Opportunistic Relay Selection for Cooperative Networks with Buffers

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***Abstract*—In this paper, a relay selection policy is proposed that fully exploits the flexibility offered by the buffering ability of the relay nodes in order to maximize the achieved diversity gain. The suggested scheme incorporates the instantaneous strength of the wireless links as well as the status of the finite relay buffers and adapts the relay selection decision on the strongest available link by dynamically switching between relay reception and transmission. We show that the proposed relay selection scheme significantly outperforms conventional relay selection policies for all cases and ensures a diversity gain equal to two times the number of relays for large buffer sizes.**

I. Introduction

We focus on a simple decode-and-forward (DF) cooperative network where a source communicates with a destination through a set of half-duplex relay nodes with the objective of performance optimisation. For this fundamental problem, the $\max-\min$ relay selection scheme [1], [2], where the selected relay holds the strongest end-to-end relaying path, achieves the optimal performance and ensures a full diversity equal to the number of the relays. However, this relay selection policy refers to a two-slot cooperative transmission where the selected relay receives the source's data during the first time slot and immediately in the next time slot forwards the data towards the destination. In order to overcome this limitation imposed by the $\max-\min$ selection scheme, recently in [3] the authors introduced data buffers at the relay nodes that allow the selection of a different relay for reception and transmission in order to extract further diversity gains. In that work, the $\max-\max$ relay selection scheme that selects the relay with the strongest source-relay channel and the strongest relay-destination channel for reception and transmission, respectively, has been investigated. The $\max-\max$ scheme refers to applications without critical *delay constraints* and provides a significant coding gain in comparison to the conventional $\max-\min$ selection scheme. However, despite the efficient use of the channel fading and the related performance benefits, the $\max-\max$ relay selection policy requires a predefined schedule for the relaying transmission (e.g., the second slot is always allocated for relaying) and therefore the available diversity degrees are not fully exploited. It is worth noting that the use of buffers in order to boost the achieved performance (in terms of throughput) has been reported in the literature in different contexts ([4]–[7] and references therein).

In this paper, we propose a new relay selection scheme, called the $\max-\text{link}$, that overcomes the above limitation of the $\max-\max$ relay selection policy and fully exploits the available *diversity degrees* offered by the wireless channels through intelligent and dynamic switching between source and relay transmission. At each slot the relay with the strongest available link is selected either for transmission or reception. The relay selection decision incorporates the instantaneous quality of the wireless links as well as the status of the finite relay buffers (e.g., full, empty, neither full nor empty) and adapts the slot allocation accordingly. We prove that the $\max-\text{link}$ relay selection achieves a significant coding gain for the low buffer sizes while it provides diversity gains as the buffer size increases. In addition, for high (but finite) buffer sizes, it achieves a full diversity gain that it is equal to two times the number of the relays; this result makes the proposed scheme an attractive and practical solution for applications without latency constraints. It is worth noting that the $\max-\text{link}$ relay selection scheme handles the cases that finite-relay buffers are full or empty without any structural modification; previous solutions overcome these cases either by changing the protocol in use [3, Sec. II. D] or by assuming infinite buffers at the relays [4].

The remainder of the paper is organised as follows. Section II introduces the system model and presents the basic assumptions made. Section III introduces the $\max-\text{link}$ relay selection policy. The state Markovian channel model and the theoretical framework for the computation of the outage probability is presented in Section IV. Some illustrative examples are also presented in Section V for better visualisation of the proposed scheme, whereas numerical results are shown and discussed in Section VI, followed by concluding remarks in Section VII.

II. System model

We assume a simple cooperative network consisting of one source S, one destination D and a cluster $\mathcal{C}$ with K DF relays $R_k \in \mathcal{C}$ $(1 \leq k \leq K)$. All nodes are characterised by the half-duplex constraint and therefore they cannot transmit and receive simultaneously. A direct link between the source and the destination does not exist (the channel gain between source and destination is in deep fading) and communication can be established only via relays (i.e., [1], [3]). Each relay R_k holds a data buffer (data queue) Q_k of finite size L (in number of data elements) where it can store data coming from the source that have been decoded at the relay and can be forwarded to the destination. Fig. 1 schematically presents the system model. At the beginning of the transmission each relay

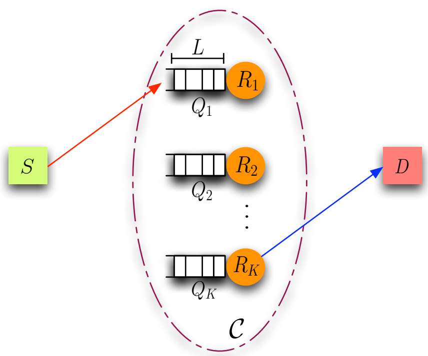

Fig. 1. The system model: Source S communicates with Destination D via a cluster of relays $R_k \in \mathcal{C}$ $(1 \leq k \leq K)$.

buffer is empty and the function $0 \leq \Psi(Q_k) \leq L$ gives the number of data elements that are stored in buffer Q_k. The buffer size $\Psi(Q_k)$ is increased by one when a source packet (data) is correctly decoded at the k-th relay and it is decreased by one in case of a successful k-th relay transmission. Time is considered to be slotted and each transmitter X (either the source S or relays R_k) transmits with a fixed power P. The source node is assumed to be saturated (infinite data backlog at the source) and the information rate is equal to r_0 bits per channel use (BPCU). The retransmission process is based on an Acknowledgement/Negative-Acknowledgement (ACK/NACK) mechanism, in which short-length error-free packets are broadcasted by the receivers Y (either a relay R_k or the destination D) over a separate narrow-band channel in order to inform the network of that packet's reception status.

In order to simplify the analysis, we assume that the clustered relay configuration ensures independent and identically distributed (i.i.d.) channel links that means equivalent average Signal-to-Noise Ratios (SNRs) for the links $S \rightarrow R_k$ and $R_k \rightarrow D$ [8]. Although this assumption simplifies the analysis and it is used in several studies in the literature [9]–[11], it can be implemented by an appropriate long-term routing process which selects the clustered nodes to be closed together [10], [11]. All wireless links exhibit fading and Additive White Gaussian Noise (AWGN). The fading is assumed to be stationary, with frequency non-selective Rayleigh block fading. This means that the fading coefficients $h_{i,j}$ (for the $i \rightarrow j$ link) remain constant during one slot, but change independently from one slot to another according to a circularly symmetric complex Gaussian distribution with zero mean and unit variance. Furthermore, the variance of the AWGN is assumed to be normalised with zero mean and unit variance and therefore the SNR for each link is equal to P. Each link $i \rightarrow j$ is characterised by the success probability $p \triangleq \mathbb{P}\{(1/2)\log_2(1+P|h_{i,j}|^2) \geq r_0\}$ which denotes the probability that the link $i \rightarrow j$ is not in outage ($\overline{p} = 1-p$ denotes the outage probability); the factor $1/2$ captures the fact that communication is performed in two time slots [3]. An outage occurs when the instantaneous capacity of the link $i \rightarrow j$ is lower than the transmitted spectral efficiency rate r_0. Finally, we assume that the destination node has a perfect channel and buffer state information and selects the relays for transmission and reception through an error-free feedback channel [3]. This assumption can be ensured by an appropriate signalling that provides global channel state information (CSI) at the destination node. On the other hand, the destination can trivially know the status of the relay buffers by monitoring the ACK/NACK signalling and the identity of the transmitting/receiving relay.

III. The $\max-\text{link}$ Relay Selection Policy

The $\max-\min$ [1], [2] and the $\max-\max$ [3] relay selection schemes are associated with a two-slot cooperative protocol where the schedule for the source and relay transmission is fixed a priori. Here, we relax this limitation and we allow each slot to be allocated dynamically to the source or a relay transmission, according to the instantaneous quality of the links and the status of the relays' buffers. More specifically, the proposed $\max-\text{link}$ relay selection scheme exploits fully the flexibility offered by the buffers at the relay nodes and at each slots it selects the strongest link for transmission (source or relay transmission) among the available links. A source-relay link is considered to be available when the corresponding relay node is not full and therefore can receive data from the source, while a relay-destination link is considered to be available when the relay node is not empty and thus can transmit source's data towards the destination. The proposed scheme compares the quality of the available links and adjusts the relay selection decision and the time slot allocation to the strongest link. If a source-relay link is the strongest link, the source transmits and the corresponding relay is selected for reception; on the other hand, if a relay-destination link is the strongest link, the corresponding relay is selected for transmission. The $\max-\text{link}$ relay selection policy can be analytically expressed as follows:

$$R^* = \arg\max_{R_k \in \mathcal{C}} \left\{ \bigcup_{R_k^a} \left\{ |h_{S,R_k}|^2 \right\} \bigcup_{R_k^e} \left\{ |h_{R_k,D}|^2 \right\} \right\}, \quad (1)$$

where R^* denotes the selected relay (either for transmission or reception), $R_k^a \triangleq R_k \in \mathcal{C} : \Psi(Q_k) \neq L$, and $R_k^e \triangleq R_k \in \mathcal{C} : \Psi(Q_k) \neq 0$.

For the $\max-\text{link}$ relay selection policy the outage probability is defined as the probability that the selected link is in outage, i.e.,

$$P_{\text{out}} \triangleq \begin{cases} \mathbb{P}\left(\frac{1}{2}\log_2(1+P|h_{S,R^*}|^2) < r_0\right) & \text{(reception);} \\ \mathbb{P}\left(\frac{1}{2}\log_2(1+P|h_{R^*,D}|^2) < r_0\right) & \text{(transmission).} \end{cases}$$

In order to be able to analyse the $\max-\text{link}$ relay selection policy, we model the possible states of the buffers and the transitions between the states as a MC. A state of the MC represents the number of elements at each buffer and thus $s_l \triangleq \big(\Psi(Q_1)\Psi(Q_2)\ldots\Psi(Q_K)\big)$ denotes the l-th state of the MC with $l \in \mathbb{N}_+$, $1 \le l \le (L+1)^K$. The states are predefined in a random way as all the possible combinations ($(L+1)^K$ combinations) of the buffer sizes and are considered as a data input for the investigated algorithm given in Section IV. The use of the MC model for the analysis of the $\max-\text{link}$ selection policy in terms of outage probability is presented in the next section.

IV. Model and outage probability analysis

In this Section, we deal with the outage probability analysis of the $\max-\text{link}$ relay selection policy and we introduce a theoretical framework that constructs the state transition matrix and calculates the outage probabilities (this performance metric is also used for the evaluation of the $\max-\max$ relay selection in [3]).

A. Construction of the state transition matrix of the MC

Let $\mathbf{A}$ denote the $(L+1)^K \times (L+1)^K$ state transition matrix of the MC, in which the entry $\mathbf{A}_{i,j} = \mathbb{P}\big(s_j \to s_i\big) = \mathbb{P}\big(X_{t+1} = s_i | X_t = s_j\big)$ is the transition probability to move from state s_i at time t to state s_j at time $(t+1)$. The transition probabilities depend on the status of the relay buffers (number of full elements at each buffer) and the related number of the available links that participate in the relay selection decision. More specifically, a relay node with a full or empty data buffer ($\Psi(Q_k) = L$ or $\Psi(Q_k) = 0$) cannot receive or transmit data, respectively, and therefore for both cases it offers only one link in the selection process; when $\Psi(Q_k) = L$ the k-th relay offers the link $R_k \to D$ and when $\Psi(Q_k) = 0$ it offers the link $S \to R_k$. Otherwise, the relay node can be used either for transmission or reception and thus it offers two links for selection ($S \to R_k, R_k \to D$). Consequently, for the s_l state of the buffers, the total number of the available links that participate in the $\max-\text{link}$ selection process is equal to $D_l = \sum_{i=1}^{K} \Phi\big(Q_i\big)$, where $\Phi\big(Q_i\big) = 2$ if $0 < \Psi(Q_i) < L$, or 1, otherwise.

In order to construct the state transition matrix $\mathbf{A}$, we need to identify the connectivity between the different states of the buffers. For each time slot, the buffer status can be modified as follows: (a) the number of elements of one relay buffer can be decreased by one, if a relay node is selected for transmission and the transmission is successful, (b) the number of elements of one buffer can be increased by one, if the source node is selected for transmission and the transmission is successful and (c) the buffer status remains unchanged in case of outage (e.g., either the source has been selected for transmission and the selected source-relay link was in outage or a relay has been selected for transmission and the relay-destination link was in outage). In order to formulate the above buffer state connectivity, we define for the s_l state the associated set U_l given by

$$U_l = \Bigg\{ \bigcup_{1 \le i \le (L+1)^K} s_i : \mathbf{s}_i - \mathbf{s}_l \in \mathcal{Q} \Bigg\}, \tag{2}$$

where $\mathbf{s}_l$ denotes a $1 \times K$ vector with entries the number of elements stored at each buffer for the s_l state and $\mathcal{Q} \triangleq \{\bigcup_{1 \le j \le K} \pm \boldsymbol{I}_{j,\bullet}\}$, where $\boldsymbol{I}_{j,\bullet}$ netoes the j-th row of the identity matrix. The set U_l contains all the buffer states that are connected to the state s_l based on the previous connectivity rule. As for the computation of the corresponding transition probabilities, we should take into account that a transition from one state to another one requires a) the selection of the corresponding channel link by the $\max-\text{link}$ selection process and b) the selected link not be in outage (e.g., successful transmission). Given our assumption for i.i.d. symmetric channel links, for the s_l buffer state, the probability to select a specific link is equal to $1/D_l$ and the probability that the selected link is not in outage can be calculated by using order statistics (the maximum among D_l i.i.d. exponential random variables); therefore the probability to leave from the state s_l is equal to

$$p_{D_l} \triangleq \frac{1}{D_l}\left[1 - \left(1 - \exp\left(-\frac{2^{2r_0}-1}{P}\right)\right)^{D_l}\right]. \tag{3}$$

On the other hand the probability to have an outage event and therefore no change in the buffer status is equal to

$$\overline{p}_{D_l} \triangleq 1 - \sum_{i=1}^{D_l} p_{D_l} = \left(1 - \exp\left(-\frac{2^{2r_0}-1}{P}\right)\right)^{D_l}. \tag{4}$$

By using the previous notation, the entries of the state transition matrix are given as

$$\mathbf{A}_{i,j} = \begin{cases} \overline{p}_{D_j} & \text{if } s_i \notin U_j \\ p_{D_j} & \text{if } s_i \in U_j \\ 0 & \text{elsewhere} \end{cases}, \quad \text{for} \quad i,j \in \{1,\ldots,(L+1)^K\} \tag{5}$$

B. Steady state distribution of the MC

We are interested in finding the stationary distribution, denoted as $\boldsymbol{\pi}$, of the MC and hence, explore how the data are being sent across the relays and the long-term share of the resources.

Proposition 1. *The state transition matrix* $\mathbf{A}$ *of the MC that models the buffer states is SIA (Stochastic Irreducible and Aperiodic).*

Proof: See [12]. ■

Proposition 2. *The state transition matrix* $\mathbf{A}$ *of the MC that models the buffer states is reversible.*

Proof: See [12]. ■

In Lemma 1, the symmetry arising due to the structure of the problem as well as the reversibility property (Proposition 2) are exploited in order to find an efficient way to calculate the steady states of the MC. Let Θ_i denote the set of states i for which the steady state probability is the same. Let $\Xi(j,\Theta_i)$ denote the states that state j has to pass through to reach a state $i \in \Theta_i$, with the state in Θ_i included; i.e., if from state i to a state that belongs in Θ_j, say l, we go through a state k, then $\Xi(i,\Theta_j) = \{k,l\}$.

Lemma 1. *The steady state for each state $i \in \Theta_i$ is given by*

$$\boldsymbol{\pi}_i = \left(\sum_{j=1}^{(L+1)^K} \frac{\prod_{k \in \Xi(i,\Theta_j)} \mathbf{A}_{i,k}}{\prod_{m \in \Xi(j,\Theta_i)} \mathbf{A}_{j,m}} \right)^{-1}. \qquad (6)$$

Proof: See [12]. ■

C. Derivation of the outage probability

By using the steady state of the MC and the fact that an outage event occurs when there is no change in the buffer status, the outage probability of the system is

$$P_{\text{out}} = \sum_{i=1}^{(L+1)^K} \boldsymbol{\pi}_i \overline{p}_{D_i} = \text{diag}(\mathbf{A})\boldsymbol{\pi}. \qquad (7)$$

The expression (7) shows that the construction of the state matrix $\mathbf{A}$ and the computation of the related steady state $\boldsymbol{\pi}$ consists of a simple theoretical framework for the computation of the outage probability for the $\max - \text{link}$ relay selection scheme with finite buffers. For large L an expression of the outage probability is proposed in Section V-B.

V. Illustrative Examples

In order to visualise the proposed approach for the computation of the achieved outage probability, we apply the proposed analysis to special, illustrative cases.

A. A simple example with $K = 2$ relays and $L = 2$

In this section, we apply the proposed analysis for a simple clustered topology with $K = 2$ relays and $L = 2$. In this case the state MC that captures the evolution of the buffers is presented in Fig. 2. The corresponding state transition matrix $\mathbf{A}$ becomes equal to

$$\mathbf{A} = \begin{pmatrix} \overline{p}_2 & p_3 & p_3 & 0 & 0 & 0 & 0 & 0 & 0 \\ p_2 & \overline{p}_3 & 0 & p_2 & p_4 & 0 & 0 & 0 & 0 \\ p_2 & 0 & \overline{p}_3 & 0 & p_4 & p_2 & 0 & 0 & 0 \\ 0 & p_3 & 0 & \overline{p}_2 & 0 & 0 & p_3 & 0 & 0 \\ 0 & p_3 & p_3 & 0 & \overline{p}_4 & 0 & p_3 & p_3 & 0 \\ 0 & 0 & p_3 & 0 & 0 & \overline{p}_2 & 0 & p_3 & 0 \\ 0 & 0 & 0 & p_2 & p_4 & 0 & \overline{p}_3 & 0 & p_2 \\ 0 & 0 & 0 & 0 & p_4 & p_2 & 0 & \overline{p}_3 & p_2 \\ 0 & 0 & 0 & 0 & 0 & 0 & p_3 & p_3 & \overline{p}_2 \end{pmatrix}. \qquad (8)$$

The steady state of the system for different values of SNR can be found by using the method described in IV-B.

B. Case with buffers of infinite size ($L \to \infty$)

As presented in Section IV-A, the total number of buffer states is equal to $(L+1)^K$. However, from these $(L+1)^K$ states, $(L-1)^K$ states are neither full nor empty. In what follows, we show that for large L the $(L-1)^K$ states dominate the system and for $L \to \infty$ the probability of being in one of these states approaches 1. Hence, as the buffer size L increases the MC approaches a symmetric matrix and therefore the steady state converges to a uniform distribution; as a result the steady state probabilities become equal. The total outage probability is approximated as

$$P_{\text{out}} = \left(\frac{L-1}{L+1}\right)^K \overline{p}_{2K} + \sum_{i=1}^{K} \frac{2^i \binom{K}{i} (L-1)^{K-i}}{(L+1)^K} \overline{p}_{2K-i}. \qquad (9)$$

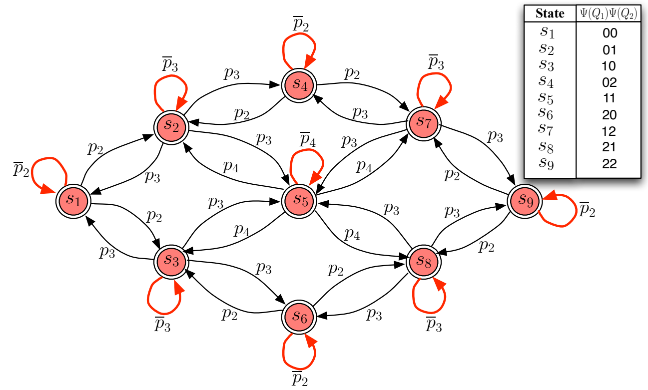

Fig. 2. State diagram of the MC representing the states of the buffers and the transitions between them for a case with $K = 2$ relays and $L = 2$.

For the extreme case with infinite buffer sizes $L \to \infty$, the outage probability is simplified to $P_{\text{out}}^{\infty} = \overline{p}_{2K}$. The expression shows that for infinite buffer sizes, the $\max - \text{link}$ relay selection policy always selects between $2K$ available links (all the links become available) and therefore it ensures a full diversity equal to two times the number of the relays. Simulation results given in the next Section corroborate our analysis, since they demonstrate that for large (but finite) values of L the actual outage probability closely approximates the above bound.

VI. Numerical Results

The relay selection policies considered are: the non-selection policy (where a fixed relay is selected for relaying), the $\max - \min$ relay selection, the $\max - \max$ relay selection (lowest bound) and the investigated $\max - \text{link}$ relay selection; the selection bound which refers to an ideal $\max - \text{link}$ selection scheme where all the channel links are always available for selection is used as a reference scheme.

In Fig. 3 we plot the outage probability versus the SNR for a simulation setting with $K = 2$ relays, $L = 2$ and $r_0 = 1$ BPCU. As it can be seen, both the $\max - \min$ and the $\max - \max$ selection policies achieve a diversity gain equal to the number of relays (e.g., 2), while the $\max - \max$ (bound) scheme offers an additional coding gain equal to 1.5 dB in comparison to the $\max - \min$ scheme at high SNRs; this observation is in line with the analysis presented in [3]. On the other hand, the proposed $\max - \text{link}$ selection policy also achieves a diversity gain equal to $K = 2$ and outperforms the $\max - \max$ (bound) policy with a gain of about 4 dB. It is worth noting that this gain concerns the optimal $\max - \max$ policy (lowest bound) and therefore the gain for a practical version of the $\max - \max$ should be higher. This result shows that the $\max - \text{link}$ selection strategy uses more efficiently the existence of the relay buffers and significantly outperforms the existing selection schemes. However, it is worth noting that for the assumed buffer size $L = 2$, the $\max - \text{link}$ does not provide a further diversity gain in comparison to the $\max - \min$ and $\max - \max$ schemes due to the small buffer size; on the other hand the selection bound provides a diversity gain equal to $2K$. Furthermore, Fig. 3 depicts the theoretical outage probability performance that has been presented in Section IV, since the theoretical curve (Eq. (7)) perfectly matches to our simulation results validating the accuracy of our analysis.

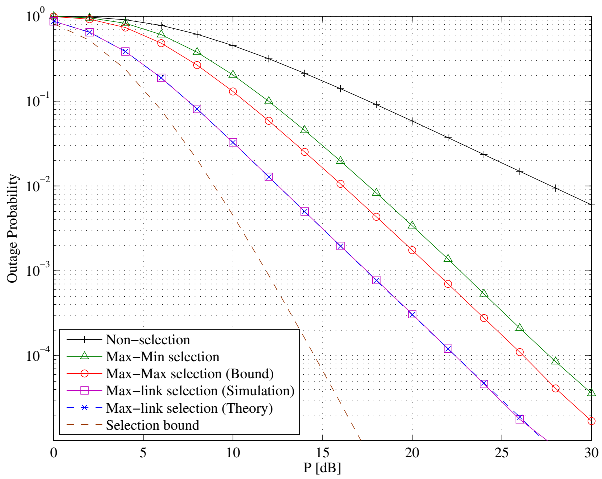

Fig. 3. Outage probability performance versus SNR (P) for a simulation setting with $K = 2$ relays, $L = 2$ and $r_0 = 1$ BPCU.

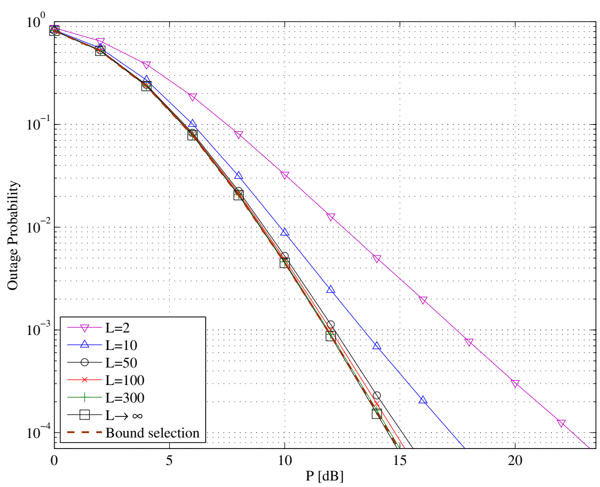

Fig. 4. Outage probability performance versus SNR (P) for $\max - \mathrm{link}$ relay selection with $K = 2$ relays, $L = 2, 10, 50, 100, 300, \infty$ and $r_0 = 1$ BPCU.

Fig. 4 focuses on the $\max - \mathrm{link}$ selection scheme and shows the impact of the buffer size on the achieved diversity gain. More specifically, Fig. 4 plots the outage probability performance versus the SNR for different buffer sizes ($L = 2, 10, 50, 100, \infty$) and for the previously used simulation parameters ($K = 2$ relays, $r_0 = 1$ BPCU). As the buffer size increases the outage probability performance is improved and approaches the selection bound that offers a diversity gain equal to 4. For a small increase of the buffer size (e.g., $L = 10$ packets), the $\max - \mathrm{link}$ relay selection achieves a diversity gain higher than 2 (the slope of the curve becomes steeper) and therefore it significantly outperforms its previous version with $L = 2$ (i.e., 5 dB gain for an outage probability equal to 10^{-3}). Furthermore, as the size of the buffers increases the diversity order is continuously improved and for $L = 100$ it approximates the selection bound and achieves a full diversity equal to 4; for the ideal case of $L \to \infty$, the $\max - \mathrm{link}$ relay selection policy matches the selection bound, an observation that follows the discussion presented in Section V-B. These remarks reveal the potential of the proposed $\max - \mathrm{link}$ selection and shows that a quite small buffer size (low complexity) can double the diversity gain in comparison to the existing relay selection schemes.

VII. Conclusions

In this paper, $\max - \mathrm{link}$ relay selection policy has been proposed for cooperative networks with finite buffers at the relay nodes. Unlike conventional approaches, the proposed scheme exploits fully the buffering capability at the relays and schedules transmissions only through the strongest available channel link in order to extract further diversity benefits. A methodology that models the buffer evolution as a MC has been adopted and the achieved outage probability performance of the system has been derived in closed form. The $\max - \mathrm{link}$ relay selection scheme outperforms previously reported schemes by providing a significant coding gain for small buffer sizes, while it ensures a diversity gain approaching the upper-bound of two-times the number of relays for large buffer sizes.

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