Switched Max-Link Relay Selection Algorithms for Buffer-Aided Relay Systems

F. L. Duarte and R. C. de Lamare

1Centre for Telecommunications Studies (CETUC), Pontifical Catholic University of Rio de Janeiro, Brazil
2Military Institute of Engineering, IME, Rio de Janeiro, RJ, Brazil
3Department of Eletronic Engineering, University of York, United Kingdom

Email: {flaviold, delamare}@cetuc.puc-rio.br

Abstract—In this paper, we investigate relay selection for cooperative multiple-antenna systems that are equipped with buffers, which increase the reliability of wireless links. In particular, we present a novel relay selection technique based on switching and the selection of the best link, that is named Switched Max-Link. We also introduce a novel relay selection criterion based on the Maximum Likelihood (ML) principle and the Pairwise Error Probability (PEP) denoted Maximum Minimum Distance (MMD) that is incorporated into the proposed Switched Max-Link protocol. We compare the proposed MMD to the existing Quadratic Norm (QN), in terms of PEP and computational complexity. Simulations are then employed to evaluate the performance of the proposed and existing techniques.

Index Terms—Cooperative communications, Relay-selection, Max-Link, Maximum Likelihood criterion

I. INTRODUCTION

In wireless networks, multipath propagation is a channel propagation phenomenon that affects the transmission of signals and can be mitigated through the use of cooperative diversity [1]–[3]. In cooperative communications with multiple relays, where a number of relays help a source in transmitting data packets to a destination, by receiving, processing (decoding) and forwarding these packets, relay selection schemes are key because of their high performance [4]–[6]. As cooperative communication can improve the throughput and extend the coverage of wireless communications systems, the task of relay selection serves as a building block to realize it. In this context, relay schemes have been included in recent/future wireless standards such as Long Term Evolution (LTE) Advanced [7], [8] and 5G standards [9].

A. Prior and Related Work

In conventional relaying, using half duplex (HD) and decode-and-forward protocols, transmission is usually organized in a prefixed schedule with two successive time slots. In the first time slot, the relay receives and decodes the data transmitted from the source, and in the second time slot the relay forwards the decoded data to the destination. Single relay selection schemes use the same relay for reception and transmission, so they are not able to simultaneously exploit the best available source-relay (SR) and relay-destination (RD) channels. The two most common schemes are bottleneck based and maximum harmonic mean based best relay selection (BRS) [4]. The performance of relaying schemes can be improved if the link with the highest power is used in each time slot. This can be achieved via a buffer-aided relaying protocol, where the relay can accumulate packets in its buffer, before transmitting. The use of buffers provides an improved performance and new degrees of freedom for system design [7], [10]. However, it suffers from additional delay that must be well managed for delay-sensitive applications. Buffer-aided relaying protocols require not only the acquisition of channel state information (CSI), but control of the buffer status. Some possible applications of buffer-aided relaying are: vehicular, cellular, and sensor networks [7]. In Max-Max Relay Selection (MMRS) [4], in the first time slot, the relay selected for reception can store the received packets in its buffer and forward them at a later time when selected for transmission. In the second time slot, the relay selected for transmission can transmit the first packet in the queue of its buffer, which was received from the source earlier. MMRS assumes infinite buffer sizes. To overcome this limitation, in [4] a hybrid relay selection (HRS) scheme, that is a combination of BRS and MMRS, was proposed. Although MMRS and HRS improve the throughput and/or SNR gain as compared to BRS, their diversity gain is limited to N (the quantity of relays). This can be improved by combining adaptive link selection with MMRS, which results in the Max-Link [11] protocol.

The main idea of Max-Link is to select in each time slot the strongest link among all the available SR and RD links (i.e., among 2N links) for transmission [12]. For independent and identically distributed (i.i.d.) links and no delay constraints, Max-Link achieves a diversity gain of 2N, which is twice the diversity gain of BRS and MMRS. Max-Link has been extended in [13] to account for direct source-destination (SD) connectivity, which provides resiliency in low transmit SNR conditions [12]. In [14]–[17], some buffer-aided relay selection protocols improve the Max-Link performance by: reducing the average packet delay, maintaining a good diversity gain, and/or achieving full diversity gain with a smaller buffer size compared to Max-Link. In summary, the previous schemes (MMRS, HRS and Max-Link) only use buffer-aided relay selection for cooperative single-antenna systems.

B. Contributions

In this work, we examine buffer-aided relay selection for cooperative multiple-antenna systems. In particular, we combine the concept of switching with the concept of selecting the best link used by the Max-Link protocol for cooperative multiple-antenna systems, which results in the proposed Switched Max-Link protocol. We also introduce the MMD criterion for selection of relays in the proposed scheme, which is based on the ML criterion and the PEP. The advantage of the MMD algorithm is that it maximizes the minimum value of the
PEP argument (PEP worst case). Simulations illustrate the performance of the proposed relay selection techniques. This paper is structured as follows. Section II describes the system model and the main assumptions made. Section III presents the proposed Switched Max-Link relay selection protocol and compares the proposed MMD criterion to the existing QN, in terms of PEP and complexity. Section IV illustrates and discusses the simulation results whereas Section V gives the concluding remarks.

II. SYSTEM DESCRIPTION

We consider a multiple-antenna relay network with one source node, $S$, one destination node, $D$, and $N$ half-duplex decode-and-forward (DF) relays, $R_1,...,R_N$. Each relay is equipped with a buffer, whose size is $J$ packets and each node is equipped with $M$ antennas, and the transmission is organized in time slots [4]. This configuration is considered for simplicity. The considered system is shown in Fig. 1.

![Fig. 1. System Model](image)

A. Assumptions

In cooperative transmissions two time slots are needed to transmit data packets from the source to the destination, so the energy transmitted in direct transmission (from the source to the destination) is twice the energy transmitted in the cooperative transmission, from the source to the relay selected for reception ($E_s$) or from the relay selected for transmission to the destination ($E_r$), $E_r = E_s$. For this reason, the energy transmitted from each antenna in cooperative transmissions is $E_s/M$ and the energy transmitted from each antenna in direct transmissions is $2E_s/M$.

We consider that the channel coefficients are mutually independent zero mean complex Gaussian random variables (Rayleigh fading). Moreover, we assume that the transmission is organized in data packets and the channels are constant for the duration of one packet and vary independently from one packet to the next. The information about the order of the data packets is contained in the preamble of each packet, so the original order is restored at the destination node. Other information such as signaling for network coordination and pilot symbols for training and knowledge of the channel (CSI) are also inserted in the preamble of the packet. We consider perfect and imperfect CSI. Furthermore, we assume that the relays do not communicate with each other.

We also assume that the destination is the central node, being responsible for deciding whether the source or the relay should transmit in a given time slot $i$. The central node has a perfect channel and buffer state information, so it may run the algorithm in each time slot and select the relay for transmission or reception through an error-free feedback channel. This assumption can be ensured by an appropriate signalling that provides global channel state information (CSI) at the destination node [11]. Furthermore, we assume that the source has no CSI and each relay has only information about its SR channel and buffer status.

B. System Model

The received signal from the source to the destination is organized in an $M \times 1$ vector $y_{s,d}[i]$ given by

$$y_{s,d}[i] = \sqrt{\frac{2E_s}{M}} x_{s,d}[i] + n_d[i],$$  \hspace{1cm} (1)

where $E_s$ represents the total energy of the symbols transmitted from the source, $x_{s,d}[i]$ represents the vector formed by $M$ symbols sent by the antennas of the source (a symbol of each packet). The quantity $H_{s,d}$ represents the $M \times M$ matrix of $SD$ links and $n_d$ denotes the zero mean additive white complex Gaussian noise (AWGN) at the destination receiver.

The received signal from the source to the selected relay is organized in an $M \times 1$ vector $y_{s,r_k}[i]$ given by

$$y_{s,r_k}[i] = \sqrt{\frac{E_s}{M}} H_{s,r_k} x_{s,d}[i] + n_{r_k}[i],$$ \hspace{1cm} (2)

where $r_k$ refers to the selected relay for reception, $H_{s,r_k}$ is the $M \times M$ matrix of $SR_k$ links and $n_{r_k}$ represents the AWGN at the relay selected for reception.

The signal transmitted from the selected relay and received at the destination is structured in an $M \times 1$ vector $y_{r_j,d}[i]$ given by

$$y_{r_j,d}[i] = \sqrt{\frac{E_{r_j}}{M}} H_{r_j,d} x_{r_j}[i] + n_d[i],$$ \hspace{1cm} (3)

where $E_{r_j}$ represents the total energy of the decoded symbols transmitted from the relay selected for transmission $r_j$, $x_{r_j}[i]$ is the vector formed by $M$ previously decoded symbols in the relay selected for reception and stored in its buffer and now transmitted by $r_j$ and $H_{r_j,d}$ is the $M \times M$ matrix of $R_j D$ links.

Assuming perfect CSI, at the relays, we employ the maximum likelihood (ML) receiver [5]:

$$x_{r_j}[i] = \arg \min_{\hat{x}_{r_j}[i]} \left( \frac{E_s}{M} H_{s,r_k} x_{r_j}[i] \right)^2,$$ \hspace{1cm} (4)

where $x'_{r_j}[i]$ represents each possible vector formed by $M$ symbols. As an example, if we have BPSK (number of
constellation symbols $N_s = 2$), unit power symbols and $M = 2$, the estimated symbol vector $x_i$ may be $[ -1 - 1 ]^T$, $[ -1 + 1 ]^T$, $[ +1 - 1 ]^T$ or $[ +1 + 1 ]^T$.

At the destination, we also resort to the ML receiver which depending on the transmission (SD or $R_j D$) yields

$$\hat{x}[i] = \arg \min_{x'[i]} \left( \left\| y_{s,d}[i] - \sqrt{\frac{2E_s}{M}} H_{s,r} x'[i] \right\|^2 \right), \quad (5)$$

$$\hat{x}[i] = \arg \min_{x'[i]} \left( \left\| y_{r,j,d}[i] - \sqrt{\frac{E_{s}}{M}} H_{r,j,d} x'[i] \right\|^2 \right), \quad (6)$$

The ML receiver of the DF relay looks for an estimate of the vector of symbols transmitted by the source $x[i]$, comparing the quadratic norm between the output $y_{s,r,k}$ and the term $\sqrt{E_s/M} H_{s,r}$ multiplied by $x'[i]$, that represents each of the $N_s^M$ possible transmitted symbols vector $x$. We compute the symbol vector which is the optimal solution for the ML rule. The same reasoning is applied to the ML receiver at the destination. Other detection techniques can also be employed [7], [21]-[28], [30]-[32], [34]-[38], [40], [41], [44], [61], [66].

Considering imperfect CSI, a channel error matrix $H_c$ is added to the channel matrix $(H_{s,r}, H_{r,j,d}$ or $H_{s,d})$ [13], where the variance of the $H_c$ coefficients is given by $\sigma_c^2 = \beta E_s^{-\alpha}$ ($\beta \geq 0$ and $0 \leq \alpha \leq 1$), in the case of the channel matrix $H_{s,r,k}$ or $H_{r,j,d}$, and $\sigma_c^2 = \beta (2E_s)^{-\alpha}$, in the case of the channel matrix $H_{s,d}$. III. PROPOSED SWITCHED MAX-LINK RELAY SELECTION PROTOCOL

In this section, we detail the proposed Switched Max-Link relay selection protocol for cooperative multiple-antenna systems. The proposed Switched Max-Link scheme can be implemented by making use of a network with one source node, $S$, one destination node, $D$, and $N$ half-duplex DF relays, $R_1,...,R_N$. Each relay is equipped with a buffer, whose size is $J$ packets, and each node is equipped with $M$ antennas, resulting in a number of $MN$ SR channels (links) for reception, $MN$ RD links for transmission and $MS$ SD links, as illustrated in Fig. 1. This scheme selects the best relay for reception ($R_k$) or the best relay for transmission ($R_j$) between $N$ relays (the best set of $M$ SR links among $N$ sets or the best set of $M$ RD links among $N$ sets). Similarly to the scheme proposed in [19], the MMD relay selection criterion (incorporated in Switched Max-Link), is based on the ML criterion. However, the metrics calculated by MMD are different from those of the scheme in [19], which leads to considerably better performance. MMD is also based on the worst case of the PEP and chooses the relay that has the highest minimum distance. So, it requires calculating the distance between the $N_s^M$ possible vectors of transmitted symbols.

For Switched Max-Link to work properly, it is not necessary that a certain number of buffer elements be filled with data before the system starts its normal operation. The buffers may be empty. Despite of that, in this work, for security, we considered that half of the buffer elements are filled in an initialization phase [4], by allowing the source to transmit a number of packets to the relays, before Switched Max-Link is used. During this initialization phase the relays do not transmit and the source transmits to the relay with the best set of $M$ SR links among the available relays.

In each time slot, the proposed Switched Max-Link Protocol may operate in two possible modes ("Direct Transmission" or "Max-Link"), with three options: a) work in "Direct Transmission" mode, by $S$ sending a quantity of $M$ packets directly to $D$; b) work in "Max-Link" mode, by $S$ sending a quantity of $M$ packets to $R_k$ and these packets are stored in its buffer; c) work in "Max-Link" mode, by $R_j$ forwarding a quantity of $M$ packets from its buffer to $D$. Table 1 shows the Switched Max-Link pseudo-code and the following subsections explain how this protocol works.

| TABLE I | SWITCHED MAX-LINK PSEUDO-CODE |
|---|---|
| 1: | Calculate the metric $D_{SR_i}$ \($D_{SR_i} = \| \sqrt{E_s/M} H_{s,r,k} x_i - \sqrt{E_s/M} H_{s,r,k} x_n \|_2 $; $i = 1, ..., N$; $l = 1, ..., N_M - 1$; $n = l + 1, ..., N_M$ |
| 2: | Find the minimum distance - $D_{min SR_i}$ \($D_{min SR_i} = \min (D_{SR_i})$; |
| 3: | Calculate the metric $D_{R_j D}$ \($D_{R_j D} = \| \sqrt{E_s/M} H_{r,j,d} x_i - \sqrt{E_s/M} H_{r,j,d} x_n \|_2 $; $i = 1, ..., N$; $l = 1, ..., N_M - 1$; $n = l + 1, ..., N_M$ |
| 4: | Find the minimum distance - $D_{min R_j D}$ \($D_{min R_j D} = \min (D_{R_j D})$; |
| 5: | Perform ordering on $D_{min SR_i}$ and $D_{min R_j D}$ |
| 6: | Find the maximum minimum distance (considering the buffer status) \($D_{max min SR - RD} = \max (D_{min SR_i}, D_{min R_j D})$; |
| 7: | Calculate the metric $D_{SD}$ \($D_{SD} = \| \sqrt{2E_s/M} H_{s,d} x_l - \sqrt{2E_s/M} H_{s,d} x_n \|_2 $; $l = 1, ..., N_M - 1$; $n = l + 1, ..., N_M$ |
| 8: | Find the minimum distance - $D_{min SD}$ \($D_{min SD} = \min (D_{SD})$; |
| 9: | Select the transmission mode \( D_{min SD} \geq D_{max min SR - RD}$ \( \) Operate in "Direct transmission mode"; else \( \) Operate in "Max-Link mode"; |

A. Calculation of relay selection metric

In the first step we calculate the metric $D_{SR_i}$ related to the SR channels of each relay $R_i$ in Max-Link mode:

$$D_{SR_i} = \| \sqrt{E_s/M} H_{s,r,k} x_l - \sqrt{E_s/M} H_{s,r,k} x_n \|_2 , \quad (7)$$

where "l" is different from "n", $x_l$ and $x_n$ represent each possible vector formed by $M$ symbols.

This metric is calculated for each of the $C_2^N$ (combination of $N_s^M$ in 2) possibilities. As an example, if $M = 2$ and
where \( N_s = 2 \), we have \( C_2^4 = 6 \) possibilities. Then, we store the information related to the smallest metric \((D_{\min,SR})\), for being critical (a bottleneck) in terms of performance, and thus each relay will have a minimum distance associated with its SR channels.

In the second step we calculate the metric \( D_{R_i,D} \) related to the RD channels of each relay \( R_i \):

\[
D_{R_i,D} = \left\| \frac{E_s}{M} H_{R_i,d} d x_l - \frac{E_s}{M} H_{d,R_i} d x_n \right\|^2,
\]

(8)

where "l" is different from "n". This metric is calculated for each one of the \( C_2^N \) possibilities. Then, we store the information related to the minimum distance \((D_{\min,R_i,D})\), and thus each relay will have a minimum distance associated with its RD channels.

In the third step, after calculating the metrics \( D_{\min,SR-RD} \) and \( D_{\min,R_i,D} \) for each of the relays, as described previously, we look for the largest value of the minimum distance:

\[
D_{\max,SR-RD} = \max(D_{\min,SR}, D_{\min,R_i,D}),
\]

(9)

where "i" is the index of each relay (1, 2, ..., \( N \)). Therefore, we select the relay that is associated with this \( D_{\max,SR-RD} \), considering its buffer status. This relay will be selected for reception (if its buffer is not full) or transmission (if its buffer is not empty), depending on this metric is associated with the SR or RD channels, respectively.

B. Calculation of the metric for direct transmission

In this step we calculate the metric \( D_{SD} \) related to the SD channels for the direct transmission mode:

\[
D_{SD} = \left\| \sqrt{\frac{2E_s}{M}} H_{s,d} d x_l - \sqrt{\frac{2E_s}{M}} H_{d,s} d x_n \right\|^2,
\]

(10)

where "l" is different from "n". This metric is calculated for each of the \( C_2^N \) possibilities. Then, we store the information related to the minimum distance \((D_{\min,SD})\), associated with SD channels.

C. Comparison of metrics and choice of transmission mode

After calculating all the metrics associated to the SR and RD channels, finding \( D_{\max,SR-RD} \) and calculating the metrics associated to the SD channels and finding \( D_{\min,SD} \), we compare these parameters and select the transmission mode:

- If \( D_{\min,SD} \geq D_{\max,SR-RD} \), we select "Direct transmission mode".
- Otherwise, we select "Max-Link mode".

If we do not consider the possibility of a direct SD connectivity ("Direct Transmission mode"), considering only the cooperative SR-RD connectivity ("Max-Link mode"), we have another scheme, called "MMD-Max-Link", instead of the proposed "Switched Max-Link" scheme.

\[ P(x_n \rightarrow x_l|H) = Q\left(\sqrt{\frac{E_s}{2N_0 M D'}}\right) \]

(11)

where \( N_0 \) is the AWGN noise spectrum density.

We may consider that the PEP will have its maximum value for the minimum value of \( D' \) (worst case of the PEP). So, for the worst case of the PEP (\( D_{\min}' \)), in direct SD transmissions, in each time slot, we have

\[ P(x_n \rightarrow x_l|H) = Q\left(\sqrt{\frac{E_s}{2N_0 M D_{\min}'}}\right) \]

(12)

However, for cooperative SR-RD transmissions, an approximated expression for computing the worst case of the PEP in each time slot (regardless of whether it is an SR or RD link) is given by

\[ P(x_n \rightarrow x_l|H) \approx 1 - \left(1 - Q\left(\sqrt{\frac{E_s}{2N_0 M D_{\min}'}}\right)\right)^2 \]

(13)

The advantage of the MMD algorithm compared to QN is that MMD maximizes the metric \( D_{\min}' \), and QN does not take it into account. The QN algorithm is based only on the total power of these links (as the traditional Max-Link). Its metric \( Q \) is related to the quadratic norm of each matrix \( H \), and the matrix selected by this criterion is: \( H^{QN} = \arg \max H \|H\|^2 \). Even though the QN criterion selects the relay that has the largest quadratic norm of the channel coefficients matrices, the minimum value of the PEP argument \( D_{\min}' \) associated with \( H^{QN} \), selected by the QN criterion, may be not as high as the minimum value of the PEP argument \( D_{\min}^{MMD} \) associated with \( H^{MMD} \), selected by the MMD criterion. So, we have

\[ P^{MMD}(x_n \rightarrow x_l|H^{MMD}) \leq P^{QN}(x_n \rightarrow x_l|H^{QN}) \]

(14)

where \( P^{MMD}(x_n \rightarrow x_l|H^{MMD}) \) is the PEP for the worst case in the MMD criterion and \( P^{QN}(x_n \rightarrow x_l|H^{QN}) \) is the PEP for the worst case in the QN criterion.

E. Complexity

As we have seen, the metric \( D \) may be calculated for each of the \( C_2^N \) possibilities. However, it is not necessary to calculate all of them. We may generalize the total number \( \lambda' \) of calculations of the metric \( D \), needed by the MMD criterion, for each matrix \( H \):

\[ \lambda' = WC_1^M + 2W^2C_2^M + 4W^3C_3^M + \ldots + 2^{M-1}W^MC_M^M \]

(15)

where \( W \) is the total number of different distances between the constellation symbols. If we have BPSK, \( W = 1 \), and QPSK, \( W = 3 \).

Table 1 shows the complexity of the MMD and QN criteria for a number of \( N \) relays, \( M \) antennas, considering only the cooperative transmission (not considering the direct transmission mode), and the constellation type.
TABLE II
MAXIMUM MINIMUM DISTANCE VERSUS QUADRATIC NORM - COMPLEXITY

| Operations/Criterion | Maximum | Minimum | Distance Quadratic Norm |
|----------------------|---------|---------|-------------------------|
| additions            | $2NM/((X-1)$ | $2N(M^2-1)$ |
| multiplications      | $2NM$  | $2NM^2$ |

Fig. 2. MMD-Max-Link and QN-Max-Link complexity.

Fig. 2 shows the complexity of the MMD and QN criteria, for $N = 3$ (a source, 3 relays and a destination), and BPSK. By the analysis of this result, it is observed that the complexity of the MMD criterion with $M = 2$ is not so higher than the complexity of the QN criterion. If we increase the number of antennas to $M = 3$ (or more) in each node, the complexity of MMD criterion becomes considerably higher than the complexity of QN criterion.

IV. SIMULATION RESULTS

This section illustrates and discusses the simulation results of the proposed "Switched Max-Link", the "MMD-Max-Link", the "conventional MIMO" (direct transmission, without relaying) and the Max-Link with the QN criterion ("QN-Max-Link"). QN-Max-Link with a single antenna is equal to the traditional Max-Link. We assume that the transmitted signals belong to BPSK or QPSK constellations. The 16-QAM constellation was not included in this work because of its higher complexity. Each relay is equipped with a buffer whose size is $J = 4$ packets. Note that we tested the performance for different $J$ but found that $J = 4$ is sufficient to ensure a good performance. We also assume unit power channels ($\sigma_s^2 = \sigma_{r,d}^2 = \sigma_{x,d}^2 = 1$), $N_0 = 1$ and $E_S = E_{r_j} = E$ (total energy transmitted). The transmit signal-to-noise ratio SNR ($E/N_0$) ranges from 0 to 12 dB and the performances of the transmission schemes were tested for 20000 packets, each containing 100 symbols.

Fig. 3 shows the PEP performance of the MMD-Max-Link and QN-Max-Link protocols, for $M = 2$, $N = 3$, 5 and 10, BPSK and perfect CSI. The performance of the MMD-Max-Link scheme is worse than the performance of the conventional MIMO scheme for a SNR less than 2 dB. Nevertheless, the performance of the proposed Switched Max-Link scheme is better than the performance of the conventional MIMO for a wide range of SNR values. It is observed, as expected, that the performance of the proposed Switched Max-Link scheme is better than the performance of the MMD-Max-Link scheme, as well as its resiliency in low transmit SNR conditions.

Fig. 4 shows the Switched Max-Link, the MMD-Max-Link, the QN-Max-Link and the conventional MIMO (direct transmission) BER performance comparison for $M = 2$, $N = 10$, BPSK and perfect CSI. We notice that the performance of the MMD-Max-Link scheme is worse than the performance of the conventional MIMO scheme for a SNR less than 2 dB. Nevertheless, the performance of the proposed Switched Max-Link scheme is better than the performance of the conventional MIMO for a wide range of SNR values. It is observed, as expected, that the performance of the proposed Switched Max-Link scheme is better than the performance of the MMD-Max-Link scheme, as well as its resiliency in low transmit SNR conditions.

Fig. 5 shows the Switched Max-Link, the MMD-Max-Link and the conventional MIMO BER performance comparison for $M = 2$, $N = 10$, QPSK and perfect CSI (the QN-Max-Link was not considered as its performance is worse than the performance of the proposed protocol). The performance of the MMD-Max-Link scheme is worse than the performance
of the conventional MIMO scheme for a SNR less than 6 dB. Nevertheless, the performance of the proposed Switched Max-Link scheme is better than the performance of the conventional MIMO for a wide range of SNR values. It is observed that the performance of the proposed Switched Max-Link scheme is better than the performance of the MMD-Max-Link scheme, as well as its resiliency in low transmit SNR conditions.

**Fig. 5.** Switched Max-Link, MMD-Max-Link and Conventional MIMO (direct transmission) BER performance.

**Fig. 6.** Switched Max-Link, MMD-Max-Link and Conventional MIMO (direct transmission) BER performance for imperfect channel knowledge.

Fig. 6 shows the Switched Max-Link, the MMD-Max-Link and the conventional MIMO BER performance comparison for $M = 2$, $N = 10$, BPSK and imperfect channel knowledge ($\beta = 1$, $\alpha = 0.5$ and $\alpha = 0.8$). As in the case of perfect channel knowledge, the performance of the proposed Switched Max-Link scheme is better than the performance of the conventional MIMO for a wide range of SNR values. It is observed that the performance of the proposed Switched Max-Link scheme is still better than the performance of the MMD-Max-Link scheme, as well as its resiliency in low transmit SNR conditions.

**V. CONCLUSIONS**

In this paper we have presented the benefits of using buffers and multiple antennas for the design of half-duplex decode-and-forward relaying protocols in cooperative communication systems, by using the MMD relay selection criterion, based on the ML criterion and the PEP. Moreover, a new cooperative protocol using multiple antennas that combines the concept of switching and the concept of selection of the best link used by Max-Link and incorporates the MMD selection criterion has been proposed. The proposed Switched Max-Link was evaluated experimentally and outperformed the conventional direct transmission and the existing QN Max-Link scheme.

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