g}]_v|^2}{\eta_{g,u,v}\sigma_{e,g}^2}, \quad (13)$$

which indicates the ratio of the direct path $|[\hat{\mathbf{R}}_{gg}\mathbf{w}_{u,g}]_v|$ power over the power of the diffuse components captured by $|[\mathbf{E}_{gg}\mathbf{w}_{u,g}]_v|$, where $\eta_{g,u,v}$ is a $\mathbf{w}_{u,g}$ specific scalar factor with $\eta_{g,u,v} \le 1$, that is due to the upper triangular character of $\mathbf{E}_{gg}$. The second is the variance of each subchannel path

$$\phi_{g,u,v} \triangleq E\{|[\mathbf{R}_{gg}\mathbf{w}_{u,g}]_v|^2\} = |[\hat{\mathbf{R}}_{gg}\mathbf{w}_{u,g}]_v|^2 + \eta_{g,u,v}\sigma_{e,g}^2$$
$$= (1+\kappa_{g,u,v})\eta_{g,u,v}\sigma_{e,g}^2. \quad (14)$$

Then the expected output SNR of the (u,v) subchannel is expressed as

$$\bar{\gamma}_{g,u,v} \triangleq E\{\gamma_{g,u,v}\} = \delta_{u,g}(1+\kappa_{g,u,v})\eta_{g,u,v}\sigma_{e,g}^2 \frac{E\{|s_{i,g}|^2\}}{2\sigma_v^2}. \quad (15)$$

Notice the average SER over the Ricean distributed $|[\mathbf{R}_{gg}\mathbf{w}_{u,g}]_v|$ will depend on $\bar{\gamma}_{g,u,v}$. It is shown in [6] that the average SER for various signal constellations can be found in close form. However, direct optimization based on the exact SER turns out to be difficult, in this paper the optimization problem will rely on an approximate SER upper bound, which will enable simple closed-form precoder solutions. Notice that the derivation will be similar to that in [6], the difference is the semi-random character of V-CSI $\mathbf{R}_{gg}$. The upper bound on the SER is expressed as

$$\tilde{P}_{g,s,bound} = \alpha \prod_{u=1}^{2}\prod_{v=1}^{2} I_{g,u,v}(\bar{\gamma}_{g,u,v}, \rho, \frac{\pi}{2}) \quad (16)$$

where ρ takes constellation specific values [6], and

$$\alpha \triangleq \frac{M-1}{M} \quad (17)$$

$$I_{g,u,v}(\bar{\gamma}_{g,u,v}, \rho, \frac{\pi}{2}) = \frac{1}{1+\delta_{u,g}\tilde{\beta}} \exp(\frac{-\kappa_{g,u,v}\delta_{u,g}\tilde{\beta}}{1+\delta_{u,g}\tilde{\beta}}) \quad (18)$$

among which

$$\tilde{\beta} \triangleq \rho\eta_{g,u,v}\sigma_{e,g}^2 \frac{E\{|s_{i,g}|^2\}}{2\sigma_v^2}. \quad (19)$$

In order to obtain the closed form solutions of $\mathbf{w}_{1,g}, \mathbf{w}_{2,g}$, we further approximate $\tilde{P}_{g,s,bound}$ by setting the $\mathbf{w}_{u,g}$ specific factor $\eta_{g,u,v} \equiv 1$. Actually this approximation has slight effect on SER performance since $\bar{\gamma}_{g,u,v}$ is mainly decided by the first item at right side of (15). Thus an approximate SER upper bound is obtained as

$$P_{g,s,bound} = \alpha \prod_{u=1}^{2}\prod_{v=1}^{2} \frac{1}{1+\delta_{u,g}\beta} \exp(\frac{-\kappa_{g,u,v}\delta_{u,g}\beta}{1+\delta_{u,g}\beta})$$
$$= \alpha |\mathbf{I}_2 + \beta\mathbf{D}_{w,g}|^{-2} \exp(-tr\{[\frac{1}{\sigma_{e,g}^2}\mathbf{U}_g^H\hat{\mathbf{R}}_{gg}^H\hat{\mathbf{R}}_{gg}\mathbf{U}_g][(\beta\mathbf{D}_{w,g})(\mathbf{I}_2+\beta\mathbf{D}_{w,g})^{-1}]\})$$
$$= \alpha |\mathbf{I}_2 + \beta\mathbf{D}_{w,g}|^{-2} \exp(-\frac{1}{\sigma_{e,g}^2} tr\{\hat{\mathbf{R}}_{gg}^H\hat{\mathbf{R}}_{gg}\})$$
$$\times \exp(\frac{1}{\sigma_{e,g}^2} tr\{\mathbf{U}_g^H\hat{\mathbf{R}}_{gg}^H\hat{\mathbf{R}}_{gg}\mathbf{U}_g(\mathbf{I}_2+\beta\mathbf{D}_{w,g})^{-1}\}) \quad (20)$$

where $\beta \triangleq \rho\sigma_{e,g}^2 \frac{E\{|s_{i,g}|^2\}}{2\sigma_v^2}$ is a constant value now, and

$$\mathbf{U}_g = [\mathbf{w}_{1,g}, \mathbf{w}_{2,g}], \; \mathbf{D}_{w,g} = diag(\delta_{1,g}, \delta_{2,g}) \quad (21)$$

We first optimize the beam directions $\mathbf{U}_g$ and assume $\mathbf{D}_{w,g}$ is fixed. If we decompose $\hat{\mathbf{R}}_{gg}^H\hat{\mathbf{R}}_{gg}$ as

$$\hat{\mathbf{R}}_{gg}^H\hat{\mathbf{R}}_{gg} = \mathbf{U}_{R,g}\mathbf{D}_{R,g}\mathbf{U}_{R,g}^H, \; \mathbf{D}_{R,g} = diag(\lambda_{1,g}, \lambda_{2,g}) \quad (22)$$

where, without loss of generality, the eigenvalues are arranged in non-increasing order. Then, the optimal beam directions by minimizing (21) are

$$\mathbf{U}_g = \mathbf{U}_{R,g}. \quad (23)$$

Given the optimal basis-beams, the power allocation parameters are further derived, a similar result as in [6, eq. (54)] is obtained

$$\delta_{1,g} = \min(\bar{\delta}_{1,g}, 1),\ \delta_{2,g} = \max(\bar{\delta}_{2,g}, 0) \tag{24}$$

with $\psi_{u,g} \triangleq \dfrac{\lambda_{u,g}}{2\sigma_{e,g}^2}$, $\xi_{u,g} \triangleq \dfrac{(1+\psi_{u,g})^2}{1+2\psi_{u,g}}$, $u = 1,2$, we have

$$\bar{\delta}_{u,g} = \frac{\xi_{u,g}}{\sum_{i=1}^{2}\xi_{i,g}}\left(1+\sum_{i=1}^{2}\frac{\xi_{i,g}}{(1+\psi_{i,g})\beta}\right) - \frac{\xi_{u,g}}{(1+\psi_{u,g})\beta},\ u = 1,2 \tag{25}$$

Compared with the optimal precoding based on the average SNR (the solution reduces to an single beamformer pointing to the strongest direction of the channel mean $\hat{\mathbf{R}}_{gg}^H \hat{\mathbf{R}}_{gg}$, i.e. 1-D beams precoder), the optimal one based on the SER bound considers not only the average receive SNR but also the reliability of the channel feedback (which is indicated by the error variance $\sigma_{e,g}^2$).

4. SIMULATION RESULTS

We consider a hybrid system equipped with four transmit and four receive antennas. Throughout the simulations, QPSK Alamouti's coding scheme over block fading Rayleigh channels is employed. The QR group receiver using SGIC is applied.

We first compare BER performance of the proposed precoder for STBC and SM hybrid system with other existing precoders. As shown in Fig.2, the proposed 2-D beams precoder outperforms the conventional open-loop hybrid system at low and middle SNRs. Compared with the hybrid system applying AAG, the proposed 2-D beams precoder combining AAG sees 1.5dB (1dB) gain at low BERs when $\sigma_{e,g}^2$ (Var-E) is 0.1 (0.2). Also, the proposed precoder exhibits considerable advantage over the 1-D beams precoder at low BERs.

In practice, $\sigma_{e,g}^2$ should be estimated at the transmitter, we will next investigate the impact of the estimation error on the system performance. When the true $\sigma_{e,g}^2$ is 0.1, we compare the performance of the overestimated case ($\sigma_{e,g}^2$ is estimated to 0.2), the underestimated case ($\sigma_{e,g}^2$ is estimated to 0.05) and the accurate estimated case, over different correlated fading channels (rho denotes the correlation coeffienct). Fig.3 shows that the different cases perform close, only slight performance penalty is observed at low BER level. The results demonstrate that the proposed precoding technique is insensitive to the estimation error for the error variance of channel feedback.

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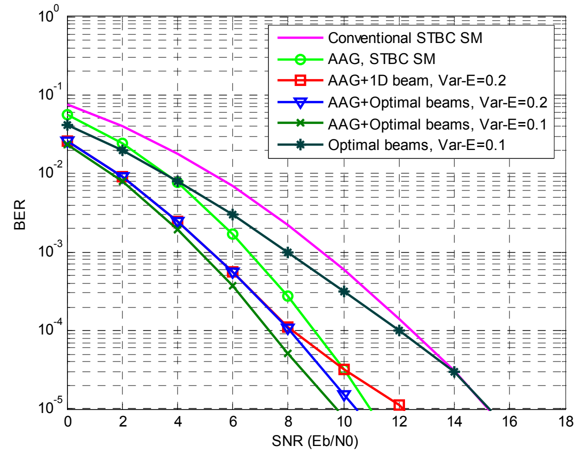

Fig.2 BER performance of (4,4) hybrid system

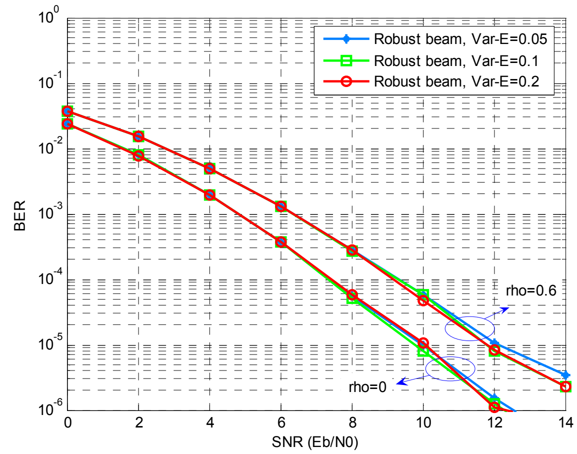

Fig.3. BER performance of the precoded (4,4) hybrid system

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