An Adaptive Power Allocation Scheme for Space-Time Block Coded MIMO Systems

Liang Xian and Huaping Liu

School of Electrical Engineering and Computer Science
Oregon State University
Corvallis, OR 97331 USA
Email: hliu@eecs.orst.edu, +1 541 737 2973, +1 541 737 1300 (fax)

***Abstract*— Receive diversity yields a higher signal-to-noise ratio (SNR) than transmit diversity when the total transmitted power and diversity order are the same. However, if the transmitter has complete or partial knowledge of channel, the SNR gap between these two schemes can be reduced. This paper introduces an adaptive power allocation scheme for space-time block coded (STBC) multiple-antenna systems to improve system performance. For any set of channel fading coefficients, the transmit power scaling factors are controlled by a single design parameter u. The proposed adaptive power allocation scheme improves the instantaneous SNR at the receiver. Special choices of u result in some existing STBC schemes. Performance gain of the proposed scheme over the conventional equal-power scheme under the condition of perfect and imperfect feedback is studied. The maximum achievable SNR gain limit over the conventional scheme is also derived.**

I. Introduction

Space-time block codes (STBC) provide transmit diversity over fading channels. In a commonly used STBC, transmit power is equally divided among all transmit antennas. However, if the transmitter has full or partial knowledge of the channel, adaptive transmit power allocation that allocates more power to the transmit antenna with a better fading condition will improve the received signal-to-noise ratio (SNR). In [1]–[4], several adaptive power allocation methods for systems with two transmit antennas were introduced. These schemes can be considered as a variation of the Alamouti scheme [5]. In [6], a method to transmit the Alamouti block code based on selecting two out of three transmit antennas was proposed. When the transmitter does not have perfect knowledge of the fading coefficients, none of the methods mentioned above can guarantee the maximum SNR at the receiver.

In this paper, we derive the maximum SNR gain limit achievable by adaptive power allocation for STBC designed for multiple-input multiple-output (MIMO) systems when perfect feedback is available. Then, an adaptive power allocation scheme with imperfect feedback is proposed and analyzed. A design parameter u is introduced to control the power scaling factors. SNR gain of the proposed scheme over the conventional scheme in which power is equally distributed among all transmit antennas is provided. The conventional STBC scheme and the adaptive scheme analyzed in [1] are special cases of the proposed scheme with specific choices of a design parameter u.

II. System model

Consider a wireless communications system with M transmit antennas and N receive antennas, denoted as an (M, N) system in this paper. Each receive antenna responds to each transmit antenna through a statistically independent fading coefficient. The received signals are further corrupted by additive white Gaussian noise that is statistically independent among different receive antennas and different symbol periods. Let the $P \times M$ transmission matrix be

$$\mathcal{G} = \begin{bmatrix} g_{1,1} & g_{1,2} & \cdots & g_{1,M} \\ g_{2,1} & g_{2,2} & \cdots & g_{2,M} \\ \vdots & \ddots & \ddots & \vdots \\ g_{P,1} & g_{P,2} & \cdots & g_{P,M} \end{bmatrix} \quad (1)$$

and the transmitted symbol vector be $\boldsymbol{s} = [s_1,\ s_2,\ \cdots,\ s_K]^T$, where $[\cdot]^T$ denotes transpose. Each element of $\mathcal{G}$ is a linear combination of symbols $s_1, s_2, \cdots, s_K$ and their complex conjugates. The (p, m)th entry of $\mathcal{G}$, $g_{p,m}$, will be transmitted at time slot p from transmit antenna m. The code rate, as defined in [7], is given as K/P, where P is the number of time slots used to transmit K symbols. The total average transmit power is normalized to 1. Average energy of each symbol is E_s. Thus, the transmitted signal at time slot p from transmit antenna m is expressed as $x_{p,m} = \alpha_m \sqrt{E_s} g_{p,m}$, where α_m is a real power scaling factor determined by feedback information. In order to maintain the same total average power after power scaling, it is required that

$$\sum_{m=1}^{M} \alpha_m^2 = 1. \quad (2)$$

For the conventional STBC scheme, $\alpha_m = \sqrt{1/M},\ m = 1, \cdots, M$.

The channel is assumed to be quasi-static, allowing it to be constant over a frame of symbols and change independently from one frame to another. Let $h_{m,n}$ denote the fading coefficient from the mth transmit antenna to the nth receive antenna of an (M, N) system. Rayleigh fading is considered so that $h_{m,n}$ is a zero-mean complex Gaussian random variable.

The average power of the channel is also normalized so that $h_{m,n}$ has a unit variance.

The received signal at time p by receive antenna n, $r_{p,n}$, is given as

$$r_{p,n} = \sum_{m=1}^{M} h_{m,n} x_{p,m} + \nu_{p,n} \tag{3}$$

where $\nu_{p,n}$ is the additive zero-mean white Gaussian noise component with variance $\mathcal{N}_0$. The maximum likelihood (ML) decoder calculates the following decision metric

$$d = \sum_{p=1}^{P} \sum_{n=1}^{N} \left| r_{p,n} - \sum_{m=1}^{M} \alpha_m \sqrt{E_s} \hat{g}_{p,m} \right|^2 \tag{4}$$

and the codeword $(\hat{s}_1, \cdots, \hat{s}_K)$ that minimizes d will be the decoder output.

III. SNR Analysis

Assuming a full-diversity system coded with orthogonal space-time block codes (OSTBC), ML decoding can be achieved using linear operations on $r_{p,n}$, α_m, and $h_{m,n}$. In a system with a rate-1 transmission matrix or with a rate-3/4 transmission matrix, the decision variable for the kth element of $\boldsymbol{s}$, $\hat{s}_k$, is expressed as [5], [7]–[9]

$$\hat{s}_k = \sqrt{E_s} \sum_{n=1}^{N} \sum_{m=1}^{M} \alpha_m^2 |h_{m,n}|^2 s_k + \xi_k \tag{5}$$

where ξ_k is the complex zero-mean Gaussian noise component whose variance is given as $\sigma_{\xi_k}^2 = \mathcal{N}_0 \sum_{n=1}^{N} \sum_{m=1}^{M} \alpha_m^2 |h_{m,n}|^2$. As an example, in a (2,1) system ($M = 2, N = 1$) with the Alamouti code [5], the received signals are expressed as

$$r_{1,1} = \sqrt{E_s} \left(\alpha_1 h_{1,1} s_1 + \alpha_2 h_{2,1} s_2 \right) + \nu_{1,1} \tag{6a}$$

$$r_{2,1} = \sqrt{E_s} \left(-\alpha_1 h_{1,1} s_2^* + \alpha_2 h_{2,1} s_1^* \right) + \nu_{2,1} \tag{6b}$$

and the decision variables are given as

$$\begin{aligned}
\hat{s}_1 &= \alpha_1 h_{1,1}^* r_{1,1} + \alpha_2 h_{2,1} r_{2,1}^* \\
&= \sqrt{E_s} \left(\alpha_1^2 |h_{1,1}|^2 + \alpha_2^2 |h_{2,1}|^2 \right) s_1 + \alpha_1 h_{1,1}^* \nu_{1,1} + \alpha_2 h_{2,1} \nu_{2,1}^* \\
\hat{s}_2 &= \alpha_2 h_{2,1}^* r_{1,1} - \alpha_1 h_{1,1} r_{2,1}^* \\
&= \sqrt{E_s} \left(\alpha_1^2 |h_{1,1}|^2 + \alpha_2^2 |h_{2,1}|^2 \right) s_2 + \alpha_2 h_{2,1}^* \nu_{1,1} - \alpha_1 h_{1,1} \nu_{2,1}^*.
\end{aligned}$$

In a system with rate-1/2 transmission matrix for complex signals, the decision variable is given as [8]

$$\hat{s}_k = 2\sqrt{E_s} \sum_{n=1}^{N} \sum_{m=1}^{M} \alpha_m^2 |h_{m,n}|^2 s_k + \eta_k \tag{8}$$

where η_k is the complex zero-mean Gaussian noise component whose variance is given as $\sigma_{\eta_k}^2 = 2\mathcal{N}_0 \sum_{n=1}^{N} \sum_{m=1}^{M} \alpha_m^2 |h_{m,n}|^2$. Obviously, the SNR for rate-1/2 codes is doubled compared with rate-1 and rate-3/4 codes. With adaptive power allocation, however, the SNR gain will be the same for codes of rate 1, 3/4, and 1/2. Specifically, let SNR_a be the SNR with adaptive power allocation and SNR_c be the SNR with the conventional equal-power scheme. The ratio $\frac{SNR_a}{SNR_c}$ will be the same for codes of rate 1, 3/4, and 1/2. Thus, in the following discussion, we will only focus on rate 1 and rate 3/4 codes. The received instantaneous SNR is obtained as

$$\gamma = \frac{E_s}{\mathcal{N}_0} \sum_{m=1}^{M} \left[\alpha_m^2 \sum_{n=1}^{N} |h_{m,n}|^2 \right]. \tag{9}$$

IV. Adaptive Power Allocation

A. Minimum Feedback Allocation Scheme (Antenna Selection)

Let $\beta_m = \sum_{n=1}^{N} |h_{m,n}|^2$. Without loss of generality, we assume that $\beta_1 \geq \beta_2 \geq ... \geq \beta_M$. Thus, we can write $\beta_{M-1} = \beta_M + \delta_1$, $\beta_{M-2} = \beta_M + \delta_1 + \delta_2$, ..., $\beta_1 = \beta_M + \delta_1 + ... + \delta_{M-1}$, where β_i and δ_j are nonnegative real numbers. The instantaneous SNR is then expressed as

$$\gamma = \frac{E_s}{\mathcal{N}_0} \left[\beta_M + \delta_1 \sum_{i=1}^{M-1} \alpha_i^2 + \delta_2 \sum_{i=1}^{M-2} \alpha_i^2 + ... + \delta_{M-1} \alpha_1^2 \right]. \tag{10}$$

Obviously, when $\alpha_1 = 1$ (note that $\sum_{m=1}^{M} \alpha_m^2 = 1$), γ is maximized to be $\frac{E_s}{\mathcal{N}_0} \beta_1$. This means that if $\beta_1 \geq ... \geq \beta_M$ holds, the system should allocate all its power to transmit antenna 1 for best performance.

The feedback required for this scheme is minimum; only $\lceil \log_2(M) \rceil$ bits for each transmission, where $\lceil \cdot \rceil$ denotes the nearest integer towards infinity. For simplicity, we will refer to this scheme as the minimum-feedback-allocation scheme (MFAS). Note that this scheme results in antenna selection (one out of M). Other advantages of the MFAS include that there are no quantization errors for the feedback. Because there is no inter-symbol interference, it is easy to realize a rate-1 transmission for complex signals with full diversity, which is a challenging issue for MIMO systems with STBCs. However, this scheme, as will be seen from simulation results in Section V, is more sensitive to feedback errors than other power allocation schemes.

B. A New Adaptive Power Allocation Scheme

In practice when feedbacks are imperfect (channel coefficients obtained by the transmitter through feedback contain errors), a very simple scheme with $\alpha_1 > \cdots > \alpha_M$ will improve the system performance if $\beta_1 > \cdots > \beta_M$. In this case there are $M-1$ variables, $\alpha_1, \cdots, \alpha_{M-1}$ ($\alpha_M = \sqrt{1 - \sum_{m=1}^{M-1} \alpha_m^2}$), to be solved, and it is rather difficult to determine which set of combinations of α_m give the best performance. Thus, we propose a new scheme with only one parameter that can be easily controlled to maximize SNR at the receiver. Additionally, this scheme is robust to feedback errors. In the proposed adaptive power allocation scheme, the real scaling factor for the mth transmit antenna is given as

$$\alpha_m = \sqrt{\frac{\beta_m^u}{\sum_{m=1}^{M} \beta_m^u}} \tag{11}$$

where for a given set of channel coefficients, $h_{m,n}$, parameter u controls the power scaling factor α_m. It is easy to verify that α_m given in (11) satisfies the requirement given in (2).

It is worth of mentioning two special cases, $u = 0$ and $u = 2$, which correspond to, respectively, the conventional STBC scheme in which power is equally distributed among all transmit antennas and the adaptive scheme proposed in [1] for a system with two transmit antennas.

By applying the power scaling factor α_m given in (11) to the instantaneous SNR given in (9), we obtain

$$\gamma_u = \frac{E_s}{\mathcal{N}_0} \frac{\sum_{m=1}^{M} \beta_m^{u+1}}{\sum_{m=1}^{M} \beta_m^{u}}. \tag{12}$$

It will be interesting to examine the relationship between SNR and parameter u for the adaptive power allocation scheme. The difference between γ_{u+1} and γ_u is obtained to be

$$\begin{aligned} \gamma_{u+1} - \gamma_u &= \frac{E_s}{\mathcal{N}_0} \left(\frac{\sum_{m=1}^{M} \beta_m^{u+2}}{\sum_{m=1}^{M} \beta_m^{u+1}} - \frac{\sum_{m=1}^{M} \beta_m^{u+1}}{\sum_{m=1}^{M} \beta_m^{u}} \right) \\ &= \frac{E_s}{\mathcal{N}_0} \frac{\left(\sum_{i=1}^{M} \beta_i^u\right)\left(\sum_{j=1}^{M} \beta_j^{u+2}\right) - \left(\sum_{j=1}^{M} \beta_j^{u+1}\right)^2}{\left(\sum_{i=1}^{M} \beta_i^u\right)\left(\sum_{j=1}^{M} \beta_j^{u+1}\right)} \\ &= \frac{E_s}{\mathcal{N}_0} \frac{\sum_{1 \le i < j \le M} \beta_i^u \beta_j^u (\beta_i - \beta_j)^2}{\sum_{i=1}^{M}\sum_{j=1}^{M} \beta_i^u \beta_j^{u+1}}. \end{aligned} \tag{13}$$

It can be seen from Eq. (13) that $\gamma_{u+1} - \gamma_u$ is always greater than or equal to 0 with equality only if $\beta_1 = \beta_2 = \cdots = \beta_M$. If this condition does not hold, which is true for any practical scenario, SNR increases monotonically with parameter u (note that u does not necessarily need to be an integer). However, performance improvement with the proposed adaptive power allocation scheme will saturate as u increases. This is proved as follows. Without loss of generality, we assume that $\beta_1 = \beta_2 = \cdots = \beta_w = max\{\beta_1, \cdots, \beta_M\}$, where $1 \le w < M$. The ratio γ_{u+1}/γ_u can be written as

$$\begin{aligned} \frac{\gamma_{u+1}}{\gamma_u} &= \frac{\beta_1^{-2u-2}\left(\beta_1^{u+2} + \cdots + \beta_M^{u+2}\right)\left(\beta_1^u + \cdots + \beta_M^u\right)}{\beta_1^{-2u-2}\left(\beta_1^{u+1} + \cdots + \beta_M^{u+1}\right)^2} \\ &= \frac{w^2 + \epsilon_1}{w^2 + \epsilon_2}. \end{aligned}$$

It can be easily determined that $\lim_{u \to +\infty} \epsilon_1 = \lim_{u \to +\infty} \epsilon_2 = 0$, which implies

$$\lim_{u \to +\infty} \gamma_{u+1}/\gamma_u = 1. \tag{14}$$

Additionally, let us consider the limit of γ_u:

$$\begin{aligned} \lim_{u \to +\infty} \gamma_u &= \frac{E_s}{\mathcal{N}_0} \lim_{u \to +\infty} \frac{\beta_1^{u+1} + \beta_2^{u+1} + ... + \beta_M^{u+1}}{\beta_1^u + \beta_2^u + ... + \beta_M^u} \\ &= \frac{E_s}{\mathcal{N}_0} \lim_{u \to +\infty} \frac{\beta_1 + \beta_2(\frac{\beta_2}{\beta_1})^u + ... + \beta_M(\frac{\beta_M}{\beta_1})^u}{1 + (\frac{\beta_2}{\beta_1})^u + ... + (\frac{\beta_M}{\beta_1})^u} \\ &= \frac{E_s}{\mathcal{N}_0} \beta_1. \end{aligned} \tag{15}$$

Eq. (15) gives the ultimately achievable maximum SNR at receiver with the proposed adaptive power allocation scheme, which is the same as the SNR achieved by antenna selection. Based on Eq. (15) and the fact that γ_u is a continuous function of u, an appropriate u could results in the maximum achievable SNR. This reduces the multidimensional problem to a one-dimensional problem.

We define the average SNR gain as the ratio of the average SNR with the adaptive power allocation scheme to the average SNR with the equal-power scheme. This ratio is expressed as $10 \log_{10} \left[\frac{E\{\gamma_u\}}{E\{\gamma_0\}} \right]$dB, where $E\{\cdot\}$ denotes expectation. Recall that the average SNR for the traditional equal-power scheme is given as

$$E\{\gamma_0\} = \frac{E_s}{M\mathcal{N}_0} E\left\{ \sum_{m=1}^{M} \left[\sum_{n=1}^{N} |h_{m,n}|^2 \right] \right\} = \frac{NE_s}{\mathcal{N}_0}. \tag{16}$$

The maximum average SNR gain in dB can be obtained as

$$10 \log_{10} \left(\frac{E\{\gamma_{+\infty}\}}{E\{\gamma_0\}} \right) = 10 \log_{10} \left(\frac{E\{max(\beta_1, \cdots, \beta_M)\}}{N} \right) \tag{17}$$

where $\beta_i,\ i = 1,\ \cdots,\ M$, are central chi-square-distributed random variables with freedom $2N$ in a Rayleigh fading environment. The cumulative distribution function (CDF) of β_i can be found in closed form as [10]

$$F_Y(y) = 1 - e^{-y/2\sigma^2} \sum_{k=0}^{N-1} \frac{1}{k!} \left(\frac{y}{2\sigma^2} \right)^k, \quad y \ge 0 \tag{18}$$

where $\sigma = \sqrt{2}/2$. The CDF of $max(\beta_1, \cdots, \beta_M)$ is given as

$$\begin{aligned} F_Y^{max}(y) &= \left[1 - e^{-y/2\sigma^2} \sum_{k=0}^{N-1} \frac{1}{k!} \left(\frac{y}{2\sigma^2} \right)^k \right]^M \\ &= \left[1 - e^{-y} \sum_{k=0}^{N-1} \frac{1}{k!} y^k \right]^M, \quad y \ge 0. \end{aligned} \tag{19}$$

The probability density function (PDF) of $max(\beta_1, \cdots, \beta_M)$, $p_Y^{max}(y)$, can be calculated by differentiating $F_Y^{max}(y)$. The expected value of $max(\beta_1, \cdots, \beta_M)$ is obtained as

$$E\{max(\beta_1, \cdots, \beta_M)\} = \int_0^\infty y p_Y^{max}(y) dy. \tag{20}$$

As an example, let us consider a (2,1) system:

$$\begin{aligned} F_Y(y) &= 1 - e^{-y}, \quad y \ge 0 \Rightarrow \\ F_Y^{max}(y) &= (1 - e^{-y})^2, \quad y \ge 0 \Rightarrow \\ p_Y^{max}(y) &= 2e^{-y}(1 - e^{-y}) \Rightarrow \\ E\{max(\beta_1, \beta_2)\} &= \int_0^\infty 2ye^{-y}(1 - e^{-y}) dy = \frac{3}{2}. \end{aligned}$$

Therefore, the maximum average SNR gain for a (2,1) system is $10 \log_{10}(\frac{3}{2}) = 1.76$ dB.

Values of the maximum average SNR gains for various combinations of M and N of a MIMO system are evaluated numerically and summarized in Table 1.

Gain (dB)	$M=2$	$M=3$	$M=4$	$M=5$	$M=6$
$N=1$	1.7609	2.6323	3.1875	3.5856	3.8917
$N=2$	1.383	2.0588	2.4886	2.797	3.0344
$N=3$	1.181	1.7567	2.1232	2.3866	2.5897
$N=4$	1.0498	1.5615	1.8876	2.1223	2.3033
$N=5$	0.9555	1.4215	1.7188	1.9329	2.0983

Table 1: The maximum gains in the average SNR for MIMO systems.

Examining Table 1, we find that the maximum gain in the average SNR due to the proposed adaptive power allocation increases as the number of transmit antennas increases, and decreases as the number of receive antenna increases. This can be intuitively explained as follows. As M increases with N fixed, $E\{max(\beta_1, \cdots, \beta_M)\}$ has more dimensions to provide a gain. On the other hand, when N increases with M fixed, the difference between $max(\beta_1, \cdots, \beta_M)$ and the average value of β_i decreases.

C. The New Scheme with Imperfect Feedback

In a practical system, channel coefficients will not be perfectly known. Even if channel coefficients were perfectly known, there will be quantization errors in the feedback. In order to resolve the problem of imperfect feedback and lower the number of feedback bits required, we pre-determine a finite set of values for α_m. The receiver only needs to inform the transmitter that which pre-determined power scaling factor should be assigned to antenna m. For example, in a system with two transmit antennas, we pre-determine a fixed set of values for α_m as $\alpha_m \in (0.8,\ 0.6)$. If the receiver finds out that $\beta_1 > \beta_2$, it then needs only 1 bit to instruct the transmitter to allocate 0.8 to antenna 1. For a general system with M transmit antennas, $\lceil \log_2(M!) \rceil$ feedback bits are needed.

For simplicity, we assume that the feedback system is a SISO system with the same constellation as the information channel. The average energy of feedback symbols is also E_s. The pre-determined power scaling factors $\alpha_m, m = 1, \cdots, M$ for a particular choice of parameter u can be determined using the method as follows. As defined earlier, β_m is a function of fading coefficients $h_{m,1}, \cdots, h_{m,N}$. For each realization of the channel coefficients, let $\beta_{max} = max\{\beta_1, \cdots, \beta_M\}$. The pre-determined largest power scaling factor α_{max} can be set as $\alpha_{max} = E\left\{\sqrt{\frac{\beta_{max}^u}{\sum_{m=1}^{M} \beta_m^u}}\right\}$. In the same manner, let β_{sec} be the second largest value among $\beta_1, \cdots, \beta_M$, for each realization of the channel. The second largest power scaling factor α_{sec} is calculated to be $\alpha_{sec} = E\left\{\sqrt{\frac{\beta_{sec}^u}{\sum_{m=1}^{M} \beta_m^u}}\right\}$. This method can be continued until the smallest scaling factor α_{min} is determined as $\alpha_{min} = \sqrt{1 - \alpha_{max}^2 - \alpha_{sec}^2 - \cdots}$. As an example, if u is chosen to be $u = 1$ for a system with $M = 3$, then the pre-determined power scaling factors can be calculated to be $(\alpha_1, \alpha_2, \alpha_3) \approx (0.7765,\ 0.5158,\ 0.3620)$. If u is chosen to be $u = 2$, then $(\alpha_1, \alpha_2, \alpha_3) \approx (0.8602,\ 0.4144,\ 0.2973)$.

For 3 transmit antennas, we have to use $\lceil \log_2(3!) \rceil = 3$ bits to feed back $3! = 6$ possible groups $(\alpha_{max},\ \alpha_{sec},\ \alpha_{min})$. However, the 3 bits could represent 8 unique groups, yielding two invalid groups. The transmission power allocation strategy for this case is that if feedback symbols are erroneously decoded as one of two invalid groups, equal power allocation will be used in next transmission.

V. Numerical Examples and Discussion

Simulated results demonstrating the performance of the proposed adaptive power allocation schemes are obtained in this section. Fig. 1 shows the error probability of different systems as a function of parameter u. It is found that for a

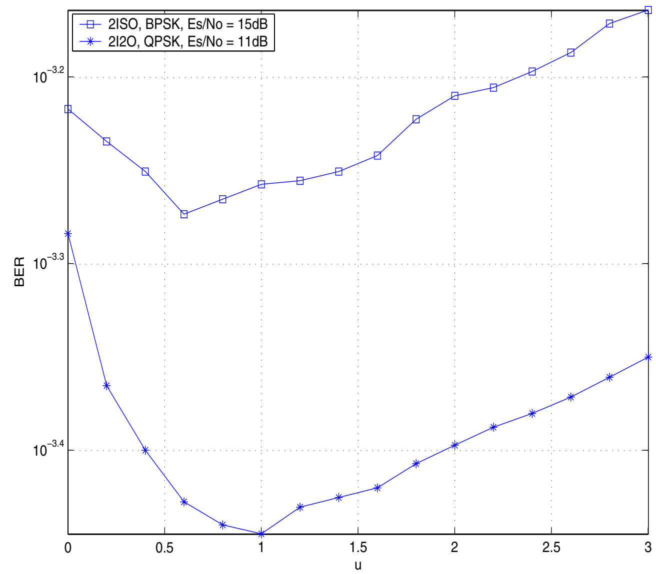

Fig. 1. BER versus parameter u ($M = 2, N = 1, 2$)

$(2, 1)$ system with BPSK modulation operating at $E_s/\mathcal{N}_0 =$ 15dB, the optimum value of u is 0.6. The corresponding power scaling factors for the proposed adaptive scheme with imperfect feedbacks can be determined to be $(\alpha_{max},\ \alpha_{min}) \approx (0.8196,\ 0.57293)$. For a $(2, 2)$ system with QPSK modulation operating at $E_s/\mathcal{N}_0 = 11$dB, the optimum value of u is found to be 1. The corresponding power scaling factors for the two transmit antennas are determined to be $(\alpha_{max},\ \alpha_{min}) \approx (0.88452,\ 0.4665)$.

It is usually not easy to determine the optimum value of u by an analytical approach since it depends on $E_s/\mathcal{N}_0$ in the information channel, the power of feedback symbols, the number of transmit and receiver antennas $(M,\ N)$, and the modulation scheme. With the feedback model and PSK modulation, the optimum u in the sense of minimizing error probabilities can be calculated numerically using the procedure described below.

According to Eq. (5), orthogonal space-time block codes in an $(M,\ N)$ system have the same performance as a $(1,\ MN)$ system (a diversity-reception only system) using maximal ratio combining, provided that the transmit power per antenna is the same in both systems to make the comparison fair. Therefore, the optimum value of u can be found by using the exact

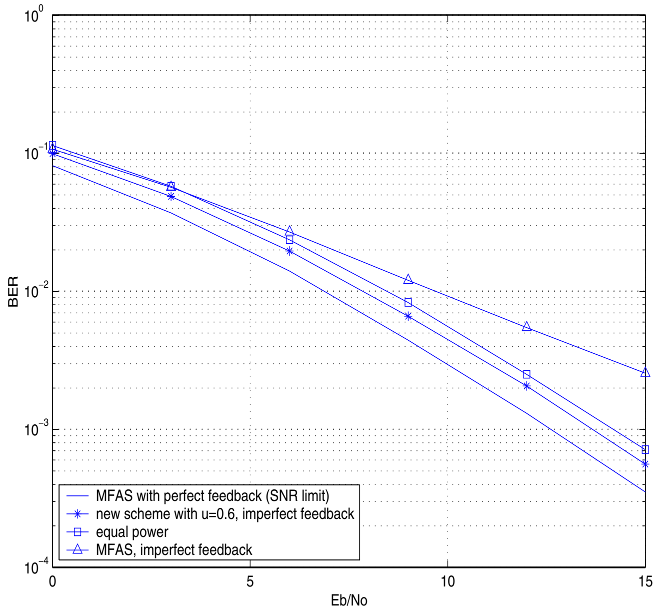

Fig. 2. BER versus $E_b/\mathcal{N}_0$ curves for different schemes ($M = 2, N = 1$, BPSK)

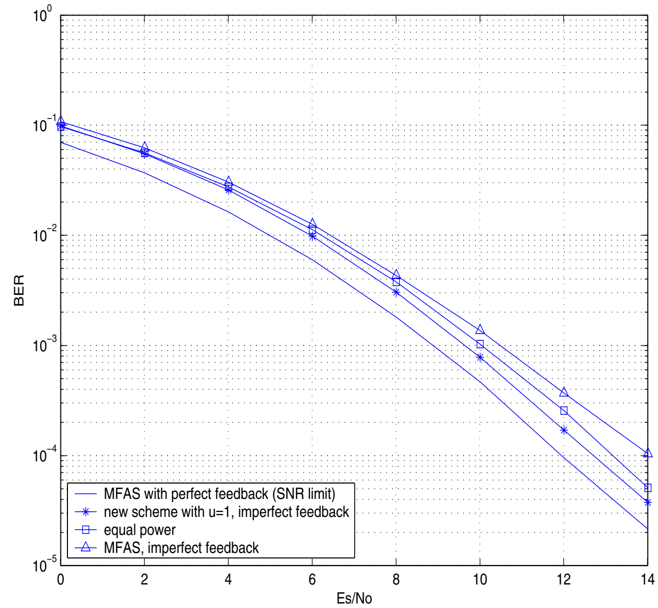

Fig. 3. BER versus $E_s/\mathcal{N}_0$ curves for different schemes ($M = 2, N = 2$, QPSK)

error probability for multichannel PSK signals given in [10], Appendix C. As an example, let us consider the Alamouti scheme using BPSK in a $(2,\ 1)$ system. We can easily compute the error probability in the feedback channel P_{feedback} and the error probability in the information channel for equal power allocation $P_{\text{i,equal}}$ (no adaptive power allocation), where $P_{\text{i,equal}} = f(\frac{E_s}{\mathcal{N}_0})$ is a function of the received signal-to-noise ratio. Additionally, we have $E\{\beta^{max}\} = 1.5$ from Table 1. Thus, $E\{\beta^{min}\} = 2 - 1.5 = 0.5$. The average error probability for the information channel with adaptive power allocation under imperfect feedback is given by $P_{\text{i,adp}} = (1 - P_{\text{feedback}})f(1.5\alpha_{max}^2 \frac{E_s}{\mathcal{N}_0}) + P_{\text{feedback}} f(0.5(1 - \alpha_{max}^2)\frac{E_s}{\mathcal{N}_0})$, where $\alpha_{max} \in (0,\ 1)$ is a variable that depends on u. If we fix $\frac{E_s}{\mathcal{N}_0}$, then $P_{\text{i,adp}}$ is a function of u. The optimal value of u can be found by minimizing $P_{\text{i,adp}}$.

Figs. 2 and 3 compare the error performances of the MFAS, the equal-power scheme, and the adaptive power allocation scheme which applies the optimum u. Although the optimum u depends on $E_s/\mathcal{N}_0$, for simplicity the values of u obtained in Fig. 1 are used for any $E_s/\mathcal{N}_0$ in Figs. 2 and 3. It is found that when perfect feedback symbols are assumed, the antenna-selection scheme works the best. However, when there are feedback symbol errors, the antenna-selection scheme suffers from diversity loss.

VI. Conclusion

We have proposed a new power allocation scheme for space-time block coded MIMO systems. If the channel coefficients are known, the power scaling factors for all transmit antennas are controlled by a single parameter u which, for some special cases, can be predetermined numerically. Different choices of parameter u yields different SNR gains. The maximum achievable SNR gain can be achieved by choosing an appropriate value of u. Some special choices of parameter u with the proposed adaptive power allocation scheme reduce to some existing STBC power allocation schemes (i.e. [1], [5]). A much simpler power allocation scheme (single antenna selection) that needs significantly less number of feedback bits is also proposed. Performance gains of the proposed schemes over the conventional equal-power STBC scheme are simulated for systems with different number of antennas and modulation schemes.

References

[1] J. H. Horng, L. Li, and J. Zhang, “Adaptive space-time transmit diversity for MIMO systems,” *Proc. of IEEE VTC’03*, Apr. 2003, pp. 1070–1073.
[2] T. Lo, “Adaptive space-time transmission with side information,” *Proc. of IEEE WCNC’03*, Mar. 2003, pp. 601–606.
[3] M. Seo and S. W. Kim, “Power adaptation in space-time block code,” *Proc. IEEE Globecom’01*, Nov. 2001, pp. 3188–3193.
[4] G. Ganesan, P. Stoica, and E. G. Larsson, “Diagonally weighted orthogonal space-time block codes,” *Proc. of Asilomar Conf. On Signals, Systems and Computers*, Nov. 2002, pp. 1147–1151.
[5] S. M. Alamouti, “Simple transmit diversity technique for wireless communications,” *IEEE Journal on Selected Areas in Communications* vol. 16, pp. 1451–1458, Oct. 1998.
[6] W. H. Wong and E. G. Larsson, “Orthogonal space-time block coding with antenna selection and power allocation,” *Electron. Lett.*, vol. 39, no. 4, pp. 379–381, Feb. 2003.
[7] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, “Space-time block codes from orthogonal designs,” *IEEE Trans. on Information Theory*, vol. 45, pp. 1456–1467, July 1999.
[8] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, “Space-time block coding for wireless communications: performance results,” *IEEE Journal on Selected Areas in Communications*, vol. 17, pp. 451–460, Mar. 1999.
[9] X. Li, T. Luo, G. Yue and C. Yin, “A squaring method to simplify the decoding of orthogonal space-time block codes,” *IEEE Trans. on Communications*, vol. 49, pp. 1700–1703, Oct. 2001.
[10] J. G. Proakis, “Digital Communications,” 4th ed, McGraw-Hill, 2001.