Joint Partial Relay Selection, Power Allocation and Cooperative Maximum Likelihood Detection for MIMO Relay Systems with Limited Feedback

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***Abstract*—In this paper, joint partial relay selection (PRS) and power allocation methods are proposed in conjunction with cooperative maximum likelihood (ML) detectors. These methods are considered for selecting relay nodes that improve the bit error rate (BER) performance of a two-phase multiple-input multiple-output (MIMO) half-duplex decode-and-forward (DF) relay system with log-normal shadowing and power constraints, as compared to using all relays available regardless of whether the additional relays will benefit the system. Limited feedback is applied to the joint PRS and power allocation techniques within the system, with results showing the effects of the proposed relay selection methods on BER performance.**

I. Introduction

The deployment of many low power relay nodes to assist in the traditional user to base station communications scenario as in consumer mobile communications, has been theoretically shown to offer improvements in power consumption, outage rates and reduced error rates over the traditional single link, which is a result of the inherent spatial diversity present in the multiple routes in which the signals are transmitted [1],[2]. However, there is an extra complexity required to successfully reconstruct and detect the transmitted data symbols from the multiple streams of information, which are often subject to different environmental and transmission conditions, and then produce a result with superior performance to the original non-cooperative system transmission [3].

In a previous work by the authors [4], a two-phase relay system with multiple relays and a global power constraint was considered and it was demonstrated how a cooperative maximum likelihood (ML) detector could be employed at the destination of the system, with a stochastic gradient (SG) based antenna power allocation algorithm designed to enhance the bit error rate (BER) performance of the system. The proposed techniques were seen to offer performance gains over the non cooperative system when the relays were within a close distance configuration of the source and destination nodes, but when this distance was increased, the performance gains were seen to reduce, and in a single relay case with no SG power allocation, be worse than the non-cooperative case.

In prior work by other authors, a scheme known as partial relay selection (PRS) was proposed [5], where only the information local to the node processing the relay selection was used in determining the relay nodes to cooperate with. Other works have used PRS as a method in their works [6],[7],[8], but the basic principle of using the relays signal-to-noise ratio (SNR) in a maximising function remains unchanged, and in the majority of works only single antenna amplify-and-forward (AF) relay nodes are considered.

In this work however, the problem of badly positioned relays reducing the system performance in a decode-and-forward (DF) MIMO relay system is considered. Two PRS strategies to choose the relays that are most beneficial to the system performance are proposed, one based on the channel power, another based on a combinatorial ML solution. A model of a two-phase cooperative MIMO system with path loss and shadowing is presented, with a joint PRS, power allocation and cooperative detector scheme being proposed. The PRS strategies do not require access to complete knowledge of the system, and thus can operate utilising only the information available at D, with limited feedback of the PRS and power allocation considered. The PRS is mapped to the SG power allocation algorithm, and log normal shadowing, feedback quantisation, and errors are considered in the system.

The rest of the paper is organised as follows: Section II outlines the MIMO cooperative relay system and signal models, Section III describes the cooperative ML detector and the SG power allocation algorithm subject to relay selection. Section IV proposes the two PRS strategies, Section V presents simulation results of the proposed strategies, and conclusions are drawn in Section VI.

II. System and Signal Models

The two-phase transmission system under consideration consists of three types of MIMO communication nodes, a single source node (S) that transmits the data in the first phase, multiple relay nodes (R) that retransmit the data they receive from the source node in the second phase, and a single destination node (D) which receives the source node transmission in the first phase of the system, and the transmission of the relay node in the second phase of communication. The relays are assumed to be DF relays, which means that they decode the received signal into bits, and then re-encode the bits into symbols for transmission in the second phase. All nodes are assumed to have the same number of transmit and receive antennas (N_t), it is assumed that all relays transmit simultaneously in the second phase, D has perfect channel knowledge and the channels are assumed to be static over a few data packets, so that the delay-free feedback in the system is applicable to the subsequent environment.

In [4], the system model made the assumption that the relays were all at the same distance from the S and D nodes in a symmetric layout. In this paper, the assumption that the relays are at the same distance away is relaxed, which requires that the system model be altered. A more realistic propagation modelling that takes into account path loss and shadowing effects is incorporated into the system. The first phase ($S \rightarrow R$ and $S \rightarrow D$) can be represented as follows:

$$\mathbf{y}_{sd} = \alpha_{sd}\beta_{sd}\mathbf{H}_{sd}\mathbf{A}_s\mathbf{x}_s + \mathbf{n}_d^{(1)} \quad (1)$$

$$\mathbf{y}_{sr_m} = \alpha_{sr_m}\beta_{sr_m}\mathbf{H}_{sr_m}\mathbf{A}_s\mathbf{x}_s + \mathbf{n}_{r_m}^{(1)}, m = 1, \ldots, M \quad (2)$$

and the second phase of communication ($R \rightarrow D$) by:

$$\mathbf{y}_{rd} = \sum_{m=1}^{M}(\alpha_{rd_m}\beta_{rd_m}\mathbf{H}_{rd_m}\mathbf{A}_{r_m}\mathbf{x}_{r_m}) + \mathbf{n}_d^{(2)} \quad (3)$$

where $\mathbf{H}_{sd}$, $\mathbf{H}_{sr_m}$ and $\mathbf{H}_{rd_m}$ are $N_t \times N_t$ matrices denoting the $S \rightarrow D$, $S \rightarrow R$ and $R \rightarrow D$ channels, respectively, where the m subscript denotes the relay number that the value is associated with up to M relays, $\mathbf{x}_s$ and $\mathbf{x}_{r_m}$ are vectors of length N_t that denote the data symbols that are transmitted from the source and relays, respectively. The matrices $\mathbf{A}_s$ and $\mathbf{A}_{r_m}$ are $N_t \times N_t$ diagonal matrices denoting the S and R power allocations, respectively, where each diagonal element corresponds to an antenna on that device. The scalars α_{sd}, α_{sr_m} and α_{rd_m} represent the distance dependent path loss in the channel, the scalars β_{sd}, β_{sr_m} and β_{rd_m} are the log-normal shadow fading channel losses, the vectors $\mathbf{y}_{sd}$, $\mathbf{y}_{sr_m}$ and $\mathbf{y}_{rd}$ are N_t length vectors that represent the received signal in the $S \rightarrow D$, $S \rightarrow R$ and $R \rightarrow D$ links, respectively, and the noise at each receiver is represented by a vector of length N_t, with $\mathbf{n}_r$ the noise at the relay, and $\mathbf{n}_d$ the noise at the destination. The superscript $^{(1)}$ or $^{(2)}$ denotes which phase of transmission the noise is applied to. The vector $\mathbf{y}_{rd}$ can be thought of as a sum of the relay transmissions in the second phase.

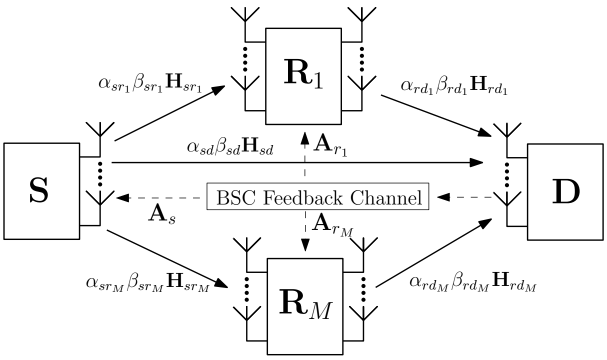

Fig. 1: MIMO cooperative multiple relay system model with power allocation and relay selection feedback channel.

Fig. 1 gives a representation of this system in a block diagram. It is assumed that the channels in the system are modelled as a Rayleigh complex distribution with block fading. The distance dependent path loss variable α for the relay links is defined by the relative distances of R from S and D [9], and so relative to the path loss of the S to D link, as follows:

$$\alpha_{sd} = \sqrt{L}, \quad (4)$$

$$\alpha_{sr_m} = \frac{\alpha_{sd}}{\sqrt{(d_{sr_m})^{\gamma}}}, m = 1, \ldots, M \quad (5)$$

$$\alpha_{rd_m} = \frac{\alpha_{sd}}{\sqrt{(d_{rd_m})^{\gamma}}}, m = 1, \ldots, M \quad (6)$$

where L is the power path loss of the S to D link, d_{sr_m} and d_{rd_m} is the relative distances of each R from the S and D as compared to the S to D link and γ is the path loss exponent, usually between 2 and 4 depending on the environment.

The log-normal shadowing [10], [11] is modelled as a log-normal random variable, that is produced from a normal distribution with a standard deviation of σ_s, which is known as the shadowing spread in dB given by:

$$\beta = 10^{\left(\frac{\sigma_s \mathcal{N}(0,1)}{10}\right)} \quad (7)$$

where $\mathcal{N}(0, 1)$ represents a normal distribution with mean 0 and variance 1, and it is assumed that each channel has log normal shadowing with the same shadowing spread.

The elements of the noise vectors $\mathbf{n}_{r_m}^{(1)}$, $\mathbf{n}_d^{(1)}$ and $\mathbf{n}_d^{(2)}$ are comprised of circular complex additive white Gaussian noise (AWGN) samples with a variance in proportion to that of the SNR at D, as given by:

$$\mathbf{n} = \left(\frac{\sigma_n}{\sqrt{2}}\right)\mathcal{CN}(0, 1), \quad (8)$$

where $\mathcal{CN}(0, 1)$ represents a complex normal distribution with mean 0 and variance 1, and σ_n is the variance of the noise at that receiver, given by:

$$\sigma_n = \sqrt{\frac{1}{SNR \cdot L}} \quad (9)$$

It is assumed that all receive antennas on all nodes are subject to the same average noise power.

The feedback channel in which the relay selection and power allocation information is transmitted to S and all R is modelled as a binary symmetric channel (BSC), which can be defined as having an error probability ρ_e of inverting a bit transmitted through it.

III. Joint Partial Relay Selection, Cooperative ML Detection and Power Allocation

Here a joint PRS, cooperative ML detection scheme and power allocation scheme is presented. Unlike the previous work on joint cooperative ML detection and power allocation reported in [4], PRS techniques are incorporated in order to mitigate the effects of links associated with poorly positioned relays, thereby improving the overall BER performance of the system.

A. Joint Relay Selection and Cooperative ML Detector

The cooperative ML detector operates on a modified ML rule, which is created by combining the two ML rules from each communication phase of the system to the destination (S to D and R to D), into an equivalent single ML rule that is modified to use available information in the system. For convenience, the scalar terms α and β will be grouped into a single term given by $\delta = \alpha\beta$. The cooperative ML detection problem can be described as the following optimisation:

$$[\hat{\mathbf{x}}, \hat{\mathbf{A}}_s, \hat{\mathbf{A}}_{r_1} \dots \hat{\mathbf{A}}_{r_M}] = \arg\min_{\substack{x_n \in Z, \\ \mathbf{A}_s, \mathbf{A}_{r_m} \in \mathcal{C}^{N_t \times N_t}}} (\|\mathbf{y}_{sd} - \delta_{sd}\mathbf{H}_{sd}\mathbf{A}_s\mathbf{x}\|^2 + \sum_{m \epsilon \Omega_s} \|\mathbf{y}_{rd_m} - \delta_{rd_m}\mathbf{H}_{rd_m}\mathbf{A}_{r_m}\mathbf{x}_m\|^2) \quad (10)$$

where Z represents the constellation set for the modulation scheme used, Ω_s is the selected relay set which is selected by a relay selection method, which will be detailed later on, and x_n is the nth element of $\mathbf{x}$. By defining the relation

$$\mathbf{S} = \sum_{m \epsilon \Omega_s} \delta_{rd_m}\mathbf{H}_{rd_m}\mathbf{A}_{r_m}, \quad (11)$$

an equivalent ML rule can be derived:

$$[\hat{\mathbf{x}}, \hat{\mathbf{A}}_e] = \arg\min_{\substack{x_n \in S, \\ \mathbf{A}_e \in \mathcal{C}^{N_t \times N_t}}} \|\mathbf{y}_e - \mathbf{H}_e\mathbf{A}_e\mathbf{x}\|^2, \quad (12)$$

$$\mathbf{H}_e\mathbf{A}_e = (\mathbf{A}_s^H\mathbf{H}_{sd}^H\delta_{sd}^H\delta_{sd}\mathbf{H}_{sd}\mathbf{A}_s + \mathbf{S}^H\mathbf{S})^{1/2} \quad (13)$$

$$\mathbf{y}_e = (\mathbf{H}_e\mathbf{A}_e)^{-1}(\mathbf{A}_s^H\mathbf{H}_{sd}^H\delta_{sd}^H\mathbf{y}_{sd} + \mathbf{S}^H\mathbf{y}_{rd}) \quad (14)$$

B. Power Allocation

A power allocation algorithm is developed based on an SG recursion. The SG power allocation works on the antennas of both the S and all R, and so modifies the power allocation matrices $\mathbf{A}$. For ease of manipulation, the diagonal $\mathbf{A}$ matrices and the data vectors $\mathbf{x}$ are rearranged into equivalent diagonal data matrices $\mathbf{X}$ and power allocation vectors $\mathbf{a}$. Also, the signals with the two phases of transmission can be stacked to produce a single set of equations to work with the SG algorithm as described by:

$$\mathbf{y}_t = \begin{bmatrix}\mathbf{y}_{sd} \\ \mathbf{y}_{rd}\end{bmatrix} = \begin{bmatrix}\delta_{sd}\mathbf{H}_{sd}\mathbf{X}_s\mathbf{a}_s \\ \sum_{m\epsilon\Omega_S}(\delta_{rd_m}\mathbf{H}_{rd_m}\mathbf{X}_{r_m}\mathbf{a}_{r_m})\end{bmatrix} + \begin{bmatrix}\mathbf{n}_d^{(1)} \\ \mathbf{n}_d^{(2)}\end{bmatrix} = \mathbf{H}_t\mathbf{X}_t\mathbf{a}_t + \mathbf{n}_t \quad (15)$$

A generic SG recursion can be described as:

$$\mathbf{Q}[i+1] = \mathbf{Q}[i] + \mu\nabla\mathbf{C}, \quad (16)$$

where μ is a fixed step size, typically very small, i is a time index, $\mathbf{Q}$ is the variable to be optimised and $\nabla\mathbf{C}$ is the instantaneous gradient of the cost function used to evaluate the variable. If the ML equation is used as the cost function $\mathbf{C} = E[\|\mathbf{y}_t - \mathbf{H}_t\mathbf{X}_t\mathbf{a}_t\|^2]$, and $\mathbf{a}_t$ as the variable to be calculated, applying the SG algorithm to (15) produces:

$$\mathbf{a}_t[i+1] = \mathbf{a}_t[i] + \mu\mathbf{X}_t^H[i]\mathbf{H}_t^H[i]\mathbf{e}_t[i], \quad (17)$$

$$\mathbf{e}_t[i] = \mathbf{y}_t[i] - \mathbf{H}_t[i]\mathbf{X}_t[i]\mathbf{a}_t[i], \quad (18)$$

with the definition of $\mathbf{H}_t[i]$ altered to

$$\mathbf{H}_t[i] = \begin{bmatrix}\delta_{sd}\mathbf{H}_{sd}[i] & \mathbf{0}_{N_t \times N_t} & \cdots & \mathbf{0}_{N_t \times N_t} \\ \mathbf{0}_{N_t \times N_t} & \delta_{rd_m}\mathbf{H}_{rd_1}[i] & \cdots & \delta_{rd_{\Omega_s}}\mathbf{H}_{rd_{\Omega_s}}[i]\end{bmatrix} \quad (19)$$

in order to compensate for the fact that only the summed received relay vector $\mathbf{y}_{rd}$ is available, not each individual relay transmission $\mathbf{y}_{rd_m}$. The vector $\mathbf{a}_t$ is then normalised to comply with the system power constraint:

$$P_t = \mathrm{tr}(\mathbf{a}_t[i]\mathbf{a}_t^H[i]), \quad (20)$$

where P_t is the total system power allowed, and tr() represents the trace operator. Thus, $\mathbf{a}_t[i]$ is normalised as follows:

$$\mathbf{a}_t^n[i] = \frac{\mathbf{a}_t[i]\sqrt{P_t}}{\sqrt{\mathrm{tr}(\mathbf{a}_t[i]\mathbf{a}_t^H[i])}}, \quad (21)$$

$\mathbf{a}_t^n[i]$ can then be separated into the different node power allocations by unstacking, then re-diagonalising it into a matrix.

IV. Proposed Partial Relay Selection Strategies

In this section, two PRS strategies will be considered, one scheme based on channel link power (CP-PRS), and another technique that utilises the ML rule (ML-PRS). Both selection strategies assume that the number of relays to be selected in the system is known, and use only the information found at D, i.e. no knowledge of the S to R link.

A. Proposed CP-PRS

Given the number of relays to be selected (R_L), D determines the sum power of each channel's MIMO paths ($p_{H_{rd_m}}$) for each R to D link with path losses, and chooses the relay set associated with the R_L largest sum channel path powers ($\hat{\Omega}_s$), according to:

$$p_{H_{rd_m}} = \sum_{j=0}^{j=N_t}\sum_{k=0}^{k=N_t}(\delta_{rd_m}\mathbf{H}_{rd_m}\mathbf{H}_{rd_m}^H\delta_{rd_m}^H)_{j,k}, m = 1, \dots, M \quad (22)$$

$$\hat{\Omega}_s = \arg\max_{\hat{\Omega}_s \mathcal{C}^{R_L}} p_{H_{rd_m}} \quad (23)$$

This selection criterion is not subject to noise given that it is assumed that D has perfect knowledge of all $\delta_{rd_m}\mathbf{H}_{rd_m}$, and can be performed once before each packet, assuming that $\delta_{rd_m}\mathbf{H}_{rd_m}$ is static over one packet. It is similar to the PRS-D in [6], but instead of instantaneous SNR, our scheme relies on the channel power alone. This relay selection method is a simple search and compare problem, which in conjunction with only having to perform the method once per packet, meaning that the complexity is quite low for determining $\hat{\Omega}_s$, as only a matrix multiplication and some summing operations are required.

B. Proposed ML-PRS

Utilising the ML rule for the second phase of transmission, a combinatorial partial relay selection is given by

$$\hat{\Omega}_s = \arg\min_{\Omega_s \epsilon \Omega_r} \|\mathbf{y}_{rd} - \sum_{l \epsilon \Omega_s}\delta_{rd_l}\mathbf{H}_{rd_l}\mathbf{A}_{r_l}\mathbf{x}_l\|^2 \quad (24)$$

where Ω_r represents all possible unique combination sets of any number of selected relays and $\hat{\Omega}_s$ is the selected relay set that gives the minimum error between the received relay transmissions and the estimated relay transmissions. In order to choose the relay set to minimise Eq. (24), an exhaustive search on all possible Ω_s set combinations can be performed, if $\mathbf{x}_l$ is assumed to be retransmitted as the pilot data $\mathbf{x}$.

Since $\mathbf{y}_{rd}$ is subject to noise $\mathbf{n}_d^{(2)}$, the instantaneous candidate set estimate $\hat{\Omega}_s$ may not be the true optimum, and so the search must be performed repeatedly for different samples (time indices). Then the R_L relays which are most often members of the instantaneous candidate set estimates are chosen for $\hat{\Omega}_s$. The ML combination partial relay selection algorithm is described below.

1) Select relay set Ω_s from a possible combination set Ω_r
2) Calculate the error (Eq. (24)) if Ω_s relays are selected
3) If the error is less than that previous tested Ω_s, store the error and Ω_s
4) Compute steps 1 to 3 for all possible Ω_s
5) Compute steps 1 to 4 for a number of time index samples
6) From the selected Ω_s for each time index, find the R_L most commonly selected relays

As the method involved requires an exhaustive set search over $2^M - 1$ possible unique relay combinations, and multiple iterations are required per packet, the complexity of this algorithm is much higher than the channel power partial relay selection method.

V. Simulation Results

In the simulations, it is assumed that pilot signals transmitted from S for the purposes of PRS and power allocation, that sphere decoders (SD) [12] are used at all R and D, and that D has perfect channel state information (CSI) knowledge, which includes the packet-wise path loss and log-normal shadowing losses. The values for the parameters used in the simulations are shown in Table I. Using these values, we can calculate the number of feedback bits required per packet for the relay selection with and without SG power allocation, which can be calculated as an overhead of 0.075% for equal power allocation, and 1.475% with SG power allocation. The authors note however, that the number of power allocation bits could be reduced by compression or by binary power adjustment strategies.

TABLE I: Simulation Parameters.

Parameter	Value
Trials	2000
Packet Length	2000 symbol vectors
P_t	1
μ	0.05
N_t	2
$\mathbf{a}_t[0]$	Half S, Half equally between all R
γ	4
R_L	2
M	6
L	0.01
σ_s	6dB
Feedback Quantisation	4 Bits for each $\Re$ and $\Im$
Modulation	QPSK

For PRS, the ML-PRS algorithm is computed for 10 different time index samples with all relays active, before relay selection takes place. It is assumed that D has channel knowledge before the packet is transmitted, and so the channel based relay selection can be computed before the packet is transmitted. In a real system, it is also likely that the CSI of the previous packet will be similar to the next packet, and so this CSI could be used for the PRS. The relays are assumed to be able to reject power allocation feedback packets, if the number of relays selected and the number of power allocation values received are mismatched, the relays will use the last known acceptable feedback packet. The SNR values used are determined as the SNR of the S to D link with no cooperation, in order to ensure a fair comparison with the non-cooperative case.

Fig. 2 shows the structure of the feedback packet, with the relay selection portion comprising of M bits, each bit corresponding to a relay's state, 0 for off, 1 for on. The power allocation data bits A are split into the real ($\Re$) and imaginary ($\Im$) parts, with each part being quantised into 4 bits in this scenario. If SG power allocation is not used, then only the relay selection bits (RS) are transmitted after the chosen relay selection strategy has completed. If power allocation is used, once the relay selection has been determined, the feedback bits are transmitted after every symbol vector is received at D, comprising the relay selection and then the power allocation.

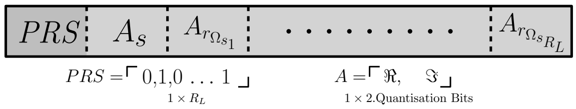

Fig. 2: Packet structure for PRS and power allocation feedback.

The position of the relays considered is set up such that two relays are positioned close to S and D, two are further away such that they might contribute to the system performance, and two are much further away, generally not being beneficial for the system performance. Fig. 3 represents this network setup.

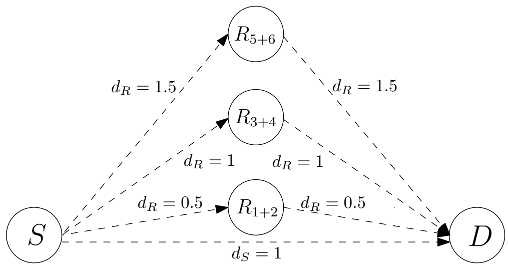

Fig. 3: Positioning of relays in the system considered.

Fig. 4 shows the BER versus SNR plot of the relay selection strategies proposed as compared to a non-cooperative case, and the cooperative case without PRS, with no SG power allocation or limited feedback applied. It can be seen that the ML combinatorial method gives the best performance of the two relay selection methods with up to 5dB over no relay selection and 10dB over the non-cooperative case. The CP-PRS scheme performs on a similar level as the ML-PRS at low SNR values, but at higher SNR values, has a decreased performance gain. It is worth considering though, that the CP-PRS scheme has a much lower complexity cost than the ML-PRS method.

Fig. 5 shows the BER versus SNR plot of the PRS strategies with and without dynamic power allocation, as compared to the non-cooperative case, without limited feedback. For both PRS strategies, the dynamic power allocation can be seen to give up to 6-7dB of gain over the equal power allocation scenario, and 12dB over the non-cooperative case.

Fig. 6 shows the BER versus SNR plot of the PRS schemes with power allocation under limited feedback. It can be seen that introducing feedback errors results in the introduction

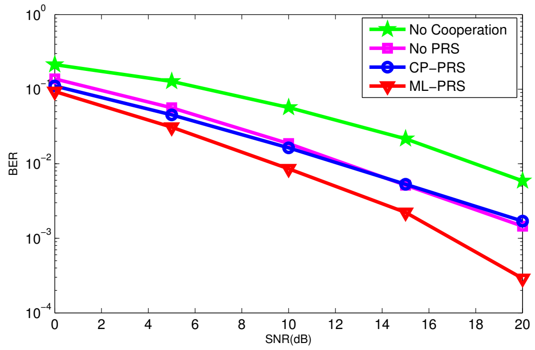

Fig. 4: BER vs $S \rightarrow D$ SNR for the 2x2 MIMO relay system, comparing the non-cooperative case with the cooperative with no PRS case, and the two proposed PRS schemes with equal power allocation

of an error floor, with the level of the error floor highly dependent on the probability of feedback error, although it can be assumed that the feedback error percentage could be reduced dramatically with the application of error correction techniques.

VI. Conclusions

In this paper, a joint PRS, power allocation and cooperative ML detector has been proposed, along with two relay selection strategies, a CP-PRS scheme, and an ML-PRS algorithm. It is seen that the system gives large BER gains over a non-cooperative case, with the PRS schemes offering gains over using all relays available in the scenario, and the addition of dynamic SG based power allocation further improving BER performance. The ML-PRS scheme is shown to have the best performance of the two proposed PRS schemes, but at the cost of a much higher complexity than the CP-PRS. It is also seen that with quantisation and limited feedback with errors results in the presence of an error floor as the SNR increases, which could potentially be counteracted with error correction coding.

Acknowledgment

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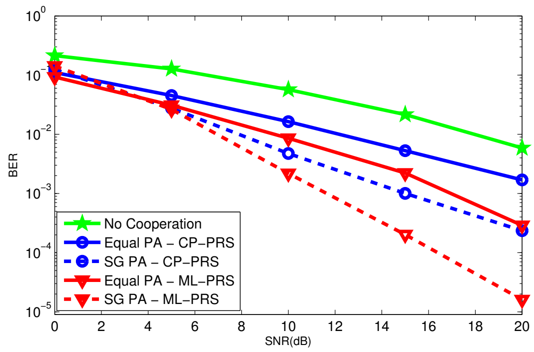
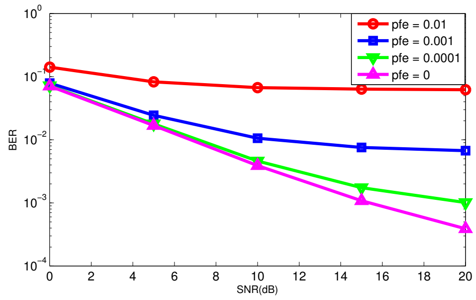
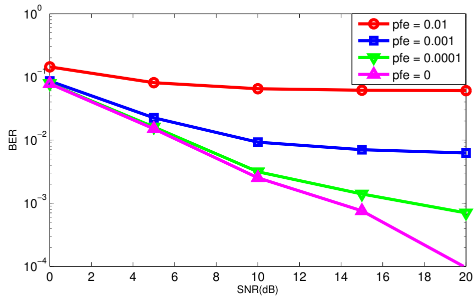


Fig. 5: BER vs $S \rightarrow D$ SNR for the 2x2 MIMO relay system, comparing the non-cooperative case with the two proposed PRS schemes, with and without the power allocation method.



(a) CP-PRS



(b) ML-PRS

Fig. 6: BER vs $S \rightarrow D$ SNR for the 2x2 MIMO relay system with power allocation, for different feedback error probabilities, for both proposed PRS schemes.

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