Study of Switched Max-Link Buffer-Aided Relay Selection for Cooperative MIMO Systems

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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 Max-Link protocol that is named Switched Max-Link. We also introduce a novel relay selection criterion based on the maximum likelihood (ML) principle denoted maximum minimum distance that is incorporated into. Simulations are then employed to evaluate the performance of the proposed and existing techniques.

Index Terms—Cooperative communications, Relay-selection, Max-Link, ML estimation

I. INTRODUCTION

In wireless networks, signal fading caused by multipath propagation is a channel damage that can be mitigated through the use of diversity [1, 2, 3]. Spatial diversity techniques are attractive as they can be combined with other forms of diversity. 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 [6, 7, 4, 5].

As cooperative communication can improve the throughput and extend the coverage of wireless communication systems, the task of relay selection serves as a building block to realize it. Simple relay schemes have been/are being included in recent/future wireless standards such as Long Term Evolution (LTE) Advanced [8] and 5G standards. 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 decode 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).

Since the relays use a prefixed schedule of transmission and reception independent of the time-varying quality of the channels in wireless systems, this may lead to performance degradation [8]. Because of the fixed schedule of transmission and reception for the relays, the system cannot exploit the best source-relay (SR) and the best relay-destination (RD) channels (the links with the highest powers). The performance could be improved if the link with the highest power could be used in each time slot. This can be achieved via a buffer-aided relaying protocol that does not have a prefixed schedule of reception and transmission for the relay. As the relay has to accumulate packets in its buffer, before transmitting, selecting the link with the largest power may not always be possible. The use of buffers provides an improved performance and new degrees of freedom for system design. However, it faces a challenge: the introduction of additional delay that must be well managed for delay-sensitive applications. Buffer-aided relaying protocols [8], [10], [9], [11], [12] require not only the acquisition of channel state information (CSI), but control of the buffer status [8]. Some possible applications of buffer-aided relaying are: vehicular, cellular, and sensor networks [8].

In Max-Max Relay Selection (MMRS) [6], 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 that the buffer of the relay selected for reception is never full and the buffer of the relay selected for transmission is never empty. It is only possible for infinite size buffers. Considering finite buffer sizes, the buffer of a relay becomes empty if the channel conditions are such that it is selected repeatedly for transmission (and not for reception) or full if it is selected repeatedly for reception (and not for transmission). To overcome this limitation, in [6] a hybrid relay selection (HRS) scheme was proposed, which is a combination of conventional BRS and MMRS. For HRS, if the buffer of the relay selected for reception is full or if the buffer of the relay selected for transmission is empty, BRS is employed; otherwise, MMRS is used. Similar to MMRS, in HRS the relays selected for reception and transmission in successive time slots may be different.

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 a protocol referred to as Max-Link [9]. 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. So each time slot is allowed to be allocated dynamically to the source or relay transmission, according to the instantaneous quality of the links and the status of the buffers. For i.i.d. links and no delay constraints, Max-Link achieves a diversity gain of 2N, which is double the diversity gain of BRS and MMRS. These relay selection protocols were developed primarily for transmission without delay constraints and relay networks with i.i.d. links. In general, a delay-constrained protocol can be obtained by limiting the size of the buffers. On the other hand, these protocols require full CSI of all links at the destination. Hence, the protocols have similar complexities and applicability [3].

In this work, we examine buffer-aided relay selection for cooperative multiple-antenna systems [36], [14]. In particular, we combine the concept of switching with the Max-Link protocol for cooperative multiple-antenna systems, which results in the proposed Switched MIMO/Max-Link relay selection technique. We also introduce the maximum minimum distance criterion for selection of multiple relays, which is based on the maximum likelihood (ML) criterion. Simulations illustrate the performance of the proposed and analyzed 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. Section IV illustrates and discusses the simulation results whereas Section V gives the concluding remarks.

II. SYSTEM DESCRIPTION

We consider a relay network with one source node, S, one destination node, D, and N half-duplex decode and forward (DF) relays, R1, ..., RN. Each relay is equipped with a buffer and each node is equipped with a quantity of M antennas, and the transmission is organized in time slots [6]. The considered system is shown in Fig. 1.

A. Assumptions

In cooperative transmissions two time slots are needed to transmit data packets from the source to the destination, as in direct transmission just one time slot will be needed to do the same, 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 or from the relay selected for transmission to the destination). For this reason, we have:

- The energy transmitted from each antenna in cooperative transmissions (from the source to the relay selected for reception) is $E_s/M$;
- The energy transmitted from each antenna in cooperative transmissions (from the relay selected for transmission to the destination) is $E_r / M = E_s / M$;
- The energy transmitted from each antenna in direct transmissions (from the source to the destination) is $2 \times E_s / M$.

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. Furthermore, we assume that the relays do not communicate with each other.

B. System Description

The received signal is organized in an $M \times 1$ vector $y_{s,d}[i]$, transmitted from the antennas of the source and collected by the receive antennas of the destination as given by

$$y_{s,d}[i] = \sqrt{2E_s/M}H_{s,d}x[i] + n_d[i], \quad (1)$$

where $E_s$ represents the total energy of the symbols transmitted from the source per time slot, $x$ represents the vector formed by $M$ symbols of the different packets being sent by each of the antennas of the source (a symbol of each packet). $H_{s,d}$ 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.

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

$$y_{s,r_k}[i] = \sqrt{E_{s}/M}H_{s,r_k}x[i] + n_{r_k}[i], \quad (2)$$

where $E_s$ represents the total energy of the symbols transmitted from the source per time slot, $x$ represents the vector formed by $M$ symbols of the different packets being sent by each of the antennas of the source (a symbol of each packet), $r_k$ 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

$$y_{r_j,d}[i] = \sqrt{E_{r_j}/M}H_{r_j,d}\hat{x}[i] + n_d[i], \quad (3)$$

where $E_{r_j}$ represents the total energy of the decoded symbols transmitted from the relay selected for transmission $r_j$ per time slot, $\hat{x}[i]$ is the vector formed by $M$ previously decoded symbols in the relay selected for reception and stored in its buffer and now transmitted by the relay selected for transmission $r_j$, $H_{r_j,d}$ is the $M \times M$ matrix of $R_jD$ links and $n_d$ is the AWGN at the destination receiver.

At the relays, we employ the maximum likelihood (ML) receiver:

$$\hat{x}[i] = \arg \min_{\hat{x}[i]} \left(\| y_{s,r_k}[i] - \sqrt{E_s/M}H_{s,r_k}x[i] \|^2 \right), \quad (4)$$
where $x'[i]$ represents each possibility of the vector formed by $M$ symbols. As an example, if $m = 2$, $x'[i]$ may be $[0 \ 0]^T$, $[0 \ 1]^T$, $[1 \ 0]^T$ or $[1 \ 1]^T$.

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

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

$$\hat{x}[i] = \arg\min_{x'[i]} \left\| y_{r_j,d}[i] - \sqrt{E_s/M}H_{r_j,d}x'[i] \right\|^2, \quad (6)$$

The ML receiver of the DF relay looks for an estimate of the square root of $x'[i]$, symbols. As an example, if $SD$ depending on the transmission ($[0 \ 1]^T$, $[1 \ 0]^T$, $[2 \ 7]^T$, $[5 \ 4]^T$, $[3 \ 2]^T$) or $R_iD$ (considering BPSK). 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 ($13$, $16$, $17$, $18$, $19$, $20$, $21$, $59$, $54$, $27$, $24$, $23$, $21$, $20$, $19$, $8$, $9$, $22$, $20$, $21$, $31$, $34$, $33$, $34$, $35$, $36$, $14$, $37$).

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, $D$, $N$ half-duplex DF relays, $R_1,...,R_N$, and the same number of $M$ antennas in each node ($N_s = N_a_r = N_a_d = M$), forming a number of $M \times N$ source-relay (SR) channels (links) for reception, $M \times N$ relay-destination (RD) links for transmission and $M$ direct source-destination links, as illustrated in Fig. 1 [13].

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). The relay selection criterion is based on the ML criterion and looks for the maximum minimum distance, which corresponds to choosing the relay that has the highest minimum distance and requires calculating the distance between the $2^m$ possible vector of transmitted symbols:

In each time slot, the proposed Switched Max-Link Relay Selection Protocol may operate in two possible modes ("Direct Transmission" or "Max-Link"), so this scheme has three options:

- a) work in "Direct Transmission" mode, by the source sending a quantity of $M$ packets directly to the destination;
- b) work in "Max-Link" mode, by the source sending a quantity of $M$ packets to the relay selected for reception and these packets are stored in its buffer;
- c) work in "Max-Link" mode, by the relay selected for transmission forwarding a quantity of $M$ packets from its buffer to the destination node.

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 |
|---|---|
| $D_{min} = []; \quad$ for $i=1:N \quad D_{SR} = []; \quad$ for $l=1:2^M - 1 \quad D_{SR_{Rl}} = \sqrt{E_s/M}H_{s,r_l}x_l; \quad D_{SD} = \sqrt{E_s/M}H_{s,d}x_n); \quad$ end $\quad D_{minSR_{Rl}} = min(D_{SR})$; $\quad D_{min} = [D_{min} \ D_{minSR_{Rl}}]$; end $\quad$ [distance,indice] = sort([D_{min}]); if indice$(2 \times N) \leq N \quad k = indice(2 \times N)$; else $k = indice(2 \times N) - N$; end $\quad$ $D_{maxminSR-RD} = max(distance)$; $\quad D_{SR} = []; \quad$ for $l=1:2^M - 1 \quad D_{SR} = \sqrt{E_s/M}H_{s,r_l}x_l; \quad D_{SR} = \sqrt{E_s/M}H_{s,d}x_n); \quad$ end $\quad D_{minSD} = min(D_{SD})$; if $D_{minSD} \geq D_{maxminSR-RD} \quad$ mode = "Direct transmission"; else $\quad$ mode = "Max-Link mode"; end |

A. Calculation of relay selection metric

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

$$D_{SR_{Rl}} = \sqrt{E_s/M}H_{s,r_l}x_l - \sqrt{E_s/M}H_{s,d}x_n; \quad (7)$$
where "1" is different from "n", \( x_i \) and \( x_n \) represent each possibility of the vector formed by \( M \) symbols. As an example, if \( M = 2 \), \( x_n \) and \( x_i \) may be \([0 \ 0]^T\), \([0 \ 1]^T\), \([1 \ 0]^T\) or \([1 \ 1]^T\).

This metric is calculated for each one of the \( C_2^M \) (combination of \( 2^M \) in 2) possibilities. So, in the example (if \( M = 2 \)), we have \( C_2^2 = 6 \) possibilities. After calculating this metric for each of the possibilities, we store the information related to the smallest metric (\( D_{\text{min} \text{RD}} \)), for being critical (a bottleneck) in terms of performance, and thus each relay will have a minimum distance associated with its SD channels.

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

\[
D_{R_i, D} = \left\| \sqrt{E_s/M} \mathbf{H}_{r,d} x_i - \sqrt{E_s/M} \mathbf{H}_{r,d} x_n \right\|^2,
\]

where "1" is different from "n". This metric is calculated for each one of the \( C_2^M \) possibilities. After calculating this metric for each of the possibilities, we store the information related to the minimum distance (\( D_{\text{min} \text{RD}} \)), and thus each relay will have a minimum distance associated with its RD channels.

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

\[
D_{\text{max} \text{Min} \text{RD}-\text{RD}} = \max(D_{\text{min} \text{SR}}, D_{\text{min} \text{RD}}),
\]

where "i" is the index of each relay (1,2,...,N). Therefore, we select the relay that is associated with this \( D_{\text{max} \text{Min} \text{RD}-\text{RD}} \). This relay will be selected for reception or transmission, depending on this metric is associated with the SR or RD channels, respectively. Note that most quantities are assumed known but for parameter estimation techniques the reader is referred to [38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70], [71, 72, 73]

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:

\[
D_{SD} = \left\| \sqrt{E_s/M} \mathbf{H}_{s,d} x_i - \sqrt{2E_s/M} \mathbf{H}_{s,d} x_n \right\|^2,
\]

where "1" is different from "n". This metric is calculated for each of the \( C_2^M \) possibilities. After calculating this metric for each of the possibilities, we store the information related to the minimum distance (\( D_{\text{min} \text{SD}} \)), 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 \( D_{\text{max} \text{Min} \text{SR}-\text{RD}} \) and calculating the metrics associated to the SD channels and finding \( D_{\text{min} \text{SD}} \), we compare these parameters and select the transmission mode:

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

If we do not consider the possibility of operating in "Direct Transmission" mode (considering only the "Max-Link" mode), we have the "Max-Link" scheme instead of the proposed "Switched Max-Link" scheme. Section IV illustrates and discusses the simulation results of the proposed "Switched Max-Link", the "Max-Link" and the "conventional MIMO" (direct transmission) schemes.

IV. SIMULATION RESULTS

The proposed Switched Max-Link scheme is considered in a network with a source node, ten relays (\( N = 10 \)) and one destination node and \( M \) antennas in each node, forming a number of \( 10 \times M \) SR links for reception and \( 10 \times M \) RD links for transmission. Each relay has its buffer size equal to 20 packets. We have considered the maximum minimum distance as the relay selection criterion. Since each packet received by the relay is not necessarily transmitted to the destination in the next time slot, it was necessary to insert in the preamble of each packet the order information (its position in the binary format, ranging from 1 to 10000).

We assume that the transmitted signals belong to a BPSK constellation, that we have unit power channels (\( \sigma_r^2 = \sigma_{r,d}^2 = \sigma_s^2 = 1 \)), \( N_0 = 1 \) (AWGN noise power) and \( E_s = E_s = E \) (total energy transmitted per time slot). The transmit signal-to-noise ratio SNR (\( E/N_0 \)) ranges from 0 to 16 dB and the performances of the transmission schemes were tested for 10000 packets, each containing 100 symbols.

Fig. 2 shows the Switched Max-Link, the Max-Link and the conventional MIMO (direct transmission) BER performance comparison. By the analysis of this result, it is observed that the performance of the Max-Link scheme with 3 antennas is worse than the performance of the conventional MIMO scheme for a SNR less than 7 dB. Nevertheless, the performance of the proposed Switched Max-Link scheme was quite better than the performance of the conventional direct transmission) for almost the total range of SNR tested. It is observed, as expected, that the performance of the proposed Switched Max-Link scheme was better than the performance of the the Max-Link scheme, with \( M \) equal to 2 and 3. So we decided to simulate the proposed scheme and compare it’s performance with the performance of the conventional MIMO for other values of \( M \).

Fig. 3 shows the Switched Max-Link and the conventional direct transmission BER performance comparison. By the analysis of this result, it is observed, as expected, that the performance of the proposed Switched Max-Link scheme was quite better than the performance of the conventional MIMO (direct transmission) to the same number of antennas, with \( M \) equal to 1, 2 and 4. It is also observed that by increasing the number of antennas, a considerable improvement in BER performance is obtained for the direct transmission scheme, but it did not happen for the proposed scheme.

It is observed that by increasing the number of antennas in the proposed scheme, the BER performance falls a bit. To illustrate this, we will talk about what happens when we increase the number of antennas from 1 to 2. The Switched
Max-Link scheme, when operating with only 1 antenna on each node, seeks and selects the best channel for reception or transmission among the 20 channels (the best SR channel among 10 of them or the best RD channel among 10 of them), or select the SD channel if it worthwhiles. Otherwise, with two antennas, this scheme seeks and selects the best pair of channels for reception or transmission between 20 pairs (the best pair of SR channels among 10 of them or the best pair of RD channels among 10 of them), or select the pair of SD channels if it worthwhiles. So it may occur that even choosing the best pair of channels, the metric (maximum minimum distance) obtained by operating with 2 antennas may be not so good as the metric obtained by operating with only 1 antenna. This has been checked experimentally.

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, introducing a new relay selection criterion called maximum minimum distance based on the ML criterion. Moreover, a new cooperative protocol using multiple antennas that combines switching and Max-Link called Switched Max-Link has been proposed. The performance of the proposed "Switched Max-Link" was evaluated experimentally and outperformed the conventional direct transmission and the existing Max-Link scheme.

REFERENCES

[1] J. N. Laneman; D. N. C. Tse; G. W. Wornell, "Cooperative Diversity in Wireless Networks: Efficient Protocols and Outage Behavior", 2004.
[2] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity – parts I and II," IEEE Trans. Communication., vol. 51, no. 11, pp. 1927-1948, November 2003.
[3] T. M. Cover, "Capacity Theorems for the Relay Channel," IEEE Transactions on Information Theory, Vol IT-25, NO 5, September 1979.
[4] T. Peng, R. C. de Lamare and A. Schmeink, "Adaptive Distributed Space-Time Coding Based on Adjustable Code Matrices for Cooperative MIMO Relaying Systems," in IEEE Transactions on Communications, Vol. 58, no. 8, October 2009, pp. 4129 - 4140.
[5] T. Wang, R. C. de Lamare and P. D. Mitchell, "Low-Complexity Set-Membership Channel Estimation for Cooperative Wireless Sensor Networks," in IEEE Transactions on Vehicular technology, vol. 60, no. 6, pp. 2594-2607, July 2011.
[6] A. Ikhlef, D. S. Michalopoulos and R. Schober, "Max-Max Relay Selection for Relays with Buffers," in IEEE Transactions on Wireless Communications, vol. 11, no. 3, pp. 1124-1135, March 2012.
[7] T. Hesketh, R. C. De Lamare and S. Wales, "Joint maximum likelihood detection and link selection for cooperative MIMO relay systems," in IET Communications, vol. 8, no. 14, pp. 2489-2499, Sept. 25 2014.
[8] N. Zlatanov, A. Ikhlef, T. Islam and R. Schober, "Buffer-aided cooperative communications: opportunities and challenges," in IEEE Communications Magazine, vol. 52, no. 4, pp. 146-153, April 2014.
[9] I. Krikidis, T. Charalambous, and J. Thompson, "BufferAided Relay Selection for Cooperative Diversity Systems Without Delay Constraints," IEEE Trans. Wireless Commun., vol. 11, no. 5, May 2012, pp. 1957-67.
[10] N. Nomikos et al., "A Survey on Buffer-Aided Relay Selection," in IEEE Communications Surveys and Tutorials, vol. 18, no. 2, pp. 1073-1097, Secondquarter 2016.
[11] T. Peng and R. C. de Lamare, "Adaptive Buffer-Aided Distributed Space-Time Coding for Cooperative Wireless Networks," in IEEE Transactions on Communications, vol. 64, no. 5, pp. 1888-1900, May 2016.
[12] J. Gu, R. C. de Lamare and M. Huemer, "Buffer-Aided Physical-Layer Network Coding With Optimal Linear Code Designs for Cooperative Networks," in IEEE Transactions on Communications, vol. 66, no. 6, pp. 2560-2575, June 2018.
[13] P. Clarke and R. C. de Lamare, "Transmit Diversity and Relay Selection Algorithms for Multicell Cooperative MIMO Systems," in IEEE Transactions on Vehicular Technology, vol. 61, no. 3, pp. 1084-1098, March 2012.
[14] W. Zhang et al., "Large-Scale Antenna Systems With UL/DL Hardware Mismatch: Achievable Rates Analysis and Calibration," in IEEE Transactions on Communications, vol. 63, no. 4, pp. 1216-1229, April 2015.
[15] R. C. de Lamare, R. Sampayo-Neto, "Adaptive MBER decision feedback multiuser receivers in frequency selective fading channels", IEEE Communications Letters, vol. 7, no. 2, Feb. 2003, pp. 73 - 75.
[16] A. Rontogiannis, V. Kekatos, and K. Berberidis, "A Square-Root Adaptive V-BLAST Algorithm for Fast Time-Varying MIMO Channels," IEEE Signal Processing Letters, Vol. 13, No. 5, pp. 265-268, May 2006.
[17] R. C. de Lamare, R. Sampayo-Neto, A. Hjorungnes, “Joint iterative interference cancellation and parameter estimation for CDMA systems", IEEE Communications Letters, vol. 11, no. 12, December 2007, pp. 916 - 918.
[18] Y. Cai and R. C. de Lamare, "Adaptive Space-Time Decision Feedback Detectors with Multiple Feedback Cancellation", IEEE Transactions on Vehicular Technology, vol. 58, no. 8, October 2009, pp. 4129 - 4140.
[19] J. W. Choi, A. C. Singer, J Lee, N. I. Cho, "Improved linear soft-input soft-output detection via soft feedback successive interference cancellation," IEEE Trans. Commun., vol.58, no.3, pp.986-996, March 2010.
[20] R. C. de Lamare and R. Sampayo-Neto, "Blind adaptive MIMO receivers for space-time block-coded DS-CDMA systems in multipath channels using the constant modulus criterion," IEEE Transactions on Communications, vol.58, no.1, pp.21-27, January 2010.
[21] R. Fa, R. C. de Lamare, "Multi-Branch Successive Interference Cancellation for MIMO Spatial Multiplexing Systems", IET Communications, vol. 5, no. 4, pp. 484 - 494, March 2011.
[22] R.C. de Lamare and R. Sampayo-Neto, "Adaptive reduced-rank equalization algorithms based on alternating optimization design techniques for MIMO systems," IEEE Trans. Veh. Technol., vol. 60, no. 6, pp. 2482-2494, July 2011.
[23] P. Li, R. C. de Lamare and R. Fa, "Multiple Feedback Successive Interference Cancellation Detection for Multisuer MIMO Systems," IEEE Transactions on Wireless Communications, vol. 10, no. 8, pp. 2434 - 2439, August 2011.
[24] P. Clarke and R. C. de Lamare, "Transmit Diversity and Relay Selection Algorithms for Multicell Cooperative MIMO Systems" IEEE Transactions on Vehicular Technology, vol.61, no. 3, pp. 1084-1098, October 2012.
[25] R.C. de Lamare, R. Sampayo-Neto, "Minimum mean-square error iterative successive parallel arbitrated decision feedback detectors for DS-CDMA systems," IEEE Trans. Commun., vol. 56, no. 5, May 2008, pp. 778-789.
[26] R. C. de Lamare and R. Sampayo-Neto, "Reduced-Rank Adaptive Filtering Based on Joint Iterative Optimization of Adaptive Filters", IEEE Signal Processing Letters, Vol. 14, no. 12, December 2007.
[27] R. C. de Lamare and R. Sampayo-Neto, "Adaptive reduced-rank equalization algorithms based on alternating optimization design techniques for MIMO systems," IEEE Trans. Veh. Technol., vol. 60, no. 6, pp. 2482-2494, July 2011.
[28] P. Li, R. C. de Lamare and J. Liu, "Adaptive Decision Feedback Detection with Parallel Interference Cancellation and Constellation Constraints for Multisuer MIMO systems", IET Communications, vol.7, 2012, pp. 538-547.
[29] J. Liu, R. C. de Lamare, "Low-Latency Reweighted Belief Propagation Decoding for LDPC Codes," IEEE Communications Letters, vol. 16, no. 10, pp. 1660-1663, October 2012.
[30] C. T. Healy and R. C. de Lamare, "Design of LDPC Codes Based on Multipath EMD Strategies for Progressive Edge Growth," IEEE Transactions on Communications, vol. 64, no. 8, pp. 3208-3219, Aug. 2016.
[31] P. Li and R. C. de Lamare, Distributed Iterative Detection With Reduced Message Passing for Networked MIMO Cellular Systems, IEEE Transactions on Vehicular Technology, vol.63, no.6, pp. 2947-2954, July 2014.
[32] A. G. D. Uchoa, C. T. Healy and R. C. de Lamare, “Iterative Detection and Decoding Algorithms For MIMO Systems in Block-Fading Channels Using LDPC Codes,” IEEE Transactions on Vehicular Technology, 2015.

[33] R. C. de Lamare, "Adaptive and Iterative Multi-Branch MMSE Decision Feedback Detection Algorithms for Multi-Antenna Systems", IEEE Trans. Wireless Commun., vol. 14, no. 10, October 2015.

[34] A. G. D. Uchoa, C. T. Healy and R. C. de Lamare, "Iterative Detection and Decoding Algorithms for MIMO Systems in Block-Fading Channels Using LDPC Codes,” IEEE Transactions on Vehicular Technology, vol. 65, no. 4, pp. 2735-2741, April 2016.

[35] Y. Cai, R. C. de Lamare, B. Champagne, B. Qin and M. Zhao, "Adaptive Reduced-Rank Receiver Processing Based on Minimum Symbol-Error-Rate Criterion for Large-Scale Multiple-Antenna Systems,” in IEEE Transactions on Communications, vol. 63, no. 11, pp. 4185-4201, Nov. 2015.

[36] R. C. de Lamare, "Massive MIMO Systems: Signal Processing Challenges and Future Trends”, Radio Science Bulletin, December 2013.

[37] Z. Shao, R. C. de Lamare and L. T. N. Landau, "Iterative Detection and Decoding for Large-Scale Multiple-Antenna Systems with 1-Bit ADCs,” IEEE Wireless Communications Letters, 2018.

[38] L. L. Scharf and D. W. Tufts, “Rank reduction for modeling stationary signals.” IEEE Transactions on Acoustics, Speech and Signal Processing, vol. ASPP-35, pp. 350-355, March 1987.

[39] A. M. Haimovich and Y. Bar-Ness, “An eigenanalysis interference canceler,” IEEE Trans. on Signal Processing, vol. 39, pp. 76-84, Jan. 1991.

[40] D. D. Pados and S. N. Batalama “Joint space-time auxiliary vector filtering for DS/CDMA systems with antenna arrays” IEEE Transactions on Communications, vol. 47, no. 9, pp. 1406 - 1415, 1999.

[41] J. S. Goldstein, I. S. Reed and L. L. Scharf “A multistage representation of the Wiener filter based on orthogonal projections” IEEE Transactions on Information Theory, vol. 44, no. 7, 1998.

[42] Y. Hua, M. Nikpour and P. Stoica, "Optimal reduced rank estimation and filtering," IEEE Transactions on Signal Processing, pp. 457-469, Vol. 49, No. 3, March 2001.

[43] M. L. Honig and J. S. Goldstein, “Adaptive reduced-rank interference suppression based on the multistage Wiener filter,” IEEE Transactions on Communications, vol. 50, no. 6, June 2002.

[44] E. L. Santos and M. D. Zoltowski, “On Low Rank MVDR Beamforming using the Conjugate Gradient Algorithm”, Proc. IEEE International Conference on Acoustics, Speech and Signal Processing, 2004.

[45] Q. Haoli and S.N. Batalama, “Data record-based criteria for the selection of an auxiliary vector estimator of the MMSE/MVDR filter”, IEEE Transactions on Communications, vol. 51, no. 10, Oct. 2003, pp. 1700 - 1708.

[46] R. C. de Lamare and R. Sampaio-Neto, “Reduced-Rank Adaptive Filtering Based on Joint Iterative Optimization of Adaptive Filters”, IEEE Signal Processing Letters, Vol. 14, no. 12, December 2007.

[47] Z. Xu and M.K. Tsatsanis, “Blind adaptive algorithms for minimum variance CDMA receivers,” IEEE Trans. Communications, vol. 49, No. 1, January 2001.

[48] R. C. de Lamare and R. Sampaio-Neto, “Low-Complexity Variable Step-Size Mechanisms for Stochastic Gradient Algorithms in Minimum Variance CDMA Receivers”, IEEE Trans. Signal Processing, vol. 54, pp. 2302 - 2317, June 2006.

[49] C. Xu, G. Feng and K. S. Kwak, “A Modified Constrained Constant Modulus Approach to Blind Adaptive Multituser Detection,” IEEE Trans. Communications, vol. 49, No. 9, 2001.

[50] Z. Xu and P. Liu, “Code-Constrained Blind Detection of CDMA Signals in Multipath Channels,” IEEE Sig. Proc. Letters, vol. 9, No. 12, December 2002.

[51] R. C. de Lamare and R. Sampaio Neto, “ Blind Adaptive Code-Constrained Constant Modulus Algorithms for CDMA Interference Suppression in Multipath Channels”, IEEE Communications Letters, vol. 9, no. 4, April 2005.

[52] L. Landau, R. C. de Lamare and M. Haardt, “Robust adaptive beamforming algorithms using the constrained constant modulus criterion,” IET Signal Processing, vol.8, no.5, pp.447-457, July 2014.

[53] R. C. de Lamare, “Adaptive Reduced-Rank LCMV Beamforming Algorithms Based on Joint Iterative Optimisation of Filters,” Electronics Letters, vol. 44, no. 9, 2008.

[54] R. C. de Lamare and R. Sampaio-Neto, “Adaptive Reduced-Rank Processing Based on Joint and Iterative Interpolation, Decimation and Filtering”, IEEE Transactions on Signal Processing, vol. 57, no. 7, July 2009, pp. 2503-2514.

[55] R. C. de Lamare and Raimundo Sampaio-Neto, “Reduced-rank Interference Suppression for DS-CDMA based on Interpolated FIR Filters”, IEEE Communications Letters, vol. 9, no. 3, March 2005.

[56] R. C. de Lamare and R. Sampaio-Neto, “Adaptive Reduced-Rank MMSE Filtering with Interpolated FIR Filters and Adaptive Interpolators”, IEEE Signal Processing Letters, vol. 12, no. 3, March, 2005.

[57] R. C. de Lamare and R. Sampaio-Neto, “Adaptive Interference Suppression for DS-CDMA Systems based on Interpolated FIR Filters with Adaptive Interpolators in Multipath Channels”, IEEE Trans. Vehicular Technology, Vol. 56, no. 6, September 2007.

[58] R. C. de Lamare, “Adaptive Reduced-Rank LCMV Beamforming Algorithms Based on Joint Iterative Optimisation of Filters,” Electronics Letters, 2008.

[59] R. C. de Lamare and R. Sampaio-Neto, “Reduced-rank adaptive filtering based on joint iterative optimization of adaptive filters”, IEEE Signal Process. Lett., vol. 14, no. 12, pp. 980-983, Dec. 2007.

[60] R. C. de Lamare, M. Haardt, and R. Sampaio-Neto, “Blind Adaptive Constrained Reduced-Rank Parameter Estimation based on Constant Modulus Design for CDMA Interference Suppression”, IEEE Transactions on Signal Processing, June 2008.

[61] M. Yukawa, R. C. de Lamare and R. Sampaio-Neto, “Efficient Acoustic Echo Cancellation With Reduced-Rank Adaptive Filtering Based on Selective Decimation and Adaptive Interpolation,” IEEE Transactions on Audio, Speech, and Language Processing, vol.16, no. 4, pp. 696-710, May 2008.

[62] R. C. de Lamare and R. Sampaio-Neto, “Reduced-rank space-time adaptive interference suppression with joint iterative least squares algorithms for spread-spectrum systems,” IEEE Trans. Vehi. Technol., vol. 59, no. 3, pp. 1217-1228, Mar. 2010.

[63] R. C. de Lamare and R. Sampaio-Neto, “Adaptive reduced-rank equalization algorithms based on alternating optimization design techniques for MIMO systems,” IEEE Trans. Vehi. Technol., vol. 60, no. 6, pp. 2482-2494, Jul. 2011.

[64] R. C. de Lamare, L. Wang, and R. Fa, “Adaptive reduced-rank LCMV beamforming algorithms based on joint iterative optimization of filters: Design and analysis,” Signal Processing, vol. 90, no. 2, pp. 640-652, Feb. 2010.

[65] R. Fa, R. C. de Lamare, and L. Wang, “Reduced-Rank STAP Schemes for Airborne Radar Based on Switched Joint Interpolation, Decimation and Filtering Algorithm,” IEEE Transactions on Signal Processing, vol.58, no.8, Aug. 2010, pp.4182-4194.

[66] L. Wang and R. C. de Lamare, “Low-Complexity Adaptive Step Size Constrained Constant Modulus SG Algorithms for Blind Adaptive Beamforming”, Signal Processing, vol. 89, no. 12, December 2009, pp. 2503-2513.

[67] L. Wang and R. C. de Lamare, “Adaptive Constrained Constant Modulus Algorithm Based on Auxiliary Vector Filtering for Beamforming,” IEEE Transactions on Signal Processing, vol. 58, no. 10, pp. 5408-5413, Oct. 2010.

[68] L. Wang, R. C. de Lamare, M. Yukawa, “Adaptive Reduced-Rank Constrained Constant Modulus Algorithms Based on Joint Iterative Optimization of Filters for Beamforming,” IEEE Transactions on Signal Processing, vol. 58, no. 6, pp. 2983-2997, June 2010.

[69] L. Wang and R. C. de Lamare, “Adaptive constrained constant modulus algorithm based on joint iterative optimization of filters for beamforming,” IEEE Transactions on Signal Processing, vol. 60, no. 1, pp. 2589-2597, January 2012.

[70] L. Wang and R. C. de Lamare, “Adaptive constrained constant modulus algorithm based on auxiliary vector filtering for beamforming,” IEEE Transactions on Signal Processing, vol. 58, no. 10, pp. 5408-5413, October 2010.

[71] R. Fa and R. C. de Lamare, “Reduced-Rank STAP Algorithms using Joint Iterative Optimization of Filters,” IEEE Transactions on Aerospace and Electronic Systems, vol.47, no.3, pp.1668-1684, July 2011.

[72] Z. Yang, R. C. de Lamare and X. Li, “L1-Regularized STAP Algorithms With a Generalized Sidelobe Canceller Architecture for Airborne Radar,” IEEE Transactions on Signal Processing, vol.60, no.2, pp.674-686, Feb. 2012.

[73] Z. Yang, R. C. de Lamare and X. Li, “Sparsity-aware space-time adaptive processing algorithms with L1-norm regularisation for airborne radar,” IET signal processing, vol. 6, no. 5, pp. 413-423, 2012.
Fig. 2. Switched Max-Link, Max-Link and Conventional multiple-antenna (direct transmission) BER performance.

Fig. 3. Switched Max-Link and Conventional MIMO (direct transmission) BER performance comparison.