Minimum BER Power Allocation for MIMO Spatial Multiplexing Systems

Neng Wang and Steven D. Blostein
Department of Electrical and Computer Engineering
Queen's University, Kingston, Ontario, Canada K7L 3N6
E-mail: {nwang,sdb}@ee.queensu.ca

***Abstract*— Power allocation for multiple-input multiple-output (MIMO) spatial multiplexing systems is investigated. Minimization of bit error rate (MBER) is employed as the optimization criterion. MBER power allocation schemes for a variety of receiver structures, including zero-forcing (ZF), successive interference cancellation (SIC), and ordered SIC (OSIC), are proposed. It is shown that the newly proposed MBER power allocation schemes improve error rate performance. Simulation results indicate that SIC and OSIC with MBER power allocation outperform MBER precoding for ZF equalization as well as minimum mean squared-error (MMSE) precoding/decoding. Performance under noisy channels and power feedback is analyzed. A modified algorithm that mitigates error propagation in interference cancellation is developed. Compared to existing precoding methods, the proposed schemes significantly reduce both processing complexity and feedback overhead, and improve error rate performance.**

I. Introduction

The capacity of wireless communication systems can be increased substantially by using multiple transmit and receive antennas, known as multiple-input multiple-output (MIMO) systems, provided that multipath scattering effects have been exploited appropriately [1]. Our goal of this paper is to investigate transmit optimization in MIMO spatial multiplexing, which is receiver-dependent. Signal reception for MIMO spatial multiplexing can employ criteria such as zero-forcing (ZF), minimum mean-squared error (MMSE), successive interference cancellation (SIC), or ordered SIC (OSIC) as, for example, in the case of the Vertical Bell Laboratories Layered Space-Time (V-BLAST) architecture [1].

In order to achieve high MIMO diversity and/or spatial multiplexing gains, appropriate transceiver designs are necessary. Efforts to optimize MIMO transceiver structures include joint transmit-receive optimization [2] and linear precoding/decoding [3]. These designs generally require high complexity processing at both the transmitter and the receiver as well as high feedback overhead. Precoded MIMO transmission with reduced feedback has been recently proposed that either quantizes the channel state information (CSI) or precoding matrix, or feeds back only a designed signal [4]. However, existing precoding schemes with reduced feedback generally also require high processing complexity, e.g., diagonalization of the channel matrix and/or precoding codebook design.

In this paper, we consider simultaneous reduction of complexity and feedback overhead by constraining precoding to transmit power allocation, i.e., we optimize only the transmitted power of signal streams, but apply a more suitable criterion. As opposed to MMSE precoding/decoding [3], we consider MBER as the optimization criterion. Compared to MBER precoding for ZF receivers, we apply MBER power allocation to SIC and OSIC as well. Such a transmission scheme would be applicable to delay-sensitive applications, e.g., voice and video communications. Power allocation also reduces feedback significantly compared to general precoding methods.

Transmitter-side power allocation ideally requires CSI or allocated power to be available at the transmitter. Regardless of availability, CSI or power feedback is imperfect in practice due to channel estimation, quantization, feedback delay, and/or errors introduced by a feedback channel [5]. This motivates performance analysis of power allocation under uncertain feedback. While a general analysis is difficult, we analyze the special cases of noisy CSI and power feedback. Based on this analysis, we propose an approximate MBER power allocation algorithm that takes statistical knowledge of noisy feedback into account.

II. MIMO Signal Reception and Performance

Consider a MIMO spatial multiplexing communication system with N_t transmit and N_r receive antennas where $N_r \geq N_t$. The received signal can be modelled as

$$\mathbf{r} = \mathbf{H}\mathbf{s} + \boldsymbol{\eta}, \tag{1}$$

where $\mathbf{s}$ is the $N_t \times 1$ transmitted signal vector; $\mathbf{H}$ is the $N_r \times N_t$ channel matrix, which is assumed to be generally correlated Ricean fading as in [6]; and $\boldsymbol{\eta}$ is the $N_r \times 1$ additive Gaussian noise vector. For simplicity of analysis, we assume white input and noise, i.e., $\mathbb{E}[\mathbf{s}\mathbf{s}^{\mathcal{H}}] = E_s\mathbf{I}_{N_t}$ and $\mathbb{E}[\boldsymbol{\eta}\boldsymbol{\eta}^{\mathcal{H}}] = N_0\mathbf{I}_{N_r}$, input signal-to-noise ratio (SNR) $\gamma_s \overset{\text{def}}{=} E_s/N_0$, and binary phase shift keying (BPSK) modulation.

A. ZF Receiver

With ZF equalization, the estimate of the transmitted signal

$$\hat{\mathbf{s}} = \mathbf{H}^{\dagger}\mathbf{r} = \mathbf{s} + \mathbf{H}^{\dagger}\boldsymbol{\eta}. \tag{2}$$

The decision-point SNR of the k-th signal stream, $1 \leq k \leq N_t$, is obtained as

$$\gamma_{Z,k} = \gamma_s \left[\left(\mathbf{H}^{\mathcal{H}}\mathbf{H}\right)^{-1}\right]_{k,k}^{-1} \overset{\text{def}}{=} \gamma_s g_{Z,k}^2, \tag{3}$$

0-7803-8938-7/05/$20.00 (C) 2005 IEEE

where $g_{Z,k}^2 \overset{\text{def}}{=} \left[\left(\mathbf{H}^{\mathcal{H}}\mathbf{H}\right)^{-1}\right]_{k,k}^{-1}$ denotes the power gain.

B. SIC Receiver

Without loss of generality, we assume that stream $k = 1$ is detected first. The interference due to the first stream is then regenerated and subtracted before stream $k = 2$ is detected. This procedure is repeated successively until all streams are detected. Assuming ZF equalization is employed at each stage, the decision-point SNR of the k-th stream can be shown to be

$$\gamma_{S,k} = \gamma_s \left[\left(\mathbf{H}_{(k)}^{\mathcal{H}}\mathbf{H}_{(k)}\right)^{\dagger}\right]_{k,k}^{-1} \overset{\text{def}}{=} \gamma_s g_{S,k}^2, \tag{4}$$

where $\mathbf{H}_{(k)}$ is generated in a recursive fashion by nulling the $(k-1)$-st column of $\mathbf{H}_{(k-1)}$ for $k = 2, \cdots, N_t$, and $\mathbf{H}_{(1)} \overset{\text{def}}{=} \mathbf{H}$.

C. OSIC Receiver

To improve SIC performance, the streams can be reordered based on SNR at each stage. This receiver differs from SIC receiver only in the detection ordering. An SNR-based ordering scheme that maximizes minimum SNR appears in [1]. The decision-point SNR of the k-th stream at the k-th stage then becomes

$$\gamma_{O,k} = \gamma_s \left[\left((\mathbf{H}_{(k)}^{O})^{\mathcal{H}}\mathbf{H}_{(k)}^{O}\right)^{\dagger}\right]_{k,k}^{-1} \overset{\text{def}}{=} \gamma_s g_{O,k}^2, \tag{5}$$

where $\mathbf{H}^O$ denotes the reordered channel matrix.

The average BER of the above receivers can be calculated as [7][1]

$$\bar{P}(\gamma_s; \{g_k^2\}) = \frac{1}{N_t}\sum_{k=1}^{N_t} \mathcal{Q}\left(\sqrt{2\gamma_s g_k^2}\right), \tag{6}$$

where $\mathcal{Q}(x) \overset{\text{def}}{=} \frac{1}{\sqrt{2\pi}}\int_x^{\infty} e^{-y^2/2}dy$; g_k^2 depends on the receiver structure and is given in (3), (4) and (5).

III. MBER Power Allocation with Perfect Feedback

A. MIMO with Power Allocation

Denote the power allocated to the k-th stream as p_k^2. The received signal can be written as

$$\mathbf{r} = \mathbf{HPs} + \boldsymbol{\eta}, \tag{7}$$

where $\mathbf{P} \overset{\text{def}}{=} \text{diag}\{p_1, \cdots, p_{N_t}\}$ denotes the power allocation matrix. We assume that the total transmit power is constrained via

$$\text{tr}(\mathbf{PP}^T) = \sum_{k=1}^{N_t} p_k^2 = N_t. \tag{8}$$

Compared with general precoding, power allocation constrains the precoder to a diagonal matrix.

B. MBER Power Allocation Algorithm

The average BER in (6) can be straightforwardly generalized to

$$\bar{P}\left(\gamma_s; \{p_k^2\}; \{g_k^2\}\right) = \frac{1}{N_t}\sum_{k=1}^{N_t} \mathcal{Q}\left(\sqrt{2\gamma_s g_k^2 p_k^2}\right). \tag{9}$$

To minimize (9) under transmit power constraint (8), no closed-form solution exists. However, taking the approach in [8], we approximate the objective function to obtain a closed-form solution with performance very close to the MBER solution. Using the approximate BER formula given in [9][2], an approximate MBER power allocation is obtained as [8]

$$p_k^2 = \gamma_s^{-1} g_k^{-2}\left(\ln g_k^2 + \nu\right)_+, \quad 1 \le k \le N_t, \tag{10}$$

where $(x)_+ \overset{\text{def}}{=} \max\{0, x\}$, and ν is chosen to satisfy the power constraint (8). A recursive algorithm can be employed to solve (10).

Some remarks are now in order.

- *MBER Power Allocation versus General Precoding*: While other precoding schemes either apply an MBER criterion to ZF equalization [10] or use an MMSE criterion [3], the proposed power allocation enables SIC and OSIC under an MBER criterion.
- *Feedback Overhead*: In channels that lack reciprocity between uplink and downlink, MIMO with general precoding requires either $N_t \times N_r$ complex channel coefficients or precoding matrix feedback. On the other hand, if the proposed power allocation scheme is employed, only N_t real coefficients are required at the transmitter, a factor of $\frac{1}{2N_r}$ savings.
- *Complexity*: Precoding schemes require diagonalization of a channel matrix as well as matrix transformations [3], [10]. Using power allocation, operations performed at the transmitter are trivial.

IV. MBER Power Allocation with Imperfect Feedback

Here we assume that perfect CSI is available at the receiver, while a noisy feedback of CSI or allocated power is available at the transmitter. Feedback noise is modelled as a zero-mean Gaussian random variable as in [11]. An SIC receiver is considered. For an OSIC receiver, the analysis applies directly after ordering. Extension to a ZF receiver is also straightforward.

A. Power Allocation with Noisy CSI Feedback

Noisy CSI is modelled by $[\mathbf{H}]_{m,n} = [\hat{\mathbf{H}}]_{m,n} + \epsilon_{m,n}^h$, for $1 \le m \le N_r, 1 \le n \le N_t$, where $\hat{\mathbf{H}}$ is the CSI feedback, and $\epsilon_{m,n}^h$ denotes a zero-mean complex Gaussian noise with variance σ_h^2. The power gains of SIC can be expressed as

$$g_k^2 = \left[\left(\mathbf{H}_{(k)}^{\mathcal{H}}\mathbf{H}_{(k)}\right)^{\dagger}\right]_{k,k}^{-1} = \left\|\boldsymbol{\Upsilon}_{\mathbf{H}_{(k+1)}}^{\perp}\mathbf{h}_k\right\|^2, \tag{11}$$

[1]This is a lower bound for SIC and OSIC due to the neglecting of error propagation, which is also an accurate approximate at moderate-to-high SNR's.

[2]The BER can be approximated as $P_b(\gamma) \approx \frac{1}{5}\exp\{-c\gamma\}$, where c is a constellation-specific constant. Therefore, extension of the results in what follows is straightforward.

where $\boldsymbol{\Upsilon}_{\mathbf{X}}^{\perp} \overset{\text{def}}{=} \mathbf{I} - \mathbf{X}(\mathbf{X}^{\mathcal{H}}\mathbf{X})^{-1}\mathbf{X}^{\mathcal{H}}$ is the orthogonal projection matrix. Conditioned on $\hat{\mathbf{H}}$, $\mathbf{H}_{(k)}^{\mathcal{H}}\mathbf{H}_{(k)}$ is distributed as complex noncentral Wishart. While it is difficult to obtain a closed-form density function of g_k^2, we approximate the gains as

$$g_k^2 = \left\| \boldsymbol{\Upsilon}_{\mathbf{H}_{(k+1)}}^{\perp} \mathbf{h}_k \right\|^2 \approx \left\| \boldsymbol{\Upsilon}_{\hat{\mathbf{H}}_{(k+1)}}^{\perp} \mathbf{h}_k \right\|^2 \overset{\text{def}}{=} \tilde{g}_k^2,$$

i.e., we use $\hat{\mathbf{H}}_{(k+1)}$ to approximate $\mathbf{H}_{(k+1)}$ at stage k.

Claim 1: The approximate power gain $\tilde{g}_k^2$, conditioned on $\hat{\mathbf{H}}$ has a noncentral chi-square density function with $2(N_r - N_t + k)$ degrees of freedom and noncentrality parameter $\hat{g}_k^2 \overset{\text{def}}{=} \hat{\mathbf{h}}_k^{\mathcal{H}} \boldsymbol{\Upsilon}_{\hat{\mathbf{H}}_{(k+1)}}^{\perp} \hat{\mathbf{h}}_k$.

The proof is omitted due to lack of space.

Using $\tilde{g}_k^2$ to approximate g_k^2, it can be shown (by using characteristic functions) that an approximate closed-form for the BER is given by

$$\begin{aligned}
\tilde{P}(\gamma_s; \mathbf{H}; \hat{\mathbf{H}}) &\approx \frac{1}{5N_t} \sum_{k=1}^{N_t} \int e^{-\gamma_s p_k^2 \tilde{g}_k^2} f_{\tilde{g}_k^2|\hat{\mathbf{H}}}\left(\tilde{g}_k^2|\hat{\mathbf{H}}\right) d\hat{\mathbf{H}} \\
&= \frac{1}{5N_t} \sum_{k=1}^{N_t} \frac{\exp\left(-\frac{\gamma_s p_k^2 \hat{g}_k^2}{1+\gamma_s p_k^2 \sigma_h^2}\right)}{(1+\gamma_s p_k^2 \sigma_h^2)^{(N_r - N_t + k)}} \\
&\overset{\text{def}}{=} \tilde{\tilde{P}}(\gamma_s; \hat{\mathbf{H}}; \sigma_h^2) \qquad (12)
\end{aligned}$$

Remarks:

- For perfect CSI at the transmitter, $\hat{\mathbf{H}} = \mathbf{H}$ and $\sigma_h^2 = 0$, and (12) reduces to

$$\tilde{\tilde{P}}(\gamma_s; \hat{\mathbf{H}}; 0) = \frac{1}{5N_t} \sum_{k=1}^{N_t} \exp\left(-\gamma_s p_k^2 g_k^2\right),$$

which is approximate BER for power allocation with perfect feedback.

- Since

$$\lim_{\gamma_s \to \infty} \frac{\tilde{\tilde{P}}(\gamma_s; \hat{\mathbf{H}}; \sigma_h^2)}{\gamma_s^{-(N_r - N_t + 1)}} = \frac{1}{5N_t} \frac{\exp\left(-\hat{g}_1^2/\sigma_h^2\right)}{(p_1^2 \sigma_h^2)^{(N_r - N_t + 1)}} \overset{\text{def}}{=} \kappa_h,$$

we have, for $\gamma_s \gg 1$, $\tilde{\tilde{P}}(\gamma_s; \hat{\mathbf{H}}; \sigma_h^2) \approx \kappa_h \cdot \gamma_s^{-(N_r - N_t + 1)}$, decreasing exponentially as $(N_r - N_t + 1)$-th power of γ_s. Therefore, robustness to noisy CSI increases as the number of receive antennas, N_r, is increased relative to the number of transmit antennas, N_t. On the other hand, from (6), the BER of MIMO without power allocation can be approximated as $\bar{P}\left(\gamma_s; \{g_k^2\}\right) \approx \frac{1}{5N_t} \sum_{k=1}^{N_t} e^{-\gamma_s g_k^2}$, decreasing exponentially in γ_s. Thus, for sufficiently large γ_s, power allocation schemes with noisy CSI at the transmitter are inferior to MIMO without power allocation, which is not affected by noisy CSI feedback.

B. Power Allocation with Noisy Power Feedback

Denote $\mathbf{p} = [p_1, \cdots, p_{N_t}]^T$ and $\hat{\mathbf{p}} = [\hat{p}_1, \cdots, \hat{p}_{N_t}]^T$, where $\hat{p}_k$ denotes noisy power feedback. Noisy power feedback is modelled as $\hat{\mathbf{p}} = \mathbf{p} + \boldsymbol{\epsilon}^p$, where $\boldsymbol{\epsilon}^p$ is a noise vector with distribution $\mathcal{N}\left(\mathbf{0}, \sigma_p^2 \mathbf{I}\right)$.

With noisy power feedback, the conditional approximate average BER can be written as

$$\tilde{P}(\gamma_s; \{g_k\}; \{\hat{p}_k\}) = \frac{1}{5N_t} \sum_{k=1}^{N_t} \exp\left\{-\gamma_s \hat{p}_k^2 g_k^2\right\}. \qquad (13)$$

By averaging both sides of (13) over the distribution of $\boldsymbol{\epsilon}^p$, the approximate BER can be obtained as

$$\tilde{\tilde{P}}\left(\gamma_s; \{g_k\}; \sigma_p^2\right) \overset{\text{def}}{=} \frac{1}{5N_t} \sum_{k=1}^{N_t} \frac{\exp\left\{-\frac{\gamma_s p_k^2 g_k^2}{1+2\gamma_s g_k^2 \sigma_p^2}\right\}}{(1+2\gamma_s g_k^2 \sigma_p^2)^{1/2}}. \qquad (14)$$

The derivation follows [12].

Remarks:

- For perfect power feedback, $\hat{\mathbf{p}} = \mathbf{p}$ and $\sigma_p^2 = 0$, and the above analysis does not apply. However, from (14), we have the limiting case of high quality feedback

$$\lim_{\sigma_p^2 \to 0} \tilde{\tilde{P}}(\gamma_s; \{g_k\}; \sigma_p^2) = \frac{1}{5N_t} \sum_{k=1}^{N_t} \exp\left\{-\gamma_s p_k^2 g_k^2\right\},$$

which reduces to the approximate BER for power allocation with perfect feedback. Therefore, (14) includes perfect power feedback as a special case.

- From (14), we have

$$\lim_{\gamma_s \to \infty} \frac{\tilde{\tilde{P}}(\gamma_s; \{g_k\}; \sigma_p^2)}{\gamma_s^{-1/2}} = \frac{1}{5N_t} \sum_{k=1}^{N_t} \frac{\exp\left\{-\frac{p_k^2}{2\sigma_p^2}\right\}}{\sqrt{2} g_k \sigma_p} \overset{\text{def}}{=} \kappa_p,$$

i.e., when $\gamma_s \gg 1$, $\tilde{\tilde{P}}(\gamma_s; \{g_k\}; \sigma_p^2) \approx \kappa_p \cdot \gamma_s^{-1/2}$, decreasing in $\gamma_s^{-1/2}$. Again, in view of (6), for sufficiently large γ_s, power allocation schemes with noisy power feedback are inferior to MIMO without power allocation.

C. MBER Power Allocation Using Feedback Noise Variance

When knowledge of the variance of noisy power feedback, σ_p^2, or noisy CSI, σ_h^2, is available at the transmitter, power allocation can be modified to take feedback noise variance into account as in [11]. To this end, a constrained optimization problem, referred to as *modified MBER power allocation,* can be formulated as

$$\begin{cases} \min \tilde{\tilde{P}} \\ \text{subject to} \quad \sum_{k=1}^{N_t} p_k^2 = N_t \end{cases}, \qquad (15)$$

where $\tilde{\tilde{P}}$ is the objective function from (12) or (14). It can be verified that $\frac{d^2 \tilde{\tilde{P}}}{d\left(p_k^2\right)^2} > 0$, i.e., $\tilde{\tilde{P}}$ is convex in p_k^2. A solution to the convex optimization problem (15) is given by $p_k^2 = (\phi_k)_+$, where ϕ_k is the root of the equation $\frac{d\tilde{\tilde{P}}}{d\left(p_k^2\right)} = \mu$, and μ is chosen to satisfy the transmit power constraint [8]. By noting the normalized transmit power constraint, we have $\min_k p_k^2 \leq 1 \leq \max_k p_k^2$, and the parameter μ can be bounded as

$$\min_k \left\{ \left. \frac{d\tilde{\tilde{P}}}{d\left(p_k^2\right)} \right|_{p_k^2=1} \right\} \leq \mu \leq \max_k \left\{ \left. \frac{d\tilde{\tilde{P}}}{d\left(p_k^2\right)} \right|_{p_k^2=1} \right\}.$$

An iterative algorithm can be used to solve this problem numerically.

V. Numerical Results and Discussions

In our simulations, we adopt the spatial fading correlation model for general non-isotropic scattering given in [6]. The following parameters are chosen: $N_t = 4$ transmit and $N_r = 8$ receive antennas; transmit and receive antenna spacings expressed in terms of wavelengths are 0.5 and 10, respectively; angles of arrival/departure of deterministic component are $\pi/6$ and 0, respectively; angle spread is $10°$; $K = 8$ dB for Ricean fading channels. Performance of transmission methods discussed earlier are simulated, and compared to MBER precoding for ZF equalization [10] as well as optimal MMSE precoding/decoding using trace criterion [3]. BPSK modulation is used for the purposes of comparison with [10].

A. MBER Power Allocation with Perfect Feedback

1) Rayleigh Fading: Fig. 1 is a plot of the average BER of the different transceivers in an uncorrelated Rayleigh fading channel. We observe that at a BER of 10^{-3}, MBER power allocation offers 1.2, 1.5 and 0.6 dB SNR gains over ZF, SIC and OSIC receivers, respectively. At all SNR's shown, MMSE precoding/decoding offers performance between that of ZF with and without MBER power allocation, while MBER precoding for ZF equalization has performance between that of SIC with and without MBER power allocation.

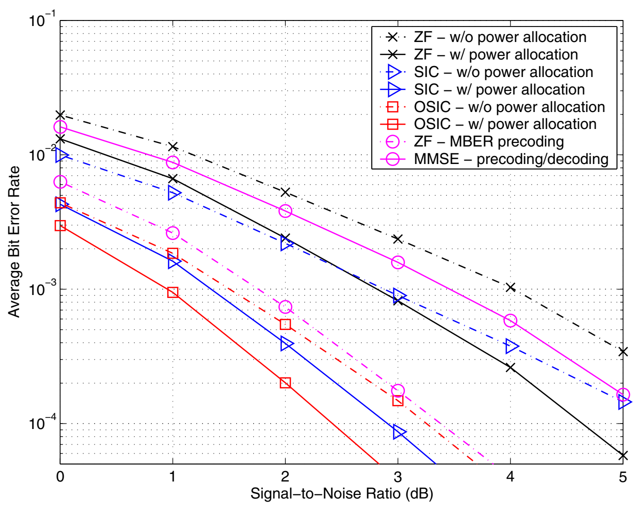

Fig. 1. Average BER performance in uncorrelated Rayleigh fading MIMO channel ($N_t = 4, N_r = 8$).

2) Ricean Fading: In Fig. 2, we illustrate average BER's in a Ricean correlated fading channel. At a BER of 10^{-3}, the SNR gains offered by MBER power allocation for SIC and OSIC are 3.1 and 2.0 dB, respectively. We also observe that MMSE precoding/decoding has performance similar to that of SIC without power allocation, while performances of MBER precoding for ZF equalization and OSIC without power allocation are nearly identical.

Remarks:

- *MBER Power Allocation versus SNR-Based Ordering for SIC*: It is also observed from simulations that SIC with MBER power allocation outperforms OSIC without power allocation, i.e., MBER power allocation outperforms SNR-based ordering for SIC receivers.
- *MBER Power Allocation versus General Precoding*: In the simulations, SIC and OSIC with MBER power allocation outperform both MMSE precoding/decoding and MBER precoding for ZF equalization.

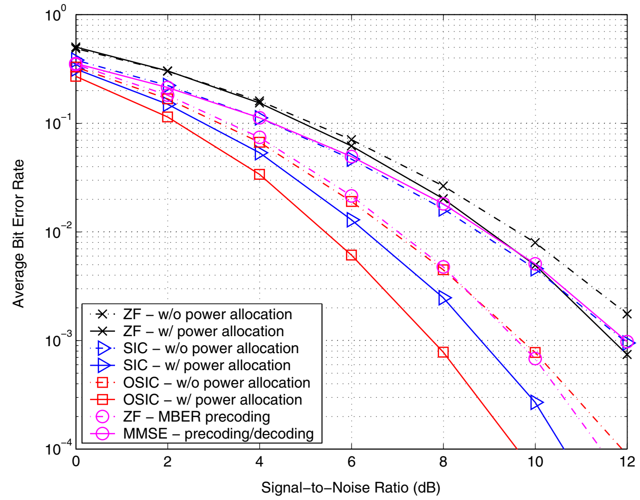

Fig. 2. Average BER performance in correlated Ricean fading MIMO channel ($N_t = 4, N_r = 8,\ K = 8$ dB).

B. MBER Power Allocation with Imperfect Feedback

1) MBER Power Allocation with Noisy Power Feedback: Fig. 3 shows an example of the instantaneous approximate BER of OSIC with and without MBER power allocation as a function of feedback power noise variance. The channel is modelled as Ricean fading with $K = 8$ dB. From Fig. 3, when the power feedback noise variance σ_p^2 is larger than 0.01, OSIC without power allocation outperforms MBER power allocation, which suggests MBER power allocation to be sensitive to imperfect power feedback.

2) MBER Power Allocation Using Noisy CSI Variance: Fig. 4 depicts average BER performances of OSIC transceivers without power allocation, with MBER power allocation (10) and with modified power allocation (Section IV-C), respectively, in a correlated Ricean fading channel. Perfect knowledge of noise variance σ_h^2 is assumed. Ordering is conducted at the transmitter based on noisy CSI. We observe that when the CSI noise variance is larger than 0.6, MBER power allocation (10) has performance inferior to that of no-power-allocation. At all CSI noise variances shown, modified power allocation outperforms the other OSIC methods.

Remark: From Fig. 4, we also observe that when $\sigma_h^2 = 0$, i.e, perfect CSI, using the modified scheme outperforms (10). This can be explained as follows: the modified power allocation solution for perfect CSI is given by $(p_k')^2 = (\phi_k)_+$,

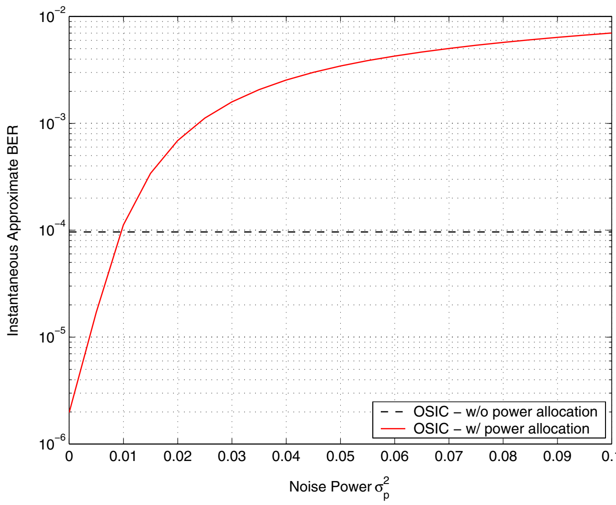

Fig. 3. An example of approximate BER versus noise variance of power feedback ($N_t = 4, N_r = 8$, $K = 8$ dB, $\gamma_s = 10$ dB).

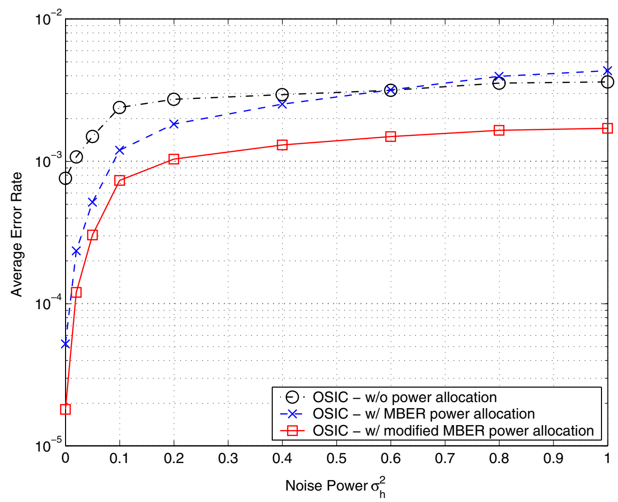

Fig. 4. Average BER performance versus noisy CSI variance in correlated Ricean fading MIMO channel ($N_t = 4, N_r = 8$, $K = 8$ dB, $\gamma_s = 10$ dB).

where ϕ_k is the solution to $\left.\frac{d\tilde{\tilde{P}}(\gamma_s;\hat{\mathbf{H}};\sigma_h^2)}{d\left({p'_k}^2\right)}\right|_{\sigma_h^2=0} = \mu$, which is equivalent to

$$(p'_k)^2 = \gamma_s^{-1} g_k^{-2} \left(\ln\left[g_k^2 - \gamma_s^{-1}(N_r - N_t + k)\right] + \mu'\right)_+, \tag{16}$$

where μ and μ' are chosen to satisfy the transmit power constraint. Comparing (16) with the MBER power allocation using (10), it is obvious that in the modified scheme, more power is allocated to earlier successive interference cancellation stages. This change has the benefit of reducing error propagation from earlier stages to later ones, which improves the error rate performance. In other words, the modified power allocation algorithm (16) takes error propagation of interference cancellation into account.

VI. Conclusions

Power allocation using a minimum BER (MBER) criterion for MIMO spatial multiplexing is studied in this paper. MBER power allocation schemes for a variety of receiver structures have been proposed. Compared with existing precoding schemes, the proposed schemes reduce both complexity and feedback overhead significantly. This method is motivated by an approximate BER analysis, which is also used to develop an MBER power allocation scheme that uses the variance of the feedback or CSI noise. Simulation results show that the proposed power allocation method improves performance for ZF, SIC and OSIC receivers. Particularly, SIC and OSIC employing MBER power allocation have the potential to offer superior performances over existing precoding schemes, e.g., in a correlated Ricean fading channel, at a BER of 10^{-3}, MBER power allocation for OSIC offers, respectively, 2.0 and 4.0 dB SNR gains over MBER precoding for ZF equalization and MMSE precoding/decoding. As future work, we need to assess the modified power allocation algorithm when knowledge of CSI error variances is imperfect.

Acknowledgment

This research is supported by grants from Samsung Electronics AIT, Korea, as well as from Bell Mobility, Canada.

References

[1] G. J. Foschini, G. D. Golden, R. A. Valenzuela, P. W. Wolniansky, "Simplified Processing for High Spectral Efficiency Wireless Communication Employing Multi-Element Arrays," *IEEE J. Select. Areas Commun.,* vol. 17, no. 11, pp. 1841-1852, Nov. 1999.

[2] J. Yang and S. Roy, "On Joint Transmitter and Receiver Optimization for Multi-Input-Multi-Output (MIMO) Transmission Systems," *IEEE Trans. Commun.,* vol. 42, no. 12, pp. 3221-3231, Dec. 1994.

[3] A. Scaglione, P. Stoica, S. Barbarossa, G. B. Giannakis and H. Sampath, "Optimal Designs for Space-Time Linear Precoders and Equalizers," *IEEE Trans. Signal Processing,* vol. 50, no. 5, pp. 1051-164, May 2002.

[4] D. J. Love and R. W. Heath Jr., "Limited Feedback Precoding for Spatial Multiplexing Systems," *Proc. IEEE Globecom 2003,* vol. 4, pp. 1857-1861, San Francisco, CA, Dec. 2003.

[5] S. Zhou and G. B. Giannakis, "Optimal Transmitter Eigen-Beamforming and Space-Time Block Coding Based on Channel Mean Feedback," *IEEE Trans. Signal Processing,* vol. 50, no. 10, pp. 2599-2613, Oct. 2002.

[6] A. Abdi and M. Kaveh, "A Space-Time Correlation Model for Multielement Antenna Systems in Mobile Fading Channels," *IEEE J. Select. Areas Commun.,* vol. 20, no. 3, pp. 550-560, Apr. 2002.

[7] J. G. Proakis, *Digital Communications,* 4th ed., New York: McGraw-Hill, 2001.

[8] N. Wang and S. D. Blostein, "Power Loading for CP-OFDM over Frequency-Selective Fading Channels," *Proc. IEEE Globecom 2003,* vol. 4, pp. 2305-2309, San Francisco, CA, Dec. 2003.

[9] S. Zhou and G. B. Giannakis, "Adaptive Modulation for Multi-Antenna Transmissions with Channel Mean Feedback," *Proc. IEEE ICC 2003*, vol. 4, pp. 2281-2285, Anchorage, AK, May 2003.

[10] Y. Ding, T. N. Davidson, Z.-Q. Luo, and K. M. Wong, "Minimum BER Block Precoders for Zero-Forcing Equalization," *IEEE Trans. Signal Processing,* vol. 51, no. 9, pp. 2410-2423, Sept. 2003.

[11] A. P. Iserte, M. A. Lagunas, and A. I. Pérez-Neira, "Robust Power Allocation for Minimum BER in a SISO-OFDM System," *Proc. IEEE ICC 2003*, vol. 2, pp. 1263-1267, Anchorage, AK, May 2003.

[12] G. Jöngren, M. Skoglund, and B. Ottersten, "Combining Bemforming and Orthogonal Space-Time Block Coding," *IEEE Trans. Info. Theory,* vol. 48, no. 3, pp. 611-627, Mar. 2002.

[13] J. K. Cavers, "Single-User and Multiuser Adaptive Maximal Ratio Transmission for Rayleigh Channels," *IEEE Trans. Veh. Technol.,* vol. 49, no. 6, pp. 2043-2050, Nov. 2000.