Nomikos, Nikolaos; Charalambous, Themistoklis; Vouyioukas, Demosthenes; Karagiannidis, George K.

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Low-Complexity Buffer-Aided Link Selection with Outdated CSI and Feedback Errors

Nikolaos Nomikos, *Member, IEEE*, Themistoklis Charalambous, *Member, IEEE*, Demosthenes Vouyioukas, *Member, IEEE*, George K. Karagiannidis, *Fellow, IEEE*

***Abstract*—Buffer-aided relays can improve the diversity of multi-hop networks, however, they increase packet delays. Thus, various delay-aware protocols have been developed, but without considering the transmission diversity. Moreover, most works adopt ideal assumptions, such as symmetric links, perfect Channel State Information (CSI) and error-free feedback channels. So, we propose a Low-Complexity (LoCo) link selection algorithm, herein called $\mathrm{LoCo-Link}$. The proposed algorithm may experience delays during CSI updates, and hence, by using outdated CSI its performance may deteriorate. To alleviate this issue, we next propose a distributed version of $\mathrm{LoCo-Link}$ ($\mathrm{d-LoCo-Link}$) dealing with outdated CSI. In both algorithms, the source performs broadcasting towards multiple relays; when the packets are transmitted by a relay to the destination, they are discarded from all other relays. This coordination relies on feedback channels. For non error-free feedback channels, we propose a scheme in which the relays listen to the transmission of the best relay and drop duplicate packets. Results show that $\mathrm{LoCo-Link}$ surpasses other algorithms, by decreasing the delay in asymmetric networks. Moreover, $\mathrm{d-LoCo-Link}$ avoids diversity losses due to outdated CSI, while the effect of non error-free feedback channels is mitigated by taking advantage of the inter-relay channels.**

***Index Terms*—Relay selection, buffer-aided relaying, delay, diversity, Markov chains, low-complexity, outdated CSI, asymmetric links, non error-free feedback.**

I. Introduction

A. Background

Cooperative relaying provides significant communication gains, such as, path-loss reduction, shadowing mitigation and link diversity improvement. The seminal work of [1], that developed a fundamental theoretical framework, triggered a furore of relaying techniques in the literature. Among those techniques, Opportunistic Relay Selection (ORS) [2], [3] and Buffer-Aided (BA) relaying (see, e.g., [4], [5] and references therein) have received considerable attention: relay-assisted cellular networks are a promising solution for enhancing the coverage of the fifth generation (5G) wireless networks.

Regarding ORS, in [6] it was proven that full diversity can be achieved without requiring multiple orthogonal channels, thus promoting spectral and energy efficiency. On the other side, BA relaying offers increased Degrees-of-Freedom (DoF) for scheduling at the cost of additional delay. The survey in [4] presented protocols combining ORS and BA relaying (hereinafter called BA–ORS protocols), outlining open challenges such as, low-complexity implementation and the naive assumptions of Channel State Information (CSI) availability and symmetric topologies. Recent studies on BA–ORS focused on outage probability reduction in delay-tolerant scenarios. The authors of [7] presented a Hybrid Relay Selection (HRS) merging the non-BA ORS protocol of [2] and the Max-Max Relay Selection (MMRS). MMRS selects two relays in one time-slot, based on the strongest Source-Relay ($\{S{\to}R\}$) and Relay-Destination ($\{R{\to}D\}$) link. It was shown that for the delay-unconstrained case, HRS offers equal diversity with non-BA ORS and additional coding gain. The $\mathrm{max-link}$ protocol with adaptive link selection was proposed by Krikidis *et al.* in [8], increasing the diversity gain of BA ORS. In $\mathrm{max-link}$, each time-slot is dedicated to either an $\{S{\to}R\}$ transmission or to an $\{R{\to}D\}$ transmission. When the number of relays K is large, a diversity gain of $2K$ can be achieved. Also, $\mathrm{max-link}$ with Source-Destination ($\{S{\to}D\}$) connectivity has been studied in [9], demonstrating a framework for switching between direct and relay transmissions.

Various works have provided delay-aware (DA) versions of HRS and $\mathrm{max-link}$. The algorithm in [10] modified HRS to maintain non-empty and balanced queues by choosing the links with the smallest (largest) data queue, among the $\{S{\to}R\}$ and $\{R{\to}D\}$ links. Tian *et al*. proposed a DA version of $\mathrm{max-link}$ in [11], prioritizing $\{R{\to}D\}$ selection. Performance evaluation showed reduced delay for low Signal-to-Noise Ratio (SNR), while for high SNR, the delay converged to two time-slots independently of the relay number or buffer size. Next, the work in [12] exploited Buffer State Information (BSI) to select the best relay, as long as buffers were not empty or full. Comparisons with $\mathrm{max-link}$ showed that for a buffer size $L \leq 3$, lower delay can be achieved. Then, in [13], two extensions of $\mathrm{max-link}$ were presented exploiting BSI. The first extension achieved low average delay by sacrificing diversity, as buffers were often empty, while the second delay- and diversity-aware extension assured that a plethora of links was available, by avoiding empty buffers. On the downside, this algorithm distributed packets to multiple buffers and when many relays were available, the delay increased. In [14] the authors presented Combined Relay Selection (CRS) for relays with small buffers. CRS selects the relay with the shortest buffer length for reception and that with the longest buffer length for transmission. Results illustrated reduced delay, compared to HRS and $\mathrm{max-link}$. MMRS and $\mathrm{max-link}$ were

N. Nomikos and D. Vouyioukas are with the Department of Information and Communication Systems Engineering, University of the Aegean, Samos, Greece. *Emails:* {nnomikos,dvouyiou}@aegean.gr.

T. Charalambous is with the Department of Electrical Engineering and Automation, School of Electrical Engineering, Aalto University, Espoo, Finland. *Email:* themistoklis.charalambous@aalto.fi.

G. K. Karagiannidis is with the Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece. *Email:* geokarag@auth.gr.

combined in [15], dividing the transmission in odd and even time-slots, selecting one relay to receive in an odd time-slot and one relay to transmit in an even time-slot. When selection fails, the protocol searches all the links to avoid outages. Results showed lower delay than $\max-\mathrm{link}$ without suffering diversity losses. Recently, the activation of multiple $\{S\to R\}$ links for BA–ORS was proposed in [16], where MMRS and $\max-\mathrm{link}$ were extended to Generalized MMRS (G-MMRS) and Generalized $\max-\mathrm{link}$ (G-ML), respectively. In these protocols, the source performs broadcasting in the first hop, reducing the delay of MMRS and $\max-\mathrm{link}$. While CSI overhead was reduced for the G-MMRS, this was not the case for the G-ML. Furthermore, in asymmetric channels with better $\{S\to R\}$ links, G-ML overflowed. This was mitigated by the balanced G-ML, introducing percentages, an approach which is not efficient and does not adapt to the network's conditions. When rate adaptation is possible, the authors in [17] derived the achievable rates for a multi-relay BA network. In addition, a BA protocol was presented to limit the average delay at the cost of rate reduction. Also, in [18], Zhou *et al*. studied stochastic throughput maximization for a single relay network with finite buffers. The analysis showed that the optimal link selection policy is defined by a queue length threshold in order to exploit the transmission opportunities in both links. In addition, a threshold-based approach has been proposed in [19] aiming to choose relays whose buffers are not on the brink of starvation. In this way, diversity was shown to be preserved.

A critical element of BA–ORS is the timely acquisition and processing of CSI. Nonetheless, the majority of BA–ORS protocols neglect the fact that the CSI used for selection, in several occasions is outdated. For non-BA ORS, various works studied the effect of outdated CSI. In [20], the outage probability of ORS with DF relays was analyzed concluding that for completely outdated CSI, the diversity of ORS was equal to that of a single relay network for high SNR values. However, for low and medium SNR, a coding gain was observed, compared to single relay networks. Next, Verde *et al.* [21] proposed a low-complexity decentralized scheme for recruiting relays without requiring acknowledgements. Performance evaluation showed that distributed coordination and selection, based on statistical CSI mitigated the effect of outdated CSI. Similarly, the authors in [22] exploited statistical CSI to reduce outages in asymmetric two-hop relay networks. Soysa *et al.* in [23] investigated the performance of partial and ORS with outdated CSI. From the analysis it was concluded that partial relay selection outperforms ORS for low correlation between the actual and the outdated CSI. Recently, Islam *et al.* in [24] studied the effect of outdated CSI on BA relaying. It was shown that even for outdated CSI, adaptive link selection offered coding gain compared to non-BA DF relaying. Finally, the authors in [25] studied a single relay network deriving the optimal relay state of the relay with outdated CSI. Results revealed a trade-off between CSI acquisition overhead and CSI quality for throughput maximization.

B. Contributions

While the literature on BA–ORS is vast, most of the works adopt simplified, impractical considerations, such as, schemes with increased implementation complexity, symmetric topologies, full CSI availability and accuracy and separate error-free feedback channels. Aiming at enhancing the practical implementation of BA–ORS, in this paper:

1) We propose a Low-Complexity link ($\mathrm{LoCo}-\mathrm{Link}$) selection algorithm, based on prioritizing the transmissions in the $\{R\to D\}$ links, even if there exist $\{S\to R\}$ links with better conditions, by selecting the relay with the largest buffer length and performing broadcast $\{S\to R\}$ transmissions. $\mathrm{LoCo}-\mathrm{Link}$ provides a three-fold gain:
    a) Delay is reduced, since $\{R\to D\}$ prioritization reduces the number of time-slots that packets have to wait in the relays before being transmitted.
    b) Diversity is preserved, as broadcast $\{S\to R\}$ transmissions and the selection of the relay with the largest buffer length avoid buffer starvation.
    c) The complexity of $\mathrm{LoCo}-\mathrm{Link}$ is low compared to other algorithms, e.g., [8], [10], [11], [13], [16], since the CSI of the $\{S\to R\}$ links is no longer required.
2) Aiming to mitigate the effect of asymmetric link quality, a threshold-based version of LoCo-Link is presented, where a buffer threshold in terms of the number of packets is imposed. More specifically, when at least one $\{S\to R\}$ transmission can be performed, $\{R\to D\}$ transmission will be prioritized only if the buffer threshold is satisfied. On the other hand, if all the $\{S\to R\}$ links are in outage, the buffer threshold will not be activated and $\{R\to D\}$ prioritization using the relay with the largest buffer length is performed.
3) The diversity order of $\mathrm{LoCo}-\mathrm{Link}$ and all ORS protocols, in general, is severely affected by outdated CSI, resulting in identical performance to random ORS for high SNR. To avoid feedback delays rendering CSI unreliable, a fully distributed algorithm is proposed, named $\mathrm{d}-\mathrm{LoCo}-\mathrm{Link}$, relying on local CSI estimation only.
4) At the same time, broadcasting may result in duplicate packets residing in the buffers of multiple relays. In this case, one-bit feedback is not sufficient, as the ID of a successfully received packet at the destination must be made known to relays that were not selected for $\{R\to D\}$ transmission. Thus, when non error-free feedback channels are available [26], the possibility of transmitting duplicate packets in the $\{R\to D\}$ link can not be ignored. To alleviate this effect, an algorithm is proposed exploiting inter-relay channels to overhear the IDs of the transmitted packets, thus reducing duplicate packets due to non error-free feedback channels.

Performance evaluation shows that $\mathrm{d}-\mathrm{LoCo}-\mathrm{Link}$ tackles the degrading effect of feedback delays as no CSI exchange is required for successful operation. In addition, the use of inter-relay channels provides increased robustness against outages during the transmission of packet IDs and thus, duplicate transmissions are significantly reduced.

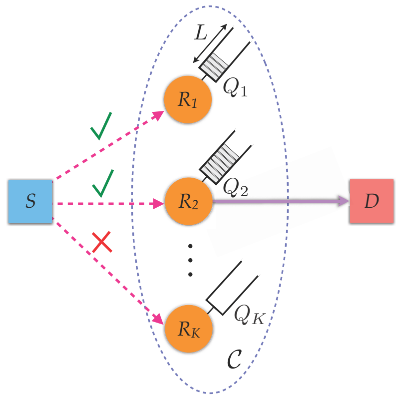

Fig. 1. A cooperative network where a source S communicates with a destination D, by broadcasting its packets towards a cluster of relays $R_k \in \mathcal{C}$, $k \in [1, K]$.

C. Structure

The remainder of this paper is organized as follows. In Section II, we introduce the system model. In Section III, we provide in detail the $\mathrm{LoCo-Link}$ link selection algorithm and present centralized and distributed implementation as well as a complexity analysis. The practical issues of outdated CSI and non error-free feedback channel with their respective solutions are discussed in Sections IV and V, respectively. Next, performance evaluation is provided in Section VI, while conclusions and future directions are given in Section VII.

II. System Model

We consider a relay-assisted network consisting of one source, S, one destination, D, and a cluster $\mathcal{C}$ of K Half-Duplex (HD) Decode-and-Forward (DF) relays $R_k \in \mathcal{C}$ $(1 \leq k \leq K)$. Due to severe fading, the direct link between the source and the destination does not exist and communication is established via relays. Each relay R_k is equipped with a buffer Q_k of size L denoting the maximum number of data elements that can be stored from the source's transmissions. The system model is depicted in Fig. 1. To transmit data to the relays, the source selects to broadcast its packets and so, depending on channel quality one or more relays might be able to receive them. Fig. 1 illustrates a successful reception with a green tick, while an unsuccessful reception is illustrated by a red ✕ mark. Next, we present four different scenarios regarding the availability of CSI and feedback channel reliability:

1. perfect CSI and error-free feedback channel;
2. perfect CSI and non error-free feedback channel;
3. outdated CSI and error-free feedback channel;
4. outdated CSI and non error-free feedback channel.

A. Perfect CSI

The quality of the wireless channels is degraded by Additive White Gaussian Noise (AWGN) and frequency non-selective Rayleigh block fading, according to a complex Gaussian distribution with zero mean and variance σ_{ij}^2 for the $\{i \rightarrow j\}$ link. For simplicity, the AWGN is assumed to be normalized with zero mean and unit variance. The channel gain, $g_{ij} \triangleq |h_{ij}|^2$, is assumed to be exponentially non-identically distributed, as is the case of asymmetric topology.

The source node is assumed to be saturated (it has always data to transmit) and the information rate, when the transmission is successful, is fixed and equal to r_0. Equivalently, a transmission from a transmitter to its corresponding receiver is successful if the SNR of the receiver is greater or equal to a threshold γ_0, called the *capture ratio*. The value of γ_0 depends on the modulation and coding characteristics of the application. So, the transmission from a transmitter i to its corresponding receiver j is successful (error-free) if the SNR of the receiver j, denoted by γ_j, is greater or equal to the *capture ratio* γ_0. The variance of thermal noise at relay R_j is denoted by η_j and it is assumed to be AWGN. The transmission is divided in time-slots of equal length and at each time-slot, the source S or one of the relays R_k attempts to transmit a packet using a fixed power level P_i (note that the power level for each transmitting node may differ due to network deployment using heterogeneous devices). Therefore,

$$\gamma_j(P_i) \triangleq \frac{g_{ij}P_i}{\eta_j} \geq \gamma_0. \tag{1}$$

On the contrary, link $\{i \rightarrow j\}$ is in outage if $\gamma_j(P_i) < \gamma_0$, i.e., $\frac{g_{ij}P_i}{\eta_j} < \gamma_0$, and the probability of outage is given by

$$p_{\text{out}} = \mathbb{P}\left[g_{ij} < \frac{\gamma_0 \eta_j}{P_i}\right]. \tag{2}$$

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 over a separate narrow-band channel.

Regarding the CSI availability, it is considered that only CSI at the receiver (CSIR) is available, thus allowing low-complexity network coordination. Also, as CSIR is assumed, the channel connectivity state is known at each receiver.

Let $\mathbf{b}_{SR} \triangleq (b_{SR_1}, b_{SR_2}, \ldots, b_{SR_K})$ and $\mathbf{b}_{RD} \triangleq (b_{R_1D}, b_{R_2D}, \ldots, b_{R_KD})$ be the binary representation of the feasible links due to the fulfilment of the channel conditions (i.e., if transmission on link R_iD is possible, then $b_{R_iD} = 1$). Similarly, let $\mathbf{q}_{SR} \triangleq (q_{SR_1}, q_{SR_2}, \ldots, q_{SR_K})$ and $\mathbf{q}_{RD} \triangleq (q_{R_1D}, q_{R_2D}, \ldots, q_{R_KD})$ be the binary representation of the feasible links due to the fulfilment of the queue conditions (i.e., for a $\{S \rightarrow R\}$ link the buffer is not full and for a $\{R \rightarrow D\}$ link the buffer is not empty). By $\mathcal{F}_{SR}$ and $\mathcal{F}_{RD}$, we denote the sets of $\{S \rightarrow R\}$ and $\{R \rightarrow D\}$ links that are feasible having cardinalities of F_{SR} and F_{RD} respectively.

B. Outdated CSI

In practical systems, the CSI used for the selection of a link is different from the one during the transmission in that link, because of the delays inherited by the feedback mechanism. More specifically, CSI may be outdated due to channel variations during the period from the end of the estimation and the start of the actual transmission [20] or because it may not be fed-back constantly, in order to avoid excessive coordination overhead [24].

The case of having wireless nodes with outdated CSI is also considered herein and its effect on the proposed link selection algorithm is investigated. In a system, where CSI feedback might be delayed, the actual channel response h_{ij} conditioned on the channel response $\hat{h}_{ij}$ that was estimated in the $\{i \rightarrow j\}$ link, during the selection process is given by [20]

$$h_{ij} | \hat{h}_{ij} \sim \mathcal{CN}(\rho_i \hat{h}_{ij}, 1 - \rho_i^2), \tag{3}$$

where $\rho_i \in [0, 1)$ denotes the correlation coefficient between h_{ij} and $\hat{h}_{ij}$. In ORS networks, it has been shown that outdated CSI has a degrading effect on the diversity of the network. In [20], it was proved that independently of the number of the available relays, a diversity order equal to one is obtained. So, the network performance reduces to that of single relay networks or to random relay selection, even when $\rho_i \approx 1$ for asymptotically high SNR values. When the Jakes' model is assumed [27], ρ_i is given by $\rho_i = J_0(2\pi f_{d_i} T_{D_i})$, where f_{d_i} is the Doppler frequency, T_{D_i} is the delay between link selection and the start of information transmission and $J_0(\cdot)$ is the zero-order Bessel function of the first kind.

C. Feedback channel with error

In the majority of studies, separate and error-free feedback channels are assumed (e.g. [2], [3], [8]). In these works unicast transmissions were assumed activating each time one relay for data reception or transmission. On the contrary, herein, broadcast transmissions in the $\{S \rightarrow R\}$ link are adopted providing increased possibilities of successful packet reception by the relays. In this way, the diversity of the $\{R \rightarrow D\}$ transmissions can be improved. However, when the destination receives a packet, its ID must be fed-back to the relays, in order to drop this packet from their buffer and avoid duplicate transmissions. As a result, one-bit feedback is not sufficient in this case and the consideration of non error-free feedback channels is of practical importance.

In order to enhance the practicality of the proposed algorithms, we adopt the framework of [26], where the transmit and feedback channels are assumed to be correlated. Thus, in this case, relays experiencing an outage in their respective $\{R \rightarrow D\}$ link are not able to know which packet was received at that time-slot by the destination as the packet ID will not be successfully fed-back to them. In this work, we provide additional discussions and a solution for the case of non-error free feedback channels by exploiting the inter-relay channels during the transmission of the best relay.

III. The $\mathrm{LoCo-Link}$ algorithm

Here, the proposed centralized algorithm, $\mathrm{LoCo-Link}$, is described, in which it is assumed that perfect CSI can be acquired and exchanged through central coordination, and the feedback channels are error-free.

A. Centralized Implementation

The $\mathrm{LoCo-Link}$ link selection algorithm aims at improving the performance of buffer-aided relay networks in terms of delay based on a low-complexity implementation. The centralized implementation of the algorithm is as follows:

1) Contrary to $\max-\mathrm{link}$, where the selection of the best link was performed among the $2K$ available ones, $\mathrm{LoCo-Link}$ prioritizes the $\{R \rightarrow D\}$ link, by activating in each time-slot the $\{R \rightarrow D\}$ link that is in $\mathcal{F}_{RD}$ and has the maximum queue length. If more than one relays have the same maximum queue length, then a link among them is randomly chosen.
2) If no $\{R \rightarrow D\}$ link is available due to severe fading or because all buffers are empty, the source broadcasts its packets to all the relays in the first hop. So, more than one relays forming the set $\mathcal{F}_{SR}$ might be able to receive and store the source's packet. As a result, in the next time-slot, the possibility of activating an $\{R \rightarrow D\}$ link is increased compared to the original $\max-\mathrm{link}$ or the delay-aware algorithm of [11] where only one relay receives the source's packet in the $\{S \rightarrow R\}$ link.

The $\mathrm{LoCo-Link}$ link selection algorithm for a single time-slot is summarized in Algorithm 1:

Algorithm 1 The $\mathrm{LoCo-Link}$ link selection algorithm

input $\mathcal{F}_{RD}$
if $\mathcal{F}_{RD} = \emptyset$ **then**
    The source broadcasts its value.
    $Q_j \leftarrow Q_j + 1, \quad \forall j \in \mathcal{F}_{SR}$
else
    $i' = \arg\max_{i \in \mathcal{F}_{RD}} Q_i \qquad (\{R \rightarrow D\}$ link)
    if more than one relays have the same maximum queue length **then**
        i^* is chosen randomly among the set of relays in i'.
    else
        $i^* = i'$.
    end if
    $Q_{i^*} \leftarrow Q_{i^*} - 1$
end if
Output Link $\{R_{i^*} \rightarrow D\}$ is activated or the set of links in $\mathcal{F}_{SR}$ receive a packet from the source, if $\mathcal{F}_{SR} \neq \emptyset$.

B. Threshold-based $\mathrm{LoCo-Link}$

As asymmetries in the quality of the $\{S \rightarrow R\}$ and $\{R \rightarrow D\}$ links might result in reduced diversity, due to full or empty buffers, it is important to introduce a scheme balancing the frequency with which, each link is activated. So, here, a threshold-based version of LoCo-Link is presented, where a buffer threshold in terms of the number of packets is imposed. More specifically, when the transmission through at least one $\{S \rightarrow R\}$ link can be successful, $\{R \rightarrow D\}$ prioritization will be performed only if the buffer threshold is satisfied. If more than one relays satisfy the buffer threshold, the relay having the largest buffer length is selected to perform a transmission towards destination. On the contrary, if there does not exist any $\{S \rightarrow R\}$ link that can be activated due to excessive fading, the buffer threshold is not adopted and $\{R \rightarrow D\}$ prioritization using the relay with the largest buffer length is performed. In the performance comparisons in Section VI, it can be observed that there is a trade-off between preserving the diversity, due to the balanced selection of each hop, and increasing the delay, as packets stay in the buffers for more time-slots.

C. Complexity analysis and CSI requirements

For the centralized $\mathrm{LoCo-Link}$ ($\mathrm{c-LoCo-Link}$) protocol, the CSI of the k-th RD channel together with the buffer state are transmitted to the destination by the k-th relay; alternative suggestions (see, e.g., [16]), in which each relay transmits a pilot block to the destination, which then estimates the CSI of the K $\{R\to D\}$ links, have the problem that the relays have to send the buffer state without knowing the CSI.

Remark 1. *Contrary to the algorithms where single link activation is performed in both hops,* $\mathrm{LoCo-Link}$ *demands that the destination will broadcast the successful reception of each packet. This information includes not only one-bit ACK/NACK but the packet ID as well and so, one-bit feedback is not sufficient in* $\mathrm{LoCo-Link}$.

D. Performance analysis

The theoretical analysis of this work is similar, *mutatis mutandis*, to that of [16]. More specifically, [16] builds on the framework proposed in [8], where the Discrete Time Markov Chain (DTMC) represents all the possible states of the buffers. Unlike [8], however, in which the state of the buffers depends only on the number of packets in each buffer, in this case it also matters whether or not the same packet appears in other buffers as well. This is necessary because a transmission from a relay to the destination might result to the removal of other identical packets from other relays as well. The framework developed by [16] applies to all algorithms for which the $\{S\to R\}$ link broadcasts its packets. The difference in the proposed algorithm is the values of the transition probabilities of the DTMC, due to the fact that we change the priority by which packets are transmitted. Similarly, for threshold-based $\mathrm{LoCo-Link}$, due to the threshold, the transition probabilities at each state will differ to those of Algorithm 1 and [16]. For completeness, we present the building blocks of the DTMC.

States of the DTMC. The states of the DTMC represent all the possible states of the buffers. The proposed algorithm allows a specific source packet to be stored in buffers of different relay nodes. For this reason one has to consider which packets are the same in the buffers and which are different. Hence, in the case of K relays of length L, there are KL possible packets and the state of being empty (hence, $KL+1$ in total). However, there is no analytical way to compute the number of states for the general case; for $K=L=2$, the number of states is 19 (see [16] for details). The transitions between the states are given by the probabilities of successful transmissions of packets either from the source or a relay. The state of the DTMC can be represented by $S_r \in \mathcal{S}$, where $\mathcal{S}$ is the set of all available states, $r \in \mathbb{N}$, $1 \leq r \leq |\mathcal{S}|$, and $|\mathcal{S}|$ represents the cardinality of all the possible combinations of the buffer states. The states are predefined and can be numbered in a random way and are considered as a data input for the proposed selection policy. Let $\mathcal{C}_r$ denote the set of links that can be active in the network (i.e., the links that are not excluded due to empty or full relay buffers). Then, the outage probability of the network at state r can be written as

$$\bar{p}_r = \prod_{\ell \in \mathcal{C}_r} \left(1 - \exp\left(-\frac{\gamma_0 \eta_{j(\ell)}}{P_{i(\ell)}}\right)\right), \quad (4)$$

where $i(\ell)$ (resp. $j(\ell)$) denotes the transmitter (resp. receiver) on link ℓ. Note that with this formulation, asymmetric links are considered, contrary to [16]. Due to the asymmetry of the links, the probability of having at least one link not in outage varies. Hence, the probability of having at least one link not in outage among the available links at state r is evaluated *on average*, i.e.,

$$p_r = \frac{1}{|\mathcal{C}_r|}\left[1 - \prod_{\ell \in \mathcal{C}_r} \left(1 - \exp\left(-\frac{\gamma_0 \eta_{j(\ell)}}{P_{i(\ell)}}\right)\right)\right]. \quad (5)$$

As noted in [20], since a relay or the destination has decoded the received signal successfully is independent of the link selection mechanism, (4), and hence (5), do not depend on the correlation parameters ρ_i.

Construction of the state transition matrix of the DTMC. Let $(X_t)_{t\geq 0}$ denote the discrete-time Markov random process capturing the evolution of the network as a system. Also, let $\mathbf{A} \in \mathbb{R}^{|\mathcal{S}|\times|\mathcal{S}|}$ denote the state transition matrix of the DTMC, in which the entry

$$\mathbf{A}_{i,j} = \mathbb{P}\big(S_j \to S_i\big) \triangleq \mathbb{P}\big(X_{t+1} = S_i | X_t = S_j\big)$$

is the transition probability to move from state S_j at time t to state S_i at time $(t+1)$. The transition probability matrix $\mathbf{A}$ is of paramount importance for this analytical framework, since its construction is essential for the computation of the outage probabilities. In order to construct the state transition matrix $\mathbf{A}$, we need to identify the connectivity between the different states of the system. For each time slot, the buffer status can be modified as follows: (a) the number of elements of one or more buffers can be decreased by one, if a relay node is selected for transmission, the transmission is successful, and also other relays may (or may not) have the same packet in their buffer and drop it; (b) the number of elements of one or more buffers can be increased by one, if the source node is selected for broadcasting and the transmission to at least one relay is successful; (c) the state of all buffers remains unchanged when there is an outage event (i.e., all the $\{S\to R\}$ and $\{R\to D\}$ links are in outage).

Properties of the DTMC. Due to the fact that the buffer of each relay is finite, the DTMC can be easily shown to be Stationary, Irreducible and Aperiodic (SIA) [8], i.e., a steady state (also known as the distribution of the DTMC) $\boldsymbol{\lambda}$ exists such that $\mathbf{A}\boldsymbol{\lambda} = \boldsymbol{\lambda}$ and $\mathbf{b}^T\boldsymbol{\lambda} = 1$, where $\mathbf{b} = \begin{bmatrix}1 & 1 \dots & 1\end{bmatrix}^T$. Steady-state $\boldsymbol{\lambda}$ of the column stochastic matrix $\mathbf{A}$ of the MC that models the states of the network system is given by [8, Lemma 1]

$$\boldsymbol{\lambda} = (\mathbf{A} - \mathbf{I} + \mathbf{B})^{-1}\mathbf{b}, \quad (6)$$

where $\mathbf{I}$ is the identity matrix of appropriate dimensions and $\mathbf{B}$ is a square matrix of appropriate dimensions with $\mathbf{B}_{ij} = 1$ for all i, j. The existence of a steady state distribution implies - by Little's law [28] - finite average packet delay. In what follows, we provide analytical expressions for the outage probability, average throughput and average packet delay, for our proposed algorithm, which can be used *in any policy defined for finite-length buffer-aided relay selection*.

Derivation of the outage probability. The DTMC is constructed in a way that an outage event occurs *only when there is no change in the buffer state*. Hence, the outage probability of the system is given by the sum of the product of the probabilities of being at a stage r and having an outage event, i.e.,

$$p_{\rm out} = \sum_{r=1}^{|\mathcal{S}|} \boldsymbol{\lambda}_r \overline{p}_r = {\rm diag}(\mathbf{A})\boldsymbol{\lambda}, \tag{7}$$

where $\overline{p}_r$ denotes the probability of outage when at state r and is given in (4). Eq. (7) shows that the construction of the state matrix $\mathbf{A}$ and the computation of the related steady state $\boldsymbol{\lambda}$ comprises a simple theoretical framework for the computation of the outage probability for a buffer-aided relay selection policy.

This simple yet powerful analytical framework can be also used to derive the average throughput and average packet delay, as we will see in the sequel.

Derivation of the average throughput. If there is only one transmission per time-slot (e.g., [7], [8]), the average data rate ρ is $1/2$ since two hops are required to reach the destination; in schemes with successive transmissions though, ρ is approaching 1. The proportion of the packets that make it through is $(1-p_{\rm out})$. Hence, the average throughput is given by $\mathbb{E}[T] = \rho(1-p_{\rm out})$, where $\rho \in \{1/2, 1\}$. Note that if the links are i.i.d., then the average throughput of relay R_j is given by

$$\mathbb{E}[T_j] = \frac{\rho(1-p_{\rm out})}{K}. \tag{8}$$

Derivation of the average packet delay. The delay of a packet is the duration of time between the time it arrives at a relay until the time it reaches the destination (i.e., no delay is measured when the packet resides at the source). The average packet delay under this framework was recently presented in [29]. We summarize the results herein for completeness. For i.i.d. channels, the average delay is the same on all relays. Hence, it is enough to analyze the average delay on a single relay. By Little's law, the average packet delay at relay R_j, denoted by $\mathbb{E}[d_j]$ is given by

$$\mathbb{E}[d_j] = \frac{\mathbb{E}[L_j]}{\mathbb{E}[T_j]}, \tag{9}$$

where $\mathbb{E}[L_j]$ and $\mathbb{E}[T_j]$ are the average queue length and average throughput, respectively. The average queue length at relay R_j is given by

$$\mathbb{E}[L_j] = \sum_{r=1}^{|\mathcal{S}|} \boldsymbol{\lambda}_r Q_j^{(r)}, \tag{10}$$

where $Q_j^{(r)}$ denotes the buffer size of relay R_j at state r. The average throughput is given in (8). Substituting (7), (8) and (10) into (9) we have that the average delay is given by

$$\mathbb{E}[d_j] = \frac{K\sum_{r=1}^{|\mathcal{S}|} \boldsymbol{\lambda}_r Q_j^{(r)}}{\rho\left(1-\sum_{r=1}^{|\mathcal{S}|} \boldsymbol{\lambda}_r \overline{p}_r\right)}. \tag{11}$$

Note that the proposed algorithm, as well as other protocols proposed in the literature, fit in this framework with $\rho = 1/2$.

E. Asymptotic performance

We analyze the asymptotic performance of the proposed relay selection scheme when the *average* channel SNR, denoted by ϕ, goes to infinity. Given our definition of the SNR in (1), on link $\{i \to j\}$ the transmit SNR ϕ_{ij} is given by $\phi_{ij} = \frac{P_i}{\eta_j}$. Therefore, in this case, we let the transmit power P_i tend to infinity. For our analysis, we adopt the framework used in [11]. Note that due to the broadcast nature of the $\{S \to R\}$ link, it is difficult to derive any closed-form expression for the diversity gain using the framework proposed in [30] for the case where relays have small buffer size or that in [8] for the case where the diversity gain is shown for infinite buffer length.

When $\phi \to \infty$, the probability of a $\{S \to R\}$ link being in outage goes to zero, provided the buffer is not full. Similarly, the probability of a $\{R \to D\}$ link being in outage goes to zero, provided the buffer is not empty. Following the procedure of the $\rm LoCo-Link$ scheme, the prioritization of the $\{R \to D\}$ links at high SNR makes the scheme deterministic. More specifically, for any initial state of the relay buffers, since $\{R \to D\}$ links are given priority, there will be a time, say t, at which all buffers will become empty. At the next time-slot (i.e., $t+1$), since there are no packets in the buffers, the source broadcasts *the same* packet to all relays. At the next time-slot (i.e., $t+2$), priority is given to the $\{R \to D\}$ links. Once a relay transmits the packet in its buffer, all other relays discard their packet and the relays become empty again. This procedure is repeated indefinitely. As a result, when $\phi \to \infty$, the buffers can only be at one of two possible states: the first state, denoted by S_e, corresponds to the case in which there are no packets in the buffers; the second state, denoted by S_f, corresponds to the case in which there is one packet in each of the relay buffers.

Derivation of the Asymptotic Outage Probability. In what follows, the asymptotic outage probability is derived. Given that the scheme switches between the two possible states, S_e and S_f, then as $\phi \to \infty$, (7) becomes

$$p_{\rm out}^{\infty} \triangleq \lim_{\phi\to\infty} p_{\rm out} = \mathbb{P}(S_e)\, p_{\rm out}^{S_e} + \mathbb{P}(S_f)\, p_{\rm out}^{S_f}, \tag{12}$$

where $\mathbb{P}(S_e)$ and $\mathbb{P}(S_f)$ are the probabilities that the state of the buffers are in S_e and S_f, respectively, and $p_{\rm out}^{S_e}$ and $p_{\rm out}^{S_f}$ are the outage probabilities to the corresponding states. Since, states S_e and S_f are switching continuously, the probability of being at one of the states at any given time is equal to $1/2$, i.e.,

$$\mathbb{P}(S_e) = \mathbb{P}(S_f) = \frac{1}{2}. \tag{13}$$

When the state is S_e, there are K available $\{S \to R\}$ links only. Therefore,

$$p_{\rm out}^{S_e} = \lim_{\phi\to\infty}\left(1-e^{-\frac{\gamma_0}{\phi}}\right)^K \overset{(a)}{\approx} \lim_{\phi\to\infty}\left(\frac{\gamma_0}{\phi}\right)^K, \tag{14}$$

where (a) stems from the fact that for very small x, $e^x \approx 1+x$. Similarly, when the state is S_f, there are K available $\{R \to D\}$

links and n ($n=0$ for $L=1$ and $n=K$ for $L\geq 2$) available $\{S\to R\}$ links (that are not used unless the $\{R\to D\}$ links are in outage). Therefore,

$$p_{\text{out}}^{S_f}=\lim_{\phi\to\infty}\left(1-e^{-\frac{\gamma_0}{\phi}}\right)^{K+n}\approx\lim_{\phi\to\infty}\left(\frac{\gamma_0}{\phi}\right)^{K+n}. \quad (15)$$

Substituting (13), (14) and (15) into (12), we get

$$p_{\text{out}}^{\infty}=\lim_{\phi\to\infty}\frac{1}{2}\left[\left(\frac{\gamma_0}{\phi}\right)^{K}+\left(\frac{\gamma_0}{\phi}\right)^{K+n}\right]. \quad (16)$$

Derivation of the diversity gain. Given the discussion above on where the $\mathrm{LoCo-Link}$ scheme converges for $\phi\to\infty$, at a given time-slot (say τ), the system will be at state S_e in which there are no packets in the buffers. Then, the source broadcasts *the same* packet to all relays, and in this case, the diversity gain is equal to the number of relay nodes, K. At the next time-slot (i.e., $\tau+1$), the system will be at state S_f and priority is given to the $\{R\to D\}$ links and the diversity gain is again K. Once a relay transmits the packet in its buffer, all other relays discard their packet and the relays become empty again. As a result, the expected diversity gain of the system is equal to K. In what follows, we justify the claim.

The diversity gain of the proposed relay selection scheme can be computed as follows:

$$\begin{aligned}d&=-\lim_{\phi\to\infty}\frac{\log p_{\text{out}}}{\log\phi}\\&=-\lim_{\phi\to\infty}\frac{\log\left[\frac{1}{2}\left(\left(\frac{\gamma_0}{\phi}\right)^{K}+\left(\frac{\gamma_0}{\phi}\right)^{K+n}\right)\right]}{\log\phi}. \quad (17)\end{aligned}$$

For buffer size $L=1$, then $n=0$, and therefore (17) becomes

$$\begin{aligned}d_{(L=1)}&=-\lim_{\phi\to\infty}\frac{\log\left(\frac{\gamma_0}{\phi}\right)^{K}}{\log\phi}\\&=\lim_{\phi\to\infty}\frac{K\left(\log\phi-\log\gamma_0\right)}{\log\phi}=K.\end{aligned}$$

For buffer size $L\geq 2$, then $n=K$, and therefore (17) becomes

$$\begin{aligned}d_{(L\geq 2)}&=-\lim_{\phi\to\infty}\frac{\log\left[\frac{1}{2}\left(\left(\frac{\gamma_0}{\phi}\right)^{K}+\left(\frac{\gamma_0}{\phi}\right)^{2K}\right)\right]}{\log\phi}\\&\overset{(a)}{=}-\lim_{\phi\to\infty}\frac{\log\left(\frac{\gamma_0}{\phi}\right)^{K}+\log\left[\left(1+\left(\frac{\gamma_0}{\phi}\right)^{K}\right)\right]}{\log\phi}\\&\overset{(b)}{=}K-\lim_{\phi\to\infty}\frac{\left(\frac{\gamma_0}{\phi}\right)^{K}}{\log\phi}\overset{(c)}{=}K,\end{aligned}$$

where (a) is the outcome of simple algebraic manipulations, (b) stems from the fact that for small x, $\log(1+x)\approx x$, and (c) from the fact that the limit of the second term is zero.

Remark 2. *For the threshold-based scheme, the diversity is the same since the priorities allow for a diversity gain K, despite the fact that the buffers are never emptied. This can be justified in the simulations in which the diversity gain remains the same for different buffer threshold; see, e.g., Fig. 3.*

IV. $\mathrm{LoCo-Link}$ WITH OUTDATED CSI

As is the case for all ORS protocols, outdated CSI introduces severe performance degradation to $\mathrm{LoCo-Link}$, reducing it to random relay selection. More specifically, even though broadcasting does not require the exchange of CSI from the relays to the source, the selection of the best relay in the $\{R\to D\}$ link requires timely CSI estimation and feedback. In $\mathrm{c-LoCo-Link}$, the relays transmit pilot sequences towards the destination and then, the destination estimates the CSI and notifies the relays on which one will be activated in the current time-slot. Meanwhile, the CSI used by the destination for relay activation might differ from the channel state experienced during the relay transmission.

A. *Distributed* $\mathrm{LoCo-Link}$

An alternative scheme based on distributed coordination, can safeguard the performance of $\mathrm{LoCo-Link}$ by avoiding excessive delay between CSI estimation and relay activation. For this reason, we examine a distributed implementation of the $\mathrm{LoCo-Link}$.

The distributed approach for the link selection process is based on the use of synchronized timers as proposed in [2] and elaborated with queue sizes in [10]. At first, the destination broadcasts a pilot sequence and each relay R_i, for which $q_{R_iD}=1$, estimates the $\{D\to R_i\}$ CSI. By assuming that the reciprocity property [31] of antennas holds[1], relays can estimate the $\{R_i\to D\}$ CSI. From that it can assess whether $b_{R_iD}=1$. If $b_{R_iD}q_{R_iD}=1$, then R_i participates in the competition for the slot, but in this case R_i starts a timer from a parameter based on the reciprocal of the buffer size $(Q_i+1+\nu_i)^{-1}$. The timer of the relay with the maximum buffer size will expire first. In case there exist more than one relays with the same buffer size, ν_i will again guarantee almost surely that the timers will expire on different time instances. The relay with the fastest timer and hence the largest queue size transmits a short duration flag packet, signaling its availability. All relays, while waiting for their timer to expire are also, in listening mode. As soon as they hear another relay to flag its presence or forwarding information, they back off.

If there is no short duration flag packet, it means that $\mathcal{F}_{RD}$ is an empty set. In this case, the source broadcasts a packet and all the relays in $\mathcal{F}_{SR}$ will receive it. All relays that received the packet start a timer from a parameter based on the buffer size $\max\{0,Q_i+\nu_i\}$, where ν_i is uniformly distributed in $(-0.5,0.5)$. The timer of the relay with the minimum buffer size will expire first. In case there exist more than one relays with the same size, ν_i will guarantee almost surely that the timers will expire on different times. The relay with the fastest timer and hence the smallest queue size broadcasts an ACK message, thus confirming reception of the packet by at least one relay. All other relays in $\mathcal{F}_{SR}$, while waiting for their timer to expire, are in listening mode. As soon as they hear another relay to flag its presence they do not need to send any

[1]Reciprocity technically applies only to antennas, which operate in a linear medium made of linear materials (e.g., magnetic materials that exhibit hysteresis are not linear). In general, any antenna can be assumed to be a reciprocal device.

ACK message. If both sets $\mathcal{F}_{RD}$ and $\mathcal{F}_{SR}$ are empty, then all the links are in outage and no packet is transmitted during that slot.

B. Complexity analysis and CSI requirements

For the distributed $\mathrm{LoCo-Link}$ protocol ($\mathrm{d-LoCo-Link}$), the destination broadcasts a pilot block to the K relays and each relay carries out the CSI estimation based on the received pilot block. No additional communication is required, as the decisions are taken locally.

The overhead required for the link selection for several protocols, including MMRS and $\mathrm{max-link}$, was recently investigated and compared in [16] in terms of the number of pilot transmissions, the estimated CSI, and the data transmissions (per link selection). In Table I, we use the same metrics, including also the $\mathrm{max-link}$ and Generalized $\mathrm{max-link}$ (G-ML) for comparison. It can be seen that both versions of $\mathrm{LoCo-Link}$ reduce the amount of CSI overhead, compared to other algorithms. Still, in $\mathrm{c-LoCo-Link}$ the CSI of the $\{R{\to}D\}$ links and the BSI from each relay must be transmitted to the node performing the selection. On the contrary, $\mathrm{d-LoCo-Link}$ does not incur any CSI overhead, as selection is performed by the relays in a distributed manner, taking into consideration CSI and BSI locally.

V. $\mathrm{LoCo-Link}$ with non error-free feedback channels

In the practical scenario where the transmit and feedback channels might be correlated [26], $\mathrm{LoCo-Link}$ should be modified to maintain its performance. In this case, the proposed solution exploits the inter-relay channels, thus complementing the non error-free feedback channels. More specifically, instead of turning off the $K-1$ relays that were not selected for $\{R{\to}D\}$ transmission, they could stay active during the transmission of the best relay in order to identify which packet is being transmitted to the destination. As a result, inter-relay channels that are not in outage will allow relays with duplicate packets to drop them from their buffers. On the other hand, this solution leads to additional energy consumption, but its effect could be mitigated by keeping the $K-1$ relays active until the transmission of the packet ID has finished.

The most unfavorable case arises when non error-free feedback channels exist simultaneously with outdated CSI knowledge. Thus, centralized relay selection algorithms might not be able to circumvent their combined effect. Again, distributed relay selection algorithms, such as $\mathrm{d-LoCo-Link}$ exploiting IR channels, can maintain the performance at an acceptable level. It must be noted, that the utilization of IR channels does not require any central coordination, so fully distributed implementation is possible as shown in Section IV-A.

An additional modification to IR exploitation is packet pre-dropping. More specifically, relays that do not experience good IR channels with the best relay, but can decode the one-bit flag packet transmitted by the best relay (cf. the procedure in the distributed implementation), drop the source's data, if they have also successfully received it. However, the relays with strong IR channels with the best relay do not drop the source's data, thus retaining the diversity of the system to some extent. The main motivation behind this modification is that one-bit flag packets require a lower SNR threshold than ID packets. In this way, the number of duplicate packets in the buffers are reduced. The benefits of this scheme can be understood more easily, if we consider clustering the relays, based on their IR channels. It is possible that, the one-bit flag packet transmitted by the first relay that successfully decoded the source's signal will be decoded by relays belonging at another cluster. So, instead of storing that packet in their buffer, the relays of the other cluster pre-drop it, in order to ensure that no duplicate transmissions will take place in the $\{R{\to}D\}$ link. More importantly, the proposed packet pre-dropping does not incur additional complexity, allowing relays belonging in the same cluster, and thus having strong IR channels, to keep the packet in order to forward it to the destination.

Remark 3. *Error-free feedback channels might exist in the $\{S{\to}R\}$ link as well. In this case, after the broadcasting has finished, one (or more) relays send one-bit ACKs notifying the source about successful reception. However, if the source does not receive any ACK, it will re-transmit the packet. Therefore, the transmission of one-bit ACKs is considered reliable in the majority of works (see e.g., [2], [3], [7], [8], [11]) and, at the same time, all the feedback channels must be in outage. This is a very unlikely case and it is not considered in this paper.*

VI. Performance Evaluation

A. Perfect CSI

In this section, the outage and delay performance of $\mathrm{LoCo-Link}$ is evaluated and comparisons with other state-of-the-art schemes are given. More specifically, $\mathrm{LoCo-Link}$ is compared to non-buffered Best Relay Selection [2], $\mathrm{max-link}$ [8], Delay-Aware (DA) $\mathrm{max-link}$ [13], the link selection policy of [11] and the G-ML [16]. In the comparisons, the rate threshold for successful reception is set at $r_0 = 1$ bit-per-channel use (BPCU), while $K = 3$ relays are available with each one having a buffer size of $L = 5$ bits. For the two cases of the threshold-based LoCo-Link, the buffer threshold is set equal to 1 and 3 bits, respectively. Moreover, two asymmetric topologies are considered where in the first case the average SNR $\bar{\gamma}_{SR}$ of the $\{R{\to}D\}$ links is higher than the average SNR of the $\{R{\to}D\}$ links $\bar{\gamma}_{RD}$ and their relationship is expressed as $\bar{\gamma}_{SR} = 2\bar{\gamma}_{RD}$, while in the second case $\bar{\gamma}_{RD} = 2\bar{\gamma}_{SR}$.

Fig. 2 shows the outage probability performance for the case where $\bar{\gamma}_{SR} = 2\bar{\gamma}_{RD}$. Due to the asymmetry, the probability of buffer overflow is high and one may observe that relay selection policies prioritizing the $\{R{\to}D\}$ transmissions can mitigate this phenomenon. Also, G-ML has the worst performance from all the BA policies as broadcasting increases the instances of full buffers. On the contrary, $\mathrm{LoCo-Link}$ alleviates this issue through $\{R{\to}D\}$ prioritization and its performance exceeds that of the policy in [11] due to the increased diversity in the $\{R{\to}D\}$ link selection. The best outage performance is exhibited by the threshold-based $\mathrm{LoCo-Link}$ preserving the diversity of the asymmetric network. Between

TABLE I
REQUIRED OVERHEADS OF $\mathrm{LoCo-Link}$, $\mathrm{max-link}$ AND G-ML PER LINK SELECTION.

	Pilot transmissions			CSI estimations			Data transmissions from relay nodes		
	S	R_j	D	S	R_j	D	$\{S\to R\}$ CSI	$\{R\to D\}$ CSI	buffer states
$\mathrm{d\text{-}LoCo-Link}$	0	0	1	0	1	0	0	0	0
$\mathrm{c\text{-}LoCo-Link}$	0	0	1	0	1	0	0	K	K
$\mathrm{max-link}$ [8]	1	1	0	0	1	K	K	K	K
$\mathrm{G\text{-}max-link}$ [16]	1	1	0	0	1	K	K	K	K

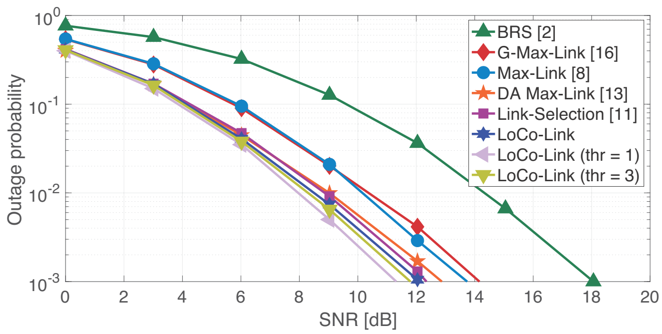

Fig. 2. Outage probability for $K = 3$, $L = 5$ and $\bar{\gamma}_{SR} = 2\bar{\gamma}_{RD}$.

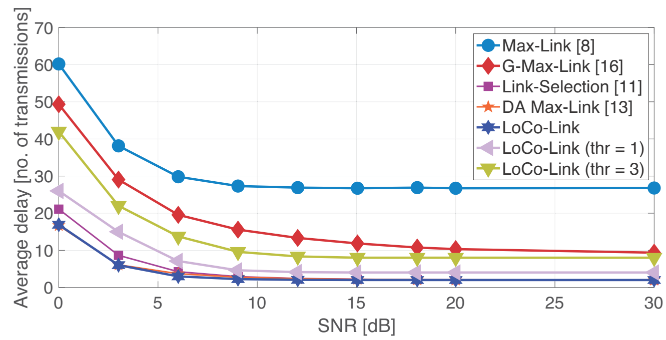

Fig. 4. Average delay for $K = 3$, $L = 5$ and $\bar{\gamma}_{SR} = 2\bar{\gamma}_{RD}$.

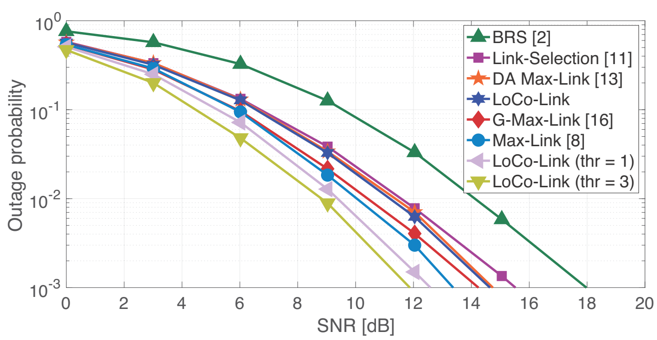

Fig. 3. Outage probability for $K = 3$, $L = 5$ and $\bar{\gamma}_{RD} = 2\bar{\gamma}_{SR}$.

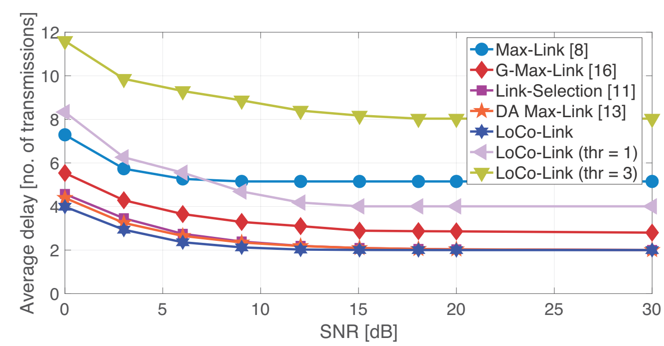

Fig. 5. Average delay for $K = 3$, $L = 5$ and $\bar{\gamma}_{RD} = 2\bar{\gamma}_{SR}$.

the two threshold cases, it can be seen that a threshold equal to three provides slightly worse performance, as $\{R\to D\}$ transmission opportunities are not exploited in many instances.

Then, Fig. 3 depicts the outage probability results for a topology where $\bar{\gamma}_{RD} = 2\bar{\gamma}_{SR}$. In this topology, the main challenge is to avoid empty buffers as $\{R\to D\}$ transmissions have a higher probability of being selected. So, it is observed that the policies providing $\{R\to D\}$ prioritization perform worse than the policies where the selection of each hop is equiprobable. Nevertheless, $\mathrm{LoCo-Link}$'s performance is slightly better than DA-$\mathrm{max-link}$ and the link selection of [11]. Furthermore, $\mathrm{max-link}$ provides lower outage probability, while G-ML tends to experience more often buffer overflow instances. Overall, the threshold-based $\mathrm{LoCo-Link}$, has the lowest outage probability among all the schemes. For this asymmetric network, avoiding empty buffers is critical and thus, imposing thresholds balances the selection of each link and improves the performance. However, in this case, a threshold equal to three offers reduced outages, since for lower values the possibility of empty buffers increases.

The average delay performance is depicted in Fig. 4 for a topology where $\bar{\gamma}_{SR} = 2\bar{\gamma}_{RD}$. In this case, excessive delay might be introduced as the selection of $\{R\to D\}$ transmissions has reduced probability and packets tend to reside for more time-slots in the relays' buffers. However, the policies with $\{R\to D\}$ prioritization overcome this challenge by first searching a transmission from the set of $\{R\to D\}$ links that provide rates above r_0. $\mathrm{LoCo-Link}$ has the best delay performance, as broadcasting offers increased diversity for the selection of a $\{R\to D\}$ transmission and for high SNR the average delay reaches a value of two time-slots, as is the case of [11]. DA-$\mathrm{max-link}$ follows closely but it must be noted that it suffers from outages. Also, G-ML has higher delay as packets from the broadcast phase will remain for more time-slots in the buffers. Finally, the threshold-based $\mathrm{LoCo-Link}$ performs better than G-ML and $\mathrm{max-link}$ but is surpassed by the other schemes. This can be justified by considering that due to the thresholds, packets tend to remain in the buffers for more time-slots and thus, an interesting trade-off between maintaining the diversity and increasing the delay arises.

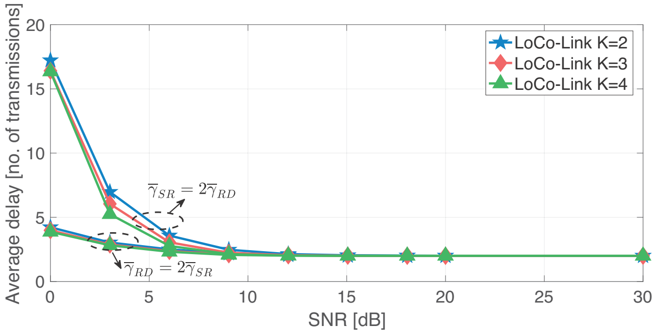

Fig. 6. Average delay for $K = 2, 3, 4$, $L = 5$ and both asymmetric cases.

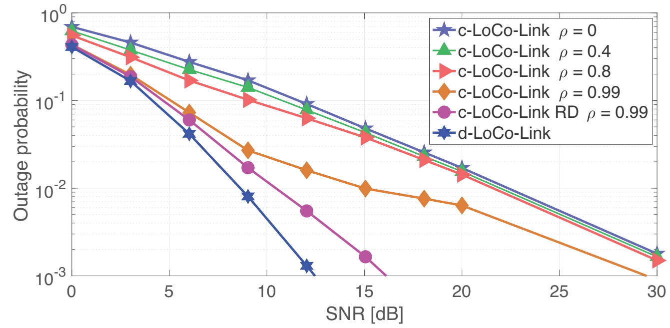

Fig. 7. Outage probability for $K = 3$, $L = 5$ and $\bar{\gamma}_{SR} = 2\bar{\gamma}_{RD}$.

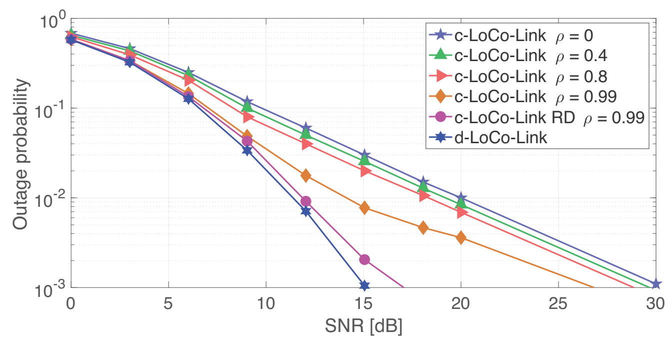

Fig. 8. Outage probability for $K = 3$, $L = 5$ and $\bar{\gamma}_{RD} = 2\bar{\gamma}_{SR}$.

After, Fig. 5 illustrates average delay curves for a topology where $\bar{\gamma}_{RD} = 2\bar{\gamma}_{SR}$. In general, all the schemes exhibit lower delay, as the asymmetry allow $\{R \rightarrow D\}$ transmissions to be performed at a higher frequency than $\{S \rightarrow R\}$ transmissions. One may see that $\mathrm{LoCo-Link}$ exhibits reduced delay, as broadcasting allows more $\{R \rightarrow D\}$ links to participate in the selection process. It must be noted that the reduced amount of $\{S \rightarrow R\}$ transmissions, especially in the low and medium SNR regimes results in increased instances of empty buffers. In the high SNR regime, $\mathrm{LoCo-Link}$, link–selection and DA $\mathrm{max-link}$ provide a delay of two time-slots, due to $\{R \rightarrow D\}$ selection prioritization. In this comparison, the threshold-based $\mathrm{LoCo-Link}$ increases the average delay, illustrating that preserving the diversity, especially for a buffer threshold equal to three packets, comes at the cost of additional delay.

The comparison in Fig. 6 considers the average delay performance for $\mathrm{LoCo-Link}$, when $K = 2, 3, 4$ relays are available with $L = 5$ buffer size, for both asymmetric topologies. From the figure, it is evident that, as the number of relays increases, the delay performance in the low and medium SNR regimes improves. It is important to note that in the high SNR regime, increasing the number of relays does not increase the average delay as is the case with $\mathrm{max-link}$ and G-ML that have equiprobable selection of each hop. So, the addition of more relays allows $\mathrm{LoCo-Link}$ to improve its delay performance for both asymmetric cases.

B. Outdated CSI

Next, the impact of outdated CSI on $\mathrm{LoCo-Link}$'s performance is investigated. Both asymmetric topologies are considered and comparisons are given for different values of the correlation coefficient ρ. Based on the findings in Table I, the case of $\mathrm{d-LoCo-Link}$ is not affected by outdated CSI. On the other hand, the different values of ρ affect $\mathrm{c-LoCo-Link}$. Also, a centralized scheme where $\{R \rightarrow D\}$ selection is prioritized without selecting the relay with the maximum number of packets is included in the comparisons, denoted as $\mathrm{c-LoCo-Link}$ RD.

Fig. 7 shows the outage probability for the asymmetric case of $\bar{\gamma}_{SR} = 2\bar{\gamma}_{RD}$. It is evident that irrespectively of the value of ρ, the diversity of $\mathrm{c-LoCo-Link}$ is equal to the diversity of a single relay network. Then, $\mathrm{LoCo-Link}$ RD has improved performance by basing the transmission on the best $\{R \rightarrow D\}$ link thus providing increased SNR margin against outdated CSI. As a result, the outage probability is reduced for a broad SNR range. The only algorithm remaining affected by outdated CSI is $\mathrm{d-LoCo-Link}$, maintaining its diversity order.

After, in Fig. 8 outage probability comparisons are given for the asymmetric case of $\bar{\gamma}_{RD} = 2\bar{\gamma}_{SR}$. Again, $\mathrm{d-LoCo-Link}$ remains unaffected from outdated CSI, as it does not require CSI feedback from the destination. The various cases of $\mathrm{c-LoCo-Link}$ exhibit reduced diversity, while $\mathrm{c-LoCo-Link}$ RD improves the performance for medium SNR values compared to the case of $\mathrm{c-LoCo-Link}$ with $\rho = 0.99$.

Fig. 9 depicts average delay results for the asymmetric case of $\bar{\gamma}_{SR} = 2\bar{\gamma}_{RD}$. The results reveal that the average delay is increased for low values of ρ for low and medium SNR. Again, $\mathrm{d-LoCo-Link}$ provides the overall best performance followed by $\mathrm{c-LoCo-Link}$ with $\rho = 0.99$ and $\mathrm{c-LoCo-Link}$ RD. Here, the consideration of buffer state by $\mathrm{LoCo-Link}$ results in reduced delay, compared to $\mathrm{c-LoCo-Link}$ RD.

The final outdated CSI comparison is included in Fig. 10, where the average delay is shown for the asymmetric case of $\bar{\gamma}_{RD} = 2\bar{\gamma}_{SR}$. Here, the average delay is in general lower compared to the asymmetric case of $\bar{\gamma}_{SR} = 2\bar{\gamma}_{RD}$. The best delay performance is provided by $\mathrm{d-LoCo-Link}$. On the contrary, $\mathrm{c-LoCo-Link}$ and $\mathrm{c-LoCo-Link}$ RD are both affected by the correlation coefficient ρ. For high SNR values, all versions of the algorithm converge to an average delay of two time-slots.

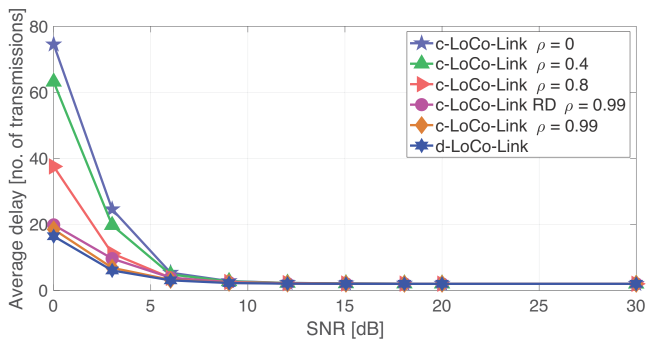

Fig. 9. Average delay for $K = 3$, $L = 5$ and $\bar{\gamma}_{SR} = 2\bar{\gamma}_{RD}$.

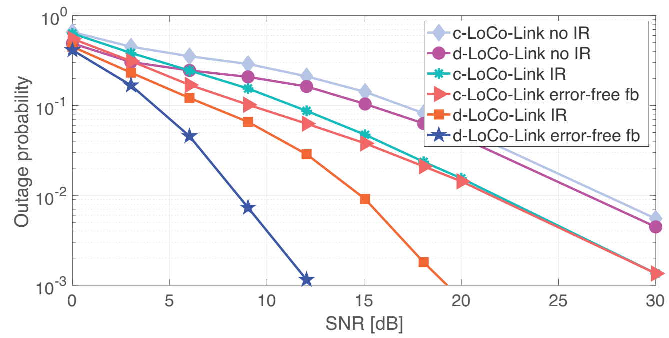

Fig. 11. Outage probability for $K = 3$, $L = 5$, $\bar{\gamma}_{SR} = 2\bar{\gamma}_{RD}$ and non error-free feedback channels.

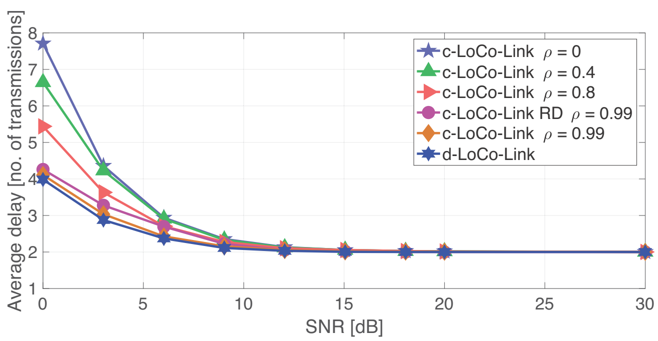

Fig. 10. Average delay for $K = 3$, $L = 5$ and $\bar{\gamma}_{RD} = 2\bar{\gamma}_{SR}$.

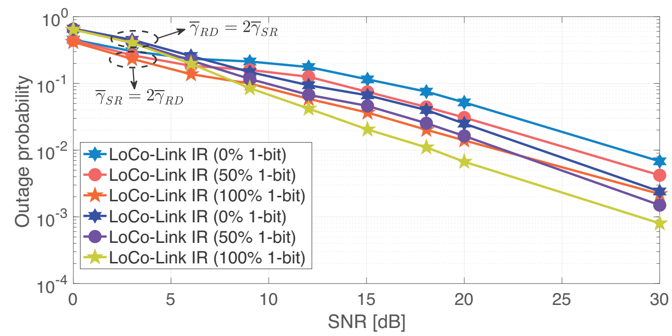

Fig. 12. Outage probability for $K = 4$, $L = 5$, $\bar{\gamma}_{SR} = 2\bar{\gamma}_{RD}$, non error-free feedback channels and strong IR channels exploitation.

C. Non error-free feedback channel

In Fig. 11, the combined effect of outdated CSI with $\rho = 0.8$ and non error-free feedback channels is examined. As already described, the schemes employing broadcast transmissions in the $\{S\rightarrow R\}$ link must contain in their feedback packets information regarding the successful transmission of a specific packet. Then, the relays having that packet in their buffer will drop it in order to avoid duplicate transmissions. In the results, we include for comparison the cases of $\mathrm{LoCo-Link}$ and $\mathrm{d-LoCo-Link}$ with error-free feedback. The other investigated scheme is the centralized and the distributed $\mathrm{LoCo-Link}$ with non error-free feedback channels. It is obvious that diversity is significantly affected when feedback outages occur and when the IR channels are not exploited. We denote these case as “no IR”, while the cases with IR channels are denoted as “IR”. From Fig. 11 it is observed that the simple, yet effective mitigation technique of keeping active the non-selected relays in order to overhear the transmission towards the destination allows them to drop duplicate packets from their buffers and increase the diversity of the transmission, as depicted by $\mathrm{LoCo-Link}$ IR. More importantly, one may observe that $\mathrm{d-LoCo-Link}$ is superior to $\mathrm{c-LoCo-Link}$ in every case, since the effect of outdated CSI is mitigated.

Finally, Fig. 12 depicts a scenario where $K = 4$ relays are available formulating two clusters each one consisting of two relays. So, the proposed modification of exploiting one-bit feedback between clusters and dropping packets immediately after the broadcast transmissions, is investigated. More specifically, three cases are considered for the two asymmetric topologies. The first case, denoted by “0% 1-bit”, assumes that the channels between the two clusters do not allow the reception of the one-bit flag packet transmitted by the first relay that managed to decode the source’s packet. This is equivalent to as if we do not adopt packet pre-dropping. The other two cases denoted by “50% 1-bit” and “100% 1-bit”, consider that corresponding percentages of one-bit flag packet can be received by relays belonging in different clusters. From the results, it is evident that pre-dropping packets from the relays that otherwise would not be able to overhear the packet IDs or would suffer from non error-free feedback channels, provides significant performance gain. Comparing the two asymmetric topologies, the case of stronger $\{R\rightarrow D\}$ links provides improved performance as the reduced diversity resulting from packet pre-dropping is mitigated by the stronger links, thus reducing the outage probability.

VII. Conclusions and Future Directions

A. Conclusions

In this paper, various practical issues in buffer-aided relay networks have been considered; namely, complexity, reduced delay CSI and feedback availability, as well as distributed implementation issues. In order to simplify the process of relay selection in these networks and reduce packet delay, we proposed $\mathrm{LoCo-Link}$, a low-complexity link selection algorithm, based on two features: firstly, the $\{R\rightarrow D\}$ links are prioritized over the $\{S\rightarrow R\}$ links choosing the feasible link, if there is any, with the largest queue size; secondly, if no transmission can occur from any of the relays, the source broadcasts its packets. Nonetheless, for the case of outdated CSI, $\mathrm{LoCo-Link}$ is significantly affected and so, a distributed implementation ($\mathrm{d-LoCo-Link}$) was developed avoiding delays in CSI exchange. Performance evaluation showed that $\mathrm{d-LoCo-Link}$ has identical performance with the case of perfect CSI contrary to other relay selection algorithms. Furthermore, we investigated the case of non error-free feedback channels threatening the exchange of BSI, resulting in duplicate packet transmissions to the destination. Thus, a solution employing the inter-relay channels as additional feedback channels was proposed, showing important performance gains.

B. Future directions

As future work, relay selection algorithms will be developed in which relay selection will take into consideration both the buffer sizes, as well as the knowledge of the exact or an estimate of the correlation coefficient ρ, aiming at alleviating the performance degradation due to the problem of outdated CSI. Furthermore, for networks with bursty traffic, the stability region of BA opportunistic relay selection could be studied, using half- [32] and full-duplex relays [33].

Also, the half-duplex loss can be recovered by adopting schemes mimicking full-duplex transmissions, such as successive relaying. Towards this end, broadcasting in the $\{S{\rightarrow}R\}$ link provides increased flexibility compared to previous studies where unicast transmissions were performed [34]–[36]. In addition, the threshold-based version of $\mathrm{LoCo-Link}$ will be further investigated in order to derive the optimal buffer threshold in terms of the number of packets, considering the buffer size and the outage-delay trade-off arising from the comparisons in this work.

Finally, buffer-aided relay selection in multi-user topologies will be studied incorporating recent advances in the area of Non-Orthogonal Multiple Access (NOMA) [37]–[40] targeting to increase the network's sum-rate.

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