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Delay- and Diversity-Aware Buffer-Aided Relay Selection Policies in Cooperative Networks

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ABSTRACT Buffer-Aided (BA) relaying has shown tremendous performance improvements in terms of throughput and outage probability, although it has been criticized of suffering from long delays that are restrictive for applications, such as video streaming, Web browsing, and file sharing. In this paper, we propose novel relay selection policies aiming at reducing the average delay by incorporating the buffer size of the relays into the decision making of the relay selection process. More specifically, we first propose two new delay-aware policies. One is based on the hybrid relay selection algorithm, where the relay selection takes into account the queue sizes so that the delay is reduced and the diversity is maintained. The other approach is based on the max $-$ link relay selection algorithm. For the max $-$ link algorithm, a delay-aware only approach starves the buffers and increases the outage probability of the system. Thus, for max $-$ link, we propose a delay- and diversity-aware BA relay selection policy targeting the reduction of the average delay, while maintaining the diversity of the transmission. The proposed policies are analyzed by means of Markov Chains and expressions for the outage, throughput, and delay are derived. The asymptotic performance of the policies is also discussed. The improved performance in terms of delays and the use of the proposed algorithms are demonstrated via extensive simulations and comparisons, signifying, at the same time, the need for adaptive mechanisms to handle the interplay between delay and diversity.

INDEX TERMS Cooperative relaying, relay selection, buffer-aided relaying, delays, diversity, Markov chains.

I. INTRODUCTION

The proliferation of mobile devices with improved capabilities, the cheap data plans and the increase in data-intensive content, applications and services have led to unprecedented high volumes of mobile data traffic [1], [2]. Since the available frequency spectrum is limited, future communication systems are expected to make a more efficient use of the available spectrum. Cooperative Relaying (CR) is known for path-loss reduction, shadowing mitigation and improved link diversity. In [3], the fundamental theoretical framework was developed, resulting in several contributions in the field of CR. CR constitutes one of the key enhancements introduced in 3GPP LTE-Advanced (LTE-A) in order to improve the performance of cellular networks, in terms of coverage extension and throughput enhancement. Two important CR

techniques are Opportunistic Relay Selection (ORS) [4], [5] and Buffer-Aided (BA) relaying (see [6], [7] and references therein), solidifying the role of CR in the context of fifth generation (5G) networks.

A. RELATED WORK

In delay-tolerant applications, emphasis is given on improving the reliability of the wireless transmission and thus, relaying techniques for increased diversity have been developed. In the literature, several works have presented ORS algorithms focusing on outage probability reduction. The seminal work in [8] showed that ORS achieves the same diversity in delay-tolerant applications as multi-relay transmission, requiring only one additional orthogonal channel. For networks where relays have buffering capabilities, the authors

of [9] presented Hybrid Relay Selection (HRS) based on non-BA ORS [4] and BA Max-Max Relay Selection (MMRS). MMRS allocates one time-slot to two relays, having the strongest Source-Relay ($\{S \to R\}$) and Relay-Destination ($\{R \to D\}$) links. So, for applications without delay constraints, HRS provides the same diversity with ORS without buffers and increased coding gain. Then, an adaptive link selection policy, namely, max − link was proposed by Krikidis *et al.* in [10], for increased diversity in BA ORS networks. More specifically, in each time-slot, max − link performs an $\{S \to R\}$ transmission or an $\{R \to D\}$ transmission. So, when a large number of relays is available, the diversity gain is twice the number of relays. In networks where a direct Source-Destination ($\{S \to D\}$) link can be established, max − link was analyzed in [11], providing a framework for selecting among direct and relay transmissions, resulting in improved diversity. For single-relay networks with adaptive link-selection, The authors of [12] have studied both fixed and mixed rate transmissions showing that, when packet delay can be tolerated, a diversity order of two is achieved for fixed rate scenarios. For a similar topology, Wicke *et al.* [13] derived the optimal scheduling for transmission/reception at the BA relay, as well as the optimal rate selection by the source, aiming to maximize the throughput. More recently, MMRS and max − link were combined by Oiwa *et al.* [14], selecting one relay for reception in odd time-slots and one relay for transmission in even time-slots. When this procedure cannot be performed, max − link is activated to avoid a complete outage. Performance evaluation showed lower delay than max − link without diversity losses. Additionally, the work in [15] focuses on maintaining the diversity of the network and having the half-full buffer state as reference, examined Buffer and Channel State Information (BSI and CSI), in order to balance the relay queues and reduce the outage probability by activating relays that deviated from the balanced state. Furthermore, the recent work in [16] proposed the classification of relays based on the number of packets residing in their queues when max − link is employed. In this way, outage probability reduction was achieved, as instances of full and empty relay buffers were avoided, thus enhancing the diversity of the network. Finally, BA link selection was shown in [17] to improve the performance of networks performing multi-hop transmissions when max − link was combined with network coding.

While all the aforementioned works achieve a considerable reduction in outage probability, this occurs at the expense of time-delays. Qiao and Gursoy in [18] highlighted the potential of BA relaying in satisfying the requirements of delay-intolerant applications, while several challenges were discussed, such as relay selection, queue-aware algorithms and resource allocation. For single relay networks with adaptive link selection, the authors in [12], derived the multiplexing gain when mixed rate transmissions are performed under delay-constrained scenarios. Also, a delay-aware (DA) BA algorithm was presented in [13] for the case of discrete transmission rates by the source. Then, for multi-relay networks,

several works have presented DA algorithms relying on HRS and max − link. A modified version of HRS was presented by the authors in [19] based on BSI to achieve non-empty and balanced relay queues by activating the links with the smallest (largest) data queue, among the $\{S \to R\}$ and $\{R \to D\}$ links. A similar approach was presented, independently, in [20], namely Combined Relay Selection (CRS) for relays with small buffers. CRS divides each frame to two time-slots, allocating the first time-slot to the relay with the shortest buffer length for reception and the second time-slot to the relay with the longest buffer length for transmission. Results illustrated reduced delay, compared to HRS and max − link. Another queue-aware relay selection technique, titled max-weight was proposed in [21] where weights were assigned to each relay according to their BSI and CSI. Compared to max − link without BSI consideration, significant delay improvement was observed. Max-weight was extended in [22], treating scenarios where selection had to choose between links with equal weights and considered prioritizing $\{R \to D\}$ transmission to reduce the delay. It should be noted that the first works introducing the prioritization of $\{R \to D\}$ transmission in max − link were [23], [24]. Through that mechanism, for low Signal-to-Noise Ratio (SNR), reduced delay was achieved, while for high SNR, the average delay converged to two time-slots, without scaling with the number of relays or the buffer size. However, as it is shown in [23], this approach, while it reduces delays in the network, it also increases the outage probability, since most of the relays have empty buffers throughout its operation. Based on this observation, in [23] a delay- and diversity-aware extension is proposed in which the selection of relays that are on the brink of starvation or of being full are avoided. Nonetheless, that algorithm allocated packets to several buffers and for a large number of relays, the delay increased. In another line of research, activating multiple $\{S \to R\}$ links was investigated in [25], where generalized versions of MMRS and max − link (G-MMRS and G-ML) were presented. Each protocol relied on broadcasting by the source, thus reducing the delay of MMRS and max − link. Also, CSI overhead was reduced for G-MMRS, but not G-ML. BA ORS with broadcasting has been extended in [26], where $\{R \to D\}$ prioritization provided low-delay transmission while practical considerations, such as outdated CSI, distributed implementation and non error-free feedback were addressed through efficient mechanisms. Also, a threshold-based approach has been proposed in [27], classifying the relays into two categories, one for transmission and one for reception, depending on their BSI. So, at each time-slot, one or more relays were activated for reception or a single relay was activated for transmission, depending on their classification, thus maintaining the diversity of the network. The buffer-state-based relay selection was extended in [28] by integrating collaborative beamforming for SNR improvement and deriving analytical bounds on the outage probability and the average delay. For adaptive rate transmission, Zlatanov *et al.* in [29] studied the achievable rates for a network with multiple BA

relays. Moreover, a BA algorithm was given, resulting in a trade-off between average delay and rate improvement. Moreover, in [30], Zhou *et al.* concluded that imposing a buffer threshold determined the optimal link selection policy and the decision among transmission and reception.

B. SUMMARY OF RESULTS

In this paper, we investigate the trade-off between maintaining the diversity gain of BA relaying without significantly increasing the delay or vice versa, reducing the delay without compromising the diversity of the network. So, we avoid link selection based solely on the best link, as the considered network performs transmissions with fixed rates and power. On the contrary, the activated link is selected based on BSI, as long as that link is not in outage. Preliminary results of this work have been initially reported in [19] and [23]. In this paper, on top of the contributions presented in [19] and [23], we provide additional theoretical analysis, we add simple examples that verify the theoretical results, we run comparisons between the proposed algorithms and we study their performance under imperfect CSI. We also extend the discussion about the implications of this work and its relevance with the recent literature on delay- and diversity-aware relaying. In greater detail, we provide the following contributions:

1) A delay- and diversity-aware policy is proposed, based on the Hybrid Relay Selection (HRS) protocol presented in [9], where the two-slot convention is assumed (as it is the case for the $\max - \max$ relay selection protocol), but the criterion now is to keep the queues non-empty and balanced. This is achieved by choosing among the feasible $\{S \rightarrow R\}$ ($\{R \rightarrow D\}$) links, the ones with the smallest (largest) data queue. We show that the proposed algorithm reduces both the average delay and the outage probability, due to establishing more balance between the data queues in the buffers. It is also shown that the average delay for high SNR depends only on the number of buffers and not on the buffer size.

2) Then, we examine the performance of the modified delay-aware policy based on $\max - \text{link}$ [10], where each slot is dedicated to an $\{S \rightarrow R\}$ or $\{R \rightarrow D\}$ transmission, aiming for delay minimization. It is shown that although the delay-aware $\max - \text{link}$ reduces the average delay, its diversity cannot be maintained and increased outages are experienced. The poor performance of this policy, pushes us to investigate another delay-aware solution, providing increased diversity.

3) So, a diversity- and delay-aware $\max - \text{link}$ algorithm is presented, guaranteeing that buffers do not underflow. Performance evaluation shows reduced outages, as well as reduced average delay, compared to that of $\max - \text{link}$. Furthermore, the analysis shows that for high SNR, delay is affected by the number of relays and not buffer size.

4) Targeting the practical implementation of the proposed policies, for each one, a distributed implementation framework is provided. The distributed operation of relay

selection results in robustness against node failures and outdated CSI, as well as scalability when a large number of relays is employed, as central processing of CSI and BSI is avoided.

5) The performance and the results of the theoretical analysis of all three algorithms are evaluated through simulations and comparisons for cases when selection is based on perfect and outdated CSI. The case of outdated CSI is of practical interest, as the wireless channel may differ in the time from the end of the estimation process and the start of the transmission [31].

C. OUTLINE

The paper is organized as follows. In Section II, the system model is presented. Then, Sections III, IV and V, provide the selection algorithms and for each algorithm, simulation results are given. Next, in Section VI, we provide the theoretical analysis of the proposed algorithms, as well as their asymptotic performance. Section VIII presents comparisons between the proposed, as well as the original schemes. Finally, Section IX includes the conclusions and future research directions.

II. SYSTEM MODEL
A. NETWORK MODEL

The network considered is constituted by a source S, a destination D and a cluster of K Half-Duplex (HD) Decode-and-Forward (DF) relays $R_k \in \mathcal{C}$, $k \in \{1, \ldots, K\}$. It is assumed that no direct link exists between the source and the destination; as a result, communication between the source and the destination is achieved via relays only. Relays are equipped with buffers (i.e., they can store data) and relay R_k is said to have queue size Q_k. The capacity of relays is finite and assumed to be L (maximum number of data elements) for all relays. Data stored in the relay buffers is source data that the relay has decoded and it will eventually forward to the destination. The vector summarizing the queue sizes at the buffers of all relays is denoted by $Q \triangleq (Q_1, Q_2, \ldots, Q_K)$. Figure 1 shows two instances of the relay-assisted network.
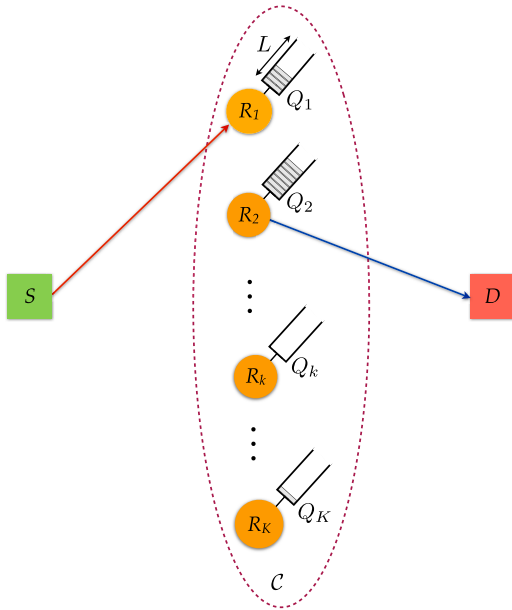
B. CHANNEL MODEL

The signals received at receiving relay R, y_R, and destination D, y_D, from source S and transmitting relay T, respectively, at any arbitrary time-slot n, are given by:

$$y_R[n] = h_{SR} x_S[n] + w_R[n], \tag{1a}$$

$$y_D[n] = h_{TD} x[p] + w_D[n], \tag{1b}$$

where $x_S[n]$ is the signal transmitted by the source at time-slot n; by $x[p]$ we denote the signal received in a previous time-slot p and stored in the buffer of the transmitting relay T at time-slot n. In (1), h_{ij} denotes the channel coefficient for the link $\{i \rightarrow j\}$ which is characterized by the effects of path-loss, fading and shadowing; $w_j[n]$ is due to the receiver noise and possibly other forms of interference at the receiving

FIGURE 1. The system model: Source *S* communicates with Destination *D* via a cluster of relays $R_k \in C$, $k \in \{1, 2, \dots, K\}$.

node *j* in time time-slot *n*. The quality of the wireless channels, h_{ij}, is characterized by frequency non-selective Rayleigh block fading and Additive White Gaussian Noise (AWGN) comprehended by a zero mean complex Gaussian distribution with variance σ_{ij}^2 for the $\{i \to j\}$ link and therefore, its envelope is Rayleigh distributed, i.e., $|h_{ij}| \sim \text{Rayleigh}(\sigma_{ij})$. The channel gains $g_{ij} \triangleq |h_{ij}|^2$ are, therefore, exponentially distributed, i.e., $g_{ij} \sim \text{Exp}(\sigma_{ij}^{-2}/2)$. Moreover, we model $w_j[n]$ as independent, zero-mean, circularly symmetric, complex Gaussian random variables with variance η (assumed the same on all nodes, for simplicity).

C. MEDIUM ACCESS MODEL
Time is slotted and at each time-slot, either the source (assumed to be saturated, i.e., it has always data to transmit) or one of the non-empty relays transmit a packet. When the transmission is successful, the transmission rate is fixed and equal to r_0. Thus, an outage event occurs when $I < r_0$, where *I* is the *maximum average mutual information* of the channel; the achievable *I* by independent and identically distributed (i.i.d.) zero-mean, circularly symmetric complex Gaussian channels, is $I = \log_2(1 + \text{SNR})$. In terms of SNR, we can equivalently say that a transmission is successful (error-free) if the SNR of the receiver is greater or equal to the *capture ratio* $\gamma_0 \triangleq 2^{r_0} - 1$, whose value depends on the modulation and coding characteristics of the radio. Therefore, a transmission from a transmitter *i* to its corresponding receiver *j* is successful if the SNR of receiver *j*, denoted by γ_j, is greater or equal to the *capture ratio* γ_0. In this work, we assume that the source and the relays transmit with fixed power *P*. As a result, we require that

$$\gamma_j(P) \triangleq \frac{g_{ij}P}{\eta} \geq \gamma_0. \tag{2}$$

Link $\{i \to j\}$ is in outage if $\gamma_j(P) < \gamma_0$, i.e., $\frac{g_{ij}P}{\eta} < \gamma_0$; hence, the probability of outage is

$$\bar{p}_{ij} = \mathbb{P}\left[g_{ij} < \frac{\gamma_0 \eta}{P}\right].$$

This *capture model* was first introduced in [32] and has been widely used thereafter. For our network model, the SNR from *S* to R_i, when relay R_i is selected for reception, is given by

$$\gamma_{R_i}(P) = \frac{g_{SR_i}P}{\eta} \geq \gamma_0 ;$$

the SNR from R_j to *D*, when relay R_j is selected for transmission, is given by

$$\gamma_D(P) = \frac{g_{R_j D}P}{\eta} \geq \gamma_0 .$$

The short-length Acknowledgement/Negative-Acknowledgement (ACK/NACK) packets are broadcasted by the receivers over a separate error-free narrow-band channel. By $b_{SR} \triangleq (b_{SR_1}, b_{SR_2}, \dots, b_{SR_K})$ and $b_{RD} \triangleq (b_{R_1D}, b_{R_2D}, \dots, b_{R_KD})$ we capture in a binary form, the links that are not in outage (i.e., if transmission on link $R_i D$ is feasible, then $b_{R_i D} = 1$). It is assumed that the receivers can estimate (accurately, if not otherwise stated) the CSI. Similarly, by $q_{SR} \triangleq (q_{SR_1}, q_{SR_2}, \dots, q_{SR_K})$ and $q_{RD} \triangleq (q_{R_1D}, q_{R_2D}, \dots, q_{R_KD})$ we represent in a binary form, the links that are feasible due to the fulfillment of the queue conditions (i.e., for non-full buffers in $\{S \to R\}$ links and for non-empty buffers in $\{R \to D\}$ links). Sets $\mathcal{F}_{SR}$ and $\mathcal{F}_{RD}$, contain the feasible $\{S \to R\}$ and $\{R \to D\}$ links, respectively. In case $b_{ij} = 0$ or $q_{ij} = 0$, no transmission is attempted on link $\{i \to j\}$; as a consequence, we say that link $\{i \to j\}$ is in *outage*.

III. DELAY-AWARE HRS
Here, we present a policy extending the HRS algorithm of [9]. Contrary to HRS, relay selection takes into consideration, the amount of packets residing in the buffers of the relays. As fixed rate transmissions are performed, information on whether or not a link is in outage can be acquired in advance. Thus, the policy decides the activation of a link according to the number of packets of relays having at least one of the $\{S \to R\}$ or $\{R \to D\}$ links available for transmission. It should be noted that independently, the authors of [20] proposed a similar modification for HRS for relay networks with small buffers. Nonetheless, herein, we do not focus merely on the case of small buffers and, moreover, we propose a novel distributed method to implement the Delay-Aware HRS (DA $-$ HRS) policy.

DA $-$ HRS, similarly to the original HRS, adopts the *two-slot convention per time-frame* (i.e., each time-frame, consists of two time-slots: the first is allocated for an $\{S \to R\}$ transmission and the second for an $\{R \to D\}$ transmission) and operates by excluding from selection, the links that are in outage; among the links in $\mathcal{F}_{SR}$ (i.e., feasible $\{S \to R\}$ links), the selected relay for reception in the first slot, is the one

having the minimum buffer size; in the second slot, among the links in $\mathcal{F}_{RD}$ (i.e., feasible $\{R \rightarrow D\}$ links), selection activates the relay having the maximum buffer size to perform a transmission to the destination. In the case where more than one relays have the same buffer size, random relay selection is employed. If either $\mathcal{F}_{SR} = \emptyset$ or $\mathcal{F}_{RD} = \emptyset$, an outage event occurs.

Algorithm 1 describes the operation of DA − HRS at an arbitrary time-frame:

Algorithm 1 Delay-Aware HRS Relay Selection

1: **input** Q, $\mathcal{F}_{SR}$, $\mathcal{F}_{RD}$
2: **if** $\mathcal{F}_{SR} \neq \emptyset$ **and** $\mathcal{F}_{RD} \neq \emptyset$ **then**
3:      $i^* = \arg\min_{i \in \mathcal{F}_{SR}} Q_i$ (slot 1)
4:      $j^* = \arg\max_{j \in \mathcal{F}_{RD}} Q_j$ (slot 2)
5: **else**
6:      No packet transmission takes place.
7: **end if**
8: **Output** Links $\{S \rightarrow R_{i*}\}$ and $\{R_{j*} \rightarrow D\}$ for transmissions at time-slots 1 and 2, respectively.

A. DISTRIBUTED IMPLEMENTATION

In order to implement DA − HRS in a distributed manner, the adoption of synchronized timers as suggested in [4] is proposed. At the *first slot*, the source transmit pilot signals and each relay R_i, with $q_{SR_i} = 1$, performs an estimation for the $\{S \rightarrow R_i\}$ CSI. So, from CSI processing it is able to decide if $b_{SR_i} = 1$. Next, if $b_{SR_i} q_{SR_i} = 1$, R_i competes to access the channel by starting a timer using a value that is set according to its buffer size $\max\{0, Q_i + \nu_i\}$, where ν_i is uniformly distributed in $(-0.5, 0.5)$. As a result, the relay whose timer has the *minimum* buffer size expires first. If more than one relays have the same size, ν_i guarantees different expiration times. So, a flag packet is transmitted by the relay with the smallest buffer, notifying the other relays to remain silent, as all the relays are in listening mode during that time. When the flag packet of another relay or forwarding information is sensed by the other relays, they back off. At the *second slot*, a pilot sequence is broadcasted by the destination and each relay R_i, with $q_{R_iD} = 1$, estimates the $\{D \rightarrow R_i\}$ CSI. Considering the reciprocity property [35] of antennas[1] relays estimate the $\{R_i \rightarrow D\}$ CSI. Through CSI processing, it can determine whether $b_{R_iD} = 1$. If $b_{R_iD} q_{R_iD} = 1$, R_i participates in the competition, but in this case, R_i's timer value depends on the reciprocal of the buffer size $(Q_i + 1 + \nu_i)^{-1}$. The timer of the relay with the *maximum* buffer size is the first to expire. If more than one relays have the same buffer size, ν_i assures different timer expiration.

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[1]Reciprocity technically only applies for antennas operating 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.
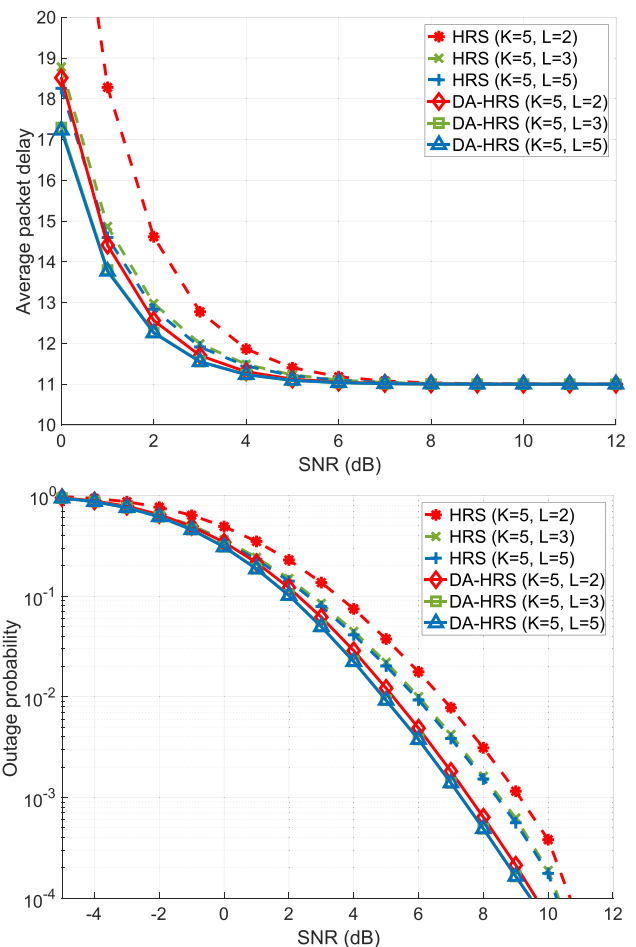
FIGURE 2. Average delay (top) and outage probability (bottom) of DA − HRS for $K = 5$ and $L = 2, 3, 5$.

B. NUMERICAL EVALUATION

For DA − HRS, simulations were performed to assess its performance, considering a varying number of relays K and buffer sizes L. It must be noted that in this case, an outage event occurs, if during a time-frame, a packet transmission cannot be performed (see Algorithm 1). Also, comparisons between DA − HRS and HRS are given for various L values, in terms of average delay and outage probability. Figure 2 shows that, DA − HRS outperforms HRS when the system operates in low and medium SNR, providing lower average delay and reduced outages.

The impact of the number of relays K is depicted in Figure 3. By increasing the number of relays, the average delay increases as well, however, less outages occur. This behaviour is justified by considering that more relays provide additional options for selection and thus, the packets reside in the buffers for more time-slots, but at the same time, a diversity gain is harvested. Through the comparisons of HRS and DA − HRS, it is observed that the average delay (top) for the proposed policy is reduced, while the two schemes perform similarly for higher SNR. Surprisingly, the outage performance (bottom) is improved as well. This can be
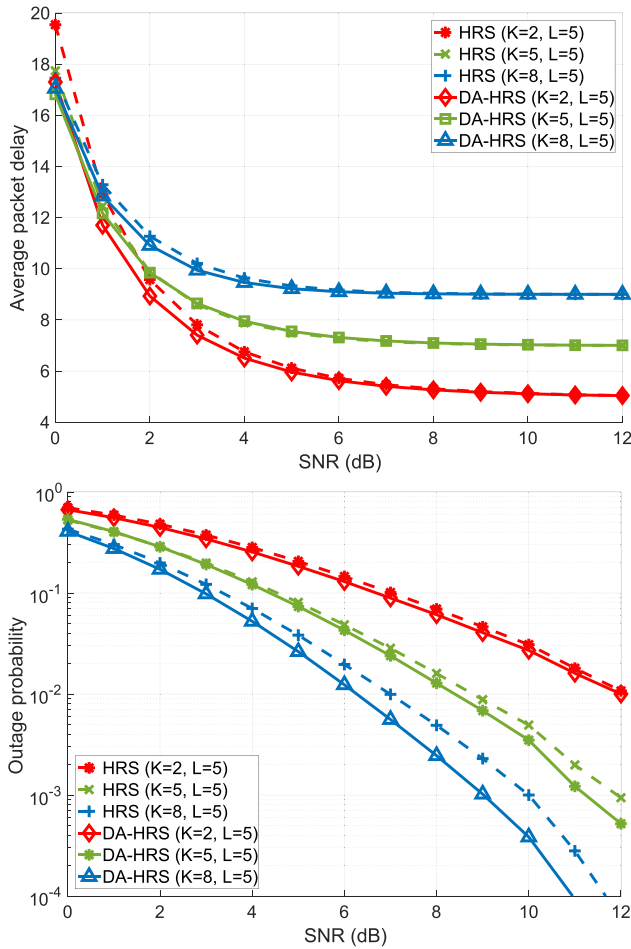
FIGURE 3. Average delay (top) and outage probability (bottom) of DA − HRS for $K = 2, 3, 4$ and $L = 5$.

explained by the more balanced relay selection, maintaining a more or less uniform buffer size and *full diversity*.

IV. DELAY-AWARE MAX-LINK

When max − link is adopted, a frame is not divided in two slots, as the policy activates an $\{S \rightarrow R\}$ or $\{R \rightarrow D\}$ link for the whole frame duration (i.e., a frame has the same duration with a time-slot). Nonetheless, in order to reduce the average delay of the transmission, prioritizing the selection of $\{R \rightarrow D\}$ would enforce packets to leave the buffers sooner and as a result, delay performance can be improved.

Based on this fact, a Delay-Aware max − link (DA − max − link) relay selection algorithm is described. In an arbitrary time-slot, among the relays that are able to transmit to the destination, relay selection is based on the number of packets residing in the buffer. The relay having the maximum number of packets is given priority over all the relays with feasible $\{R \rightarrow D\}$ links. If an $\{R \rightarrow D\}$ transmission cannot be performed, $\{S \rightarrow R\}$ link activation is targeted through the reception of a source packet by the relay with the minimum buffer size. If no feasible $\{S \rightarrow R\}$ link exists, the system is in outage, as packet transmission cannot take place. For cases when more than one relays have equal buffer sizes, a random

relay is activated. As aforementioned in the introduction, the prioritization of $\{R \rightarrow D\}$ transmission in max − link was first introduced by the authors in [23] and [24].

Algorithm 2 presents the selection process of DA − max − link during an arbitrary time-slot:

Algorithm 2 Delay-Aware max − link Relay Selection

1: **input** $Q, \mathcal{F}_{SR}, \mathcal{F}_{RD}$
2: **if** $\mathcal{F}_{SR} = \emptyset$ **and** $\mathcal{F}_{RD} = \emptyset$ **then**
3:     No packet transmission takes place.
4: **else**
5:     **if** $\mathcal{F}_{RD} \neq \emptyset$ **then**
6:         $j = \arg \max_{i \in \mathcal{F}_{RD}} Q_i$ ($\{R \rightarrow D\}$ link)
7:     **else**
8:         $k = \arg \min_{i \in \mathcal{F}_{SR}} Q_i$ ($\{S \rightarrow R\}$ link)
9:     **end if**
10: **end if**
11: **Output** Link $\{R_j \rightarrow D\}$ or $\{S \rightarrow R_k\}$ for transmission.

A. DISTRIBUTED IMPLEMENTATION

Even though at every time-slot, all available links are competing, in the DA − max − link algorithm priorities between $\{S \rightarrow R\}$ and $\{R \rightarrow D\}$ are set. In this case, CSI acquisition is done in the same way as in DA − HRS, with the difference that the competition takes place in two phases: in the *first phase*, the competition is done for the $\{R \rightarrow D\}$ link (as in the second time-slot for the DA − HRS) and if there is no short duration flag packet, it means that $\mathcal{F}_{RD} = \emptyset$; then the *second phase* is initiated with the competition for the $\{S \rightarrow R\}$ link (as in the first time-slot for the DA − HRS). Note that if a flag packet appears in the first phase, the second phase is skipped.

B. NUMERICAL EVALUATION

The impact of various buffer size L values on the delay and outage performance of DA − max − link and max − link is shown in Figure 4. It is observed that L does not affect the average delay of DA − max − link, but rather, it degrades its outage probability. Although the improvement of the average delay is significant, outages are experienced more frequently. When channel conditions improve, outage probability improves an order of magnitude more for DA − max − link compared to max − link. This stems from the fact that the majority of relays have empty buffers during most of the time-slots. So, naturally, in Figure 4, diversity is reduced, as can be observed by the curves for the two algorithms.

The next set of comparisons focuses on the effect of the number of relays K on the performance of DA − max − link and max − link, in terms of average delay and outage probability. The results are shown in Figure 5. Again, as only a single relay is activated during a time-slot, DA − max − link's average delay is not affected by K. However, outage probability performance degrades. For each case, DA − max − link performs significantly worse than max − link.
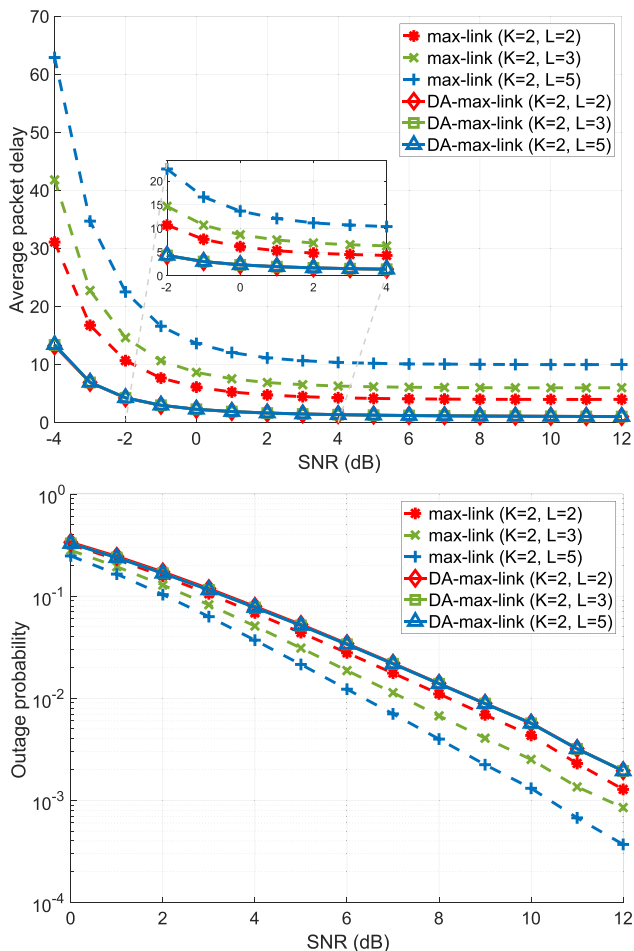
FIGURE 4. Average delay (top) and outage probability (bottom) of DA − max − link algorithm for *K* = 2 and *L* = 2, 3, 5.

Remark 1: We omit any analysis for this scheme, since we believe it is not a good choice for reducing the average delay. As we have observed in the numerical evaluation, this scheme results in empty buffers with a consequence of diversity loss and hence, while the delay is reduced, the throughput of the system is low. This triggered the work appearing in Section V, where we propose another scheme that accounts for the diversity of the network as well.

V. DELAY- AND DIVERSITY-AWARE RELAY SELECTION

Regarding the diversity gain of the network, it has been observed that the prioritization of packets residing in the relays' buffers over packets awaiting to be transmitted by the source degrades the diversity of DA − max − link, resulting in increased outages. This is depicted for larger *L* values in Figure 6.

Below, another protocol is presented, overcoming diversity degradation by sacrificing the improvement of the average delay performance, in order to maintain higher diversity. It should be noted that DA − HRS does not suffer from reduced diversity. This is explained by the decision process in the two time-slots of a frame: In the first slot,
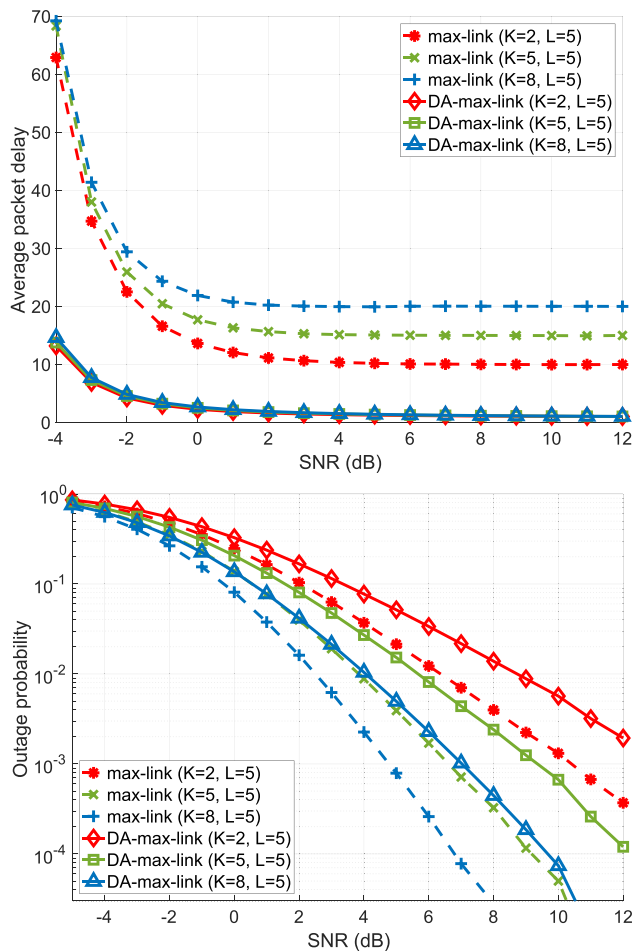
FIGURE 5. Comparison of average delay (top) and outage probability (bottom) between DA − max − link and max − link algorithms for *K* = 2, 5, 8 and *L* = 5.
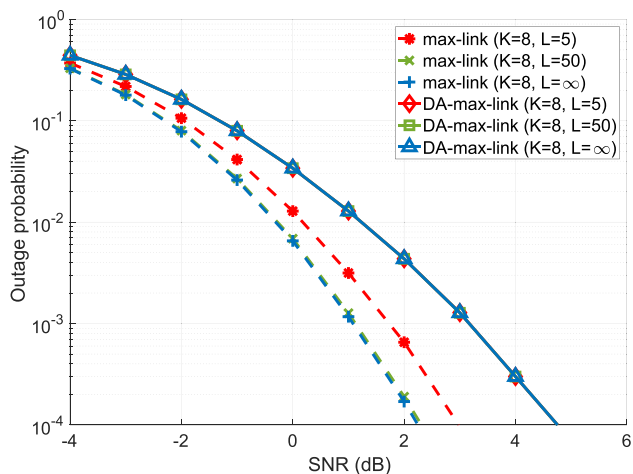
FIGURE 6. Comparison between max − link and DA − max − link algorithms of outage probability for *K* = 8 and *L* = 5, 50, ∞.

a packet is transmitted towards the relay with the minimum number of packets in its buffer, thus prioritizing empty buffers. Then, in the second slot, packet transmission is performed from the relay with the maximum number of

packets in its buffer, and so, relays with a single packet are not frequently selected for transmission towards the destination. Algorithm 3 describes, the Diversity- and Delay-Aware (DDA) $\max-\text{link}$ ($\text{DDA}-\max-\text{link}$) policy.

Algorithm 3 Diversity- and Delay-Aware $\max-\text{link}$ Relay Selection

1: **input** Q, $\mathcal{F}_{SR}$, $\mathcal{F}_{RD}$
2: **if** $\mathcal{F}_{SR} = \emptyset$ **and** $\mathcal{F}_{RD} = \emptyset$ **then**
3:      No packet transmission takes place.
4: **else**
5:      **if** $\mathcal{F}_{SR} = \emptyset$ **then**
6:          $j = \arg\max_{i \in \mathcal{F}_{RD}} Q_i$ ($\{R \rightarrow D\}$ link)
7:      **else**
8:          $\widetilde{\mathcal{F}}_{SR} \triangleq \{i : i \in \mathcal{F}_{SR}, Q_i \leq 1\}$
9:          **if** $\widetilde{\mathcal{F}}_{SR} \neq \emptyset$ **then**
10:            $k = \arg\min_{i \in \widetilde{\mathcal{F}}_{SR}} Q_i$ ($\{S \rightarrow R\}$ link)
11:          **else**
12:            $\widetilde{\mathcal{F}}_{RD} \triangleq \{i : i \in \mathcal{F}_{RD}, Q_i \geq 2\}$
13:            **if** $\widetilde{\mathcal{F}}_{RD} \neq \emptyset$ **then**
14:               $j = \arg\max_{i \in \widetilde{\mathcal{F}}_{RD}} Q_i$ ($\{R \rightarrow D\}$ link)
15:            **else**
16:               $\hat{\mathcal{F}}_{SR} \triangleq \{i : i \in \mathcal{F}_{SR}, Q_i \geq 2\}$
17:               $k = \arg\min_{i \in \hat{\mathcal{F}}_{SR}} Q_i$ ($\{S \rightarrow R\}$ link)
18:            **end if**
19:          **end if**
20:      **end if**
21: **end if**
22: **Output** Link $\{R_j \rightarrow D\}$ or $\{S \rightarrow R_k\}$ for transmission.

A. DISTRIBUTED IMPLEMENTATION

Again, even though at every time-slot, all available links are competing, in the $\text{DDA}-\max-\text{link}$ policy, priorities are interchanged between $\{S \rightarrow R\}$ and $\{R \rightarrow D\}$ depending on the queue length as follows. The CSI acquisition is done in the same way, as in $\text{DA}-\text{HRS}$ and the competition takes place in *three* phases: in the *first phase*, the competition is done for the $\{S \rightarrow R\}$ link (contrary to $\text{DA}-\max-\text{link}$), where the relays with one or no packet in their queue compete. If there is no short duration flag packet it means that $\widetilde{\mathcal{F}}_{SR}$, as defined in Algorithm 3 is an empty set. Then, the *second phase* is initiated with the competition for the $\{R \rightarrow D\}$ link, where the relays with two or more packets in their queue compete. If there is no short duration flag packet it means that $\widetilde{\mathcal{F}}_{RD}$, as defined in Algorithm 3 is an empty set. Then, the *third phase* is initiated with a competition for the $\{S \rightarrow R\}$ link, where the relays with more than one packets in their queue compete. Note that if a flag packet appears in the first phase, the second phase is skipped; similarly, if a flag packet appears in the second phase, the third phase is skipped.

B. NUMERICAL EVALUATION

Figure 7 includes the performance comparison of $\text{DDA}-\max-\text{link}$ and $\max-\text{link}$, when $K = 2$ and buffer

FIGURE 7. Average delay (top) and outage probability (bottom) for the $\text{DDA}-\max-\text{link}$ algorithm for $K = 2$ and $L = 2, 3, 5$.

size L varies. In terms of average delay, $\max-\text{link}$ is superior for small buffer sizes ($L < 4$). For $L = 5$, $\text{DDA}-\max-\text{link}$ outperforms $\max-\text{link}$. It must be noted that the average delay values in the examples of $\text{DDA}-\max-\text{link}$ (and $\max-\text{link}$) reach the theoretical values, as derived later in the asymptotic performance analysis in Section VII.

Next, Figure 8 shows additional examples for fixed buffer size $L = 5$ and varying K. Since $L \geq 4$, as discussed in the analysis, $\text{DDA}-\max-\text{link}$ exhibits improved delay performance compared to $\max-\text{link}$. Moreover, $\text{DDA}-\max-\text{link}$ is superior to $\max-\text{link}$, when the outage probability is considered, when compared to $\text{DA}-\max-\text{link}$, providing significantly inferior performance.

VI. THEORETICAL ANALYSIS

Networks consisting of nodes equipped with finite (and infinite) buffer sizes have been traditionally modeled using Discrete Time Markov Chains (DTMC). For the network model that we consider, [10] proposed a framework to analyze the performance of the $\max-\text{link}$ algorithm, which is general enough and has been subsequently used in numerous works in the field to analyze buffer-aided relay selection mechanisms.
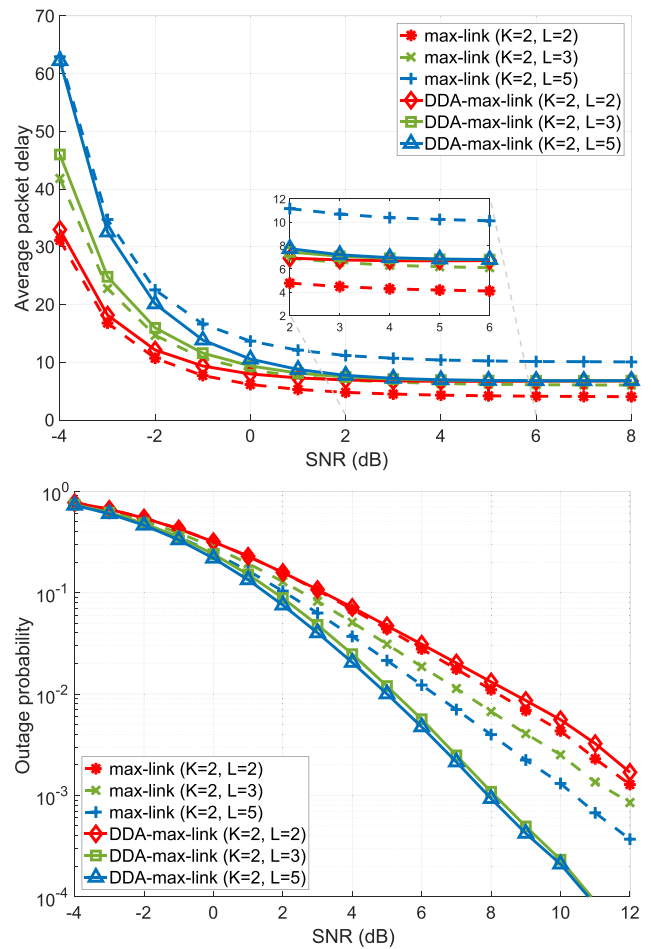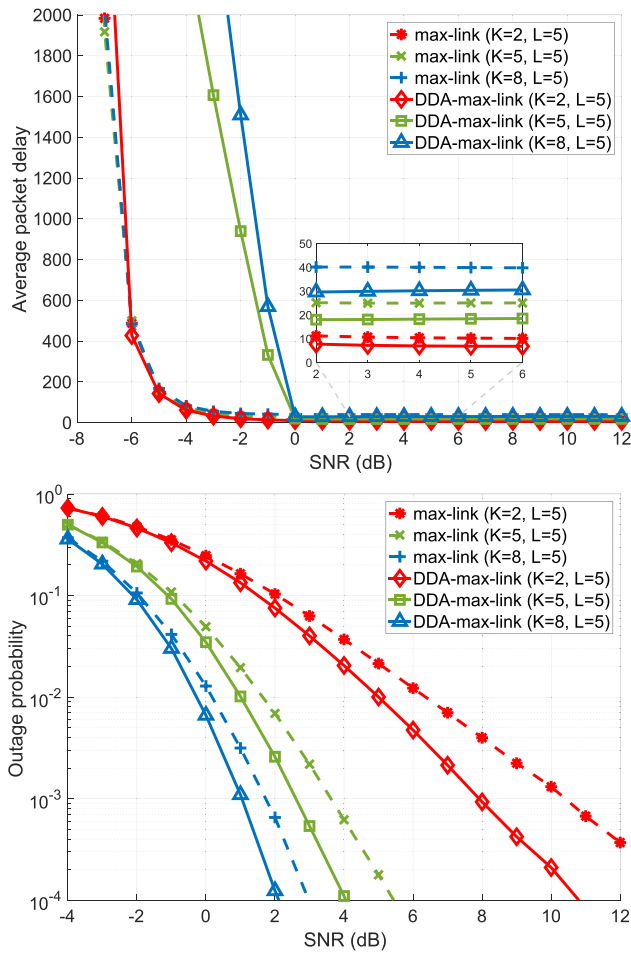
FIGURE 8. Average delay (top) and outage probability (bottom) for the DDA $-$ max $-$ link algorithm for $K = 2, 5, 8$ and $L = 5$.

In what follows, we first provide the general framework and next, we give examples of our proposed algorithms which are justified by numerical examples.

States of the DTMC: Each possible state of the buffers is represented by a state of the DTMC, i.e., all the possible $(L + 1)^K$ combinations of the buffer sizes comprise the states of the DTMC, which can be predefined in a random way. Hence, the state of the DTMC can be expressed as

$$S_r \triangleq \left(Q_1^{(r)} Q_2^{(r)} \ldots Q_K^{(r)} \right), \quad r \in \mathbb{N}_+, \ 1 \leq r \leq (L + 1)^K.$$

Construction of the state transition matrix of the DTMC: Given the states of the DTMC, the transition probabilities between the different states are given by the probabilities of successful transmission of packets either on the $\{S \to R\}$ link or the $\{R \to D\}$ link. Assume that at every transmission, one packet is transmitted. Denote by $\mathbf{A} \in \mathbb{R}^{(L+1)^K \times (L+1)^K}$ the matrix of transition probabilities of the DTMC, in which entry

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

is the probability to transit from state S_j at time t to state S_i at time $t + 1$. To construct the transition matrix $\mathbf{A}$, we need to

determine the probabilities of transiting between the different states of the buffers. More specifically, at each time-slot, the state of the buffers can be changed as follows:

(i) the number of packets of a buffer can be increased by one, if the source node is selected for transmission and the transmission to the relay is successful,

(ii) the number of packets of a relay buffer can be decreased by one, if a relay node is selected for transmission and the transmission is successful, and

(iii) the buffer state does not change when all the possible $\{S \to R\}$ and $\{R \to D\}$ links are in outage.

By denoting $\mathcal{C}_r$ the set of active links (i.e., those not excluded due to empty or full buffers) at a specific time-slot, then the outage probability of the system at state r is given by

$$\bar{p}_r = \prod_{\ell \in \mathcal{C}_r} \left(1 - \exp\left(-\frac{\gamma_0 \eta_{j(\ell)}}{P_{i(\ell)}} \right) \right), \quad (3)$$

where $i(\ell)$ (resp. $j(\ell)$) denotes the transmitter (resp. receiver) on link ℓ and $P_{i(\ell)}$ denotes its transmit power. Even though with this formulation we can consider asymmetric links (contrary to [25]), we investigate the case of symmetric links only for simplicity of exposition. For symmetric links, the outage probability of the system at state r is given by

$$\bar{p}_r = \left(1 - \exp\left(-\frac{\gamma_0 \eta}{P} \right) \right)^{|\mathcal{C}_r|}. \quad (4)$$

In the case of symmetric links, the probability of at least one link not being in outage among the available active links at state r is

$$p_r = \frac{1}{|\mathcal{C}_r|} \left[1 - \left(1 - \exp\left(-\frac{\gamma_0 \eta}{P} \right) \right)^{|\mathcal{C}_r|} \right]. \quad (5)$$

Properties of the DTMC: Since the states of the DTMC are finite and they form a strongly connected directed graph, it can be shown [10] that the DTMC is Stationary, Irreducible and Aperiodic (SIA), and as a result, a steady state π exists and satisfies $\mathbf{A}\pi = \pi$. Next, we revise *general* analytical expressions for *(a)* the outage probability, *(b)* the average throughput and, *(c)* the average packet delay. These expressions are useful in almost any relay selection proposed mechanism for finite-length BA relay selection.

Outage probability: When an outage event occurs, there is no change in the buffer state. As a result, one can easily compute the outage probability by considering the probabilities of being at a stage and having an outage, i.e.,

$$p_{\text{out}} = \sum_{r=1}^{(L+1)^K} \pi_r \bar{p}_r = \text{diag}(\mathbf{A})\pi. \quad (6)$$

From Eq. (6) it is easy to deduce that once the state matrix $\mathbf{A}$ is constructed and the steady state π is computed, the outage probability is easily computed.

Average throughput: When at a given time-slot there is only one transmission (either from the source or from a relay (see [10], [24]), the average data rate ρ is $1/2$ since the

destination is reached in two hops. However, if the mechanism proposed accounts for successive transmissions as well, then ρ approaches 1. The percentage of successfully transmitted packets is given by $(1 - p_{\text{out}})$, and therefore, the average throughput is given by

$$\mathbb{E}[T] = \rho(1 - p_{\text{out}}),$$

where $\rho \in \{1/2, 1\}$. If the links are i.i.d., the average throughput of each relay R_j is the same as all the other relays, i.e.,

$$\mathbb{E}[T_j] = \frac{\rho(1 - p_{\text{out}})}{K}. \tag{7}$$

Average packet delay: In this work, we consider the delay of a packet to be the number of time-slots between the time the packet arrives at a relay until the time it reaches the destination. Note that when the packet is at the source, no delay is assumed. The average packet delay under this framework has been derived in [33]. We include the results herein for i.i.d. channels, for completeness of exposition. Since the channels are i.i.d., the average delay is the same on all relays. As a result, it is sufficient to consider the average delay on one relay only. By Little's law [34], the existence of a steady state implies finite average packet delay, denoted by $\mathbb{E}[d_j]$, and it can be expressed as

$$\mathbb{E}[d_j] = \frac{\mathbb{E}[L_j]}{\mathbb{E}[T_j]}, \tag{8}$$

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 can be deduced from the DTMC and it is given by

$$\mathbb{E}[L_j] = \sum_{r=1}^{(L+1)^K} \pi_r Q_j^{(r)}, \tag{9}$$

and the average throughput is given in (7). By substituting (6) into (7), and then (7) and (9) into (8), we obtain the expression for the average delay, i.e.,

$$\mathbb{E}[d_j] = \frac{K \sum_{r=1}^{(L+1)^K} \pi_r Q_j^{(r)}}{\rho \left(1 - \sum_{r=1}^{(L+1)^K} \pi_r \bar{p}_r\right)}. \tag{10}$$

Note that all the proposed algorithms in this paper, as well as other protocols proposed in the literature, fit in this framework with $\rho = 1/2$, once the state transition matrix of the DTMC is constructed for each algorithm. Then, analytical expressions for performance metrics, such as outage probability and average delay, can be derived.

A. DA − HRS

In the case of HRS and, subsequently DA − HRS, the evolution of the system can be obtained by forming two Markov chains: one for the first time-slot of the time-frame and one for the second time-slot of the time-frame; this approach was proposed in [25] for the generalized MMRS (G-MMRS). Following this approach *mutatis mutandis*, a state transition
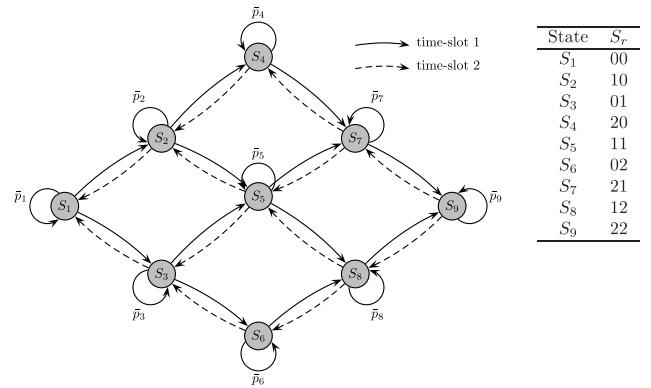
FIGURE 9. DTMC of a 2-hop network, in which time-frames are divided into two time-slots, consisting of $K = 2$ relays with buffers of size $L = 2$. In the first time-slot, the DTMC consists of the solid lines (self-loops included). In the second time-slot, the DTMC consists of the dashed lines and the self-loops.

from the first slot of a time-frame to that of the next time-frame is given by the transition matrix $\mathbf{A}_{2,1} \triangleq \mathbf{A}_2\mathbf{A}_1$, where $\mathbf{A}_1$ is the transition matrix corresponding to the Markov chain of the first time-slot and $\mathbf{A}_2$ is the transition matrix corresponding to the Markov chain of the second time-slot. Correspondingly, a state transition from the second time-slot of a time-frame to that of the next time-frame is given by the transition matrix $\mathbf{A}_{1,2} \triangleq \mathbf{A}_1\mathbf{A}_2$. It can be easily shown that both transitions matrices are SIA and, therefore, there exists a steady state distribution for each Markov chain. Let $\pi_{1,2}$ and $\pi_{2,1}$ correspond to the steady state distribution of $\mathbf{A}_{1,2}$ and $\mathbf{A}_{2,1}$, respectively. Then, the outage probability is given by

$$p_{\text{out}} = p_{\text{out}}^{(2,1)} + \left(1 - p_{\text{out}}^{(2,1)}\right) p_{\text{out}}^{(1,2)}$$
$$\overset{(a)}{=} \text{diag}(\mathbf{A}_1)\pi_{2,1} + \left(1 - \text{diag}(\mathbf{A}_1)\pi_{2,1}\right) \text{diag}(\mathbf{A}_2)\pi_{1,2}, \tag{11}$$

where $p_{\text{out}}^{(1,2)}$ and $p_{\text{out}}^{(2,1)}$ correspond to the outage probabilities for each of the Markov chains and (a) stems from Eq. (6).

Remark 2: It must be noted that, if one had proposed the delay-aware MMRS (DA − MMRS), the analysis would have been the same with the difference that the outage probability would be given by [25]

$$p_{\text{out}} = p_{1,2}p_{\text{out}}^{(1,2)} + p_{2,1}p_{\text{out}}^{(2,1)} = \frac{1}{2}\left(p_{\text{out}}^{(1,2)} + p_{\text{out}}^{(2,1)}\right)$$
$$= \frac{1}{2}\text{diag}(\mathbf{A}_2)\pi_{1,2} + \frac{1}{2}\text{diag}(\mathbf{A}_1)\pi_{2,1}, \tag{12}$$

where $p_{2,1}$ and $p_{1,2}$ are the probabilities of being in the first or the second slot, respectively; note that $p_{2,1} = p_{1,2} = 1/2$ (the steady state distribution of a TDMC with 2 states).

Example: Consider the case of 2 relays with a buffer of size 2 each, i.e., $K = L = 2$.

For simplicity of exposition, we assume that all the links are i.i.d. with probability of success equal to p (and, correspondingly, the probability of failure is equal to $\bar{p}$;
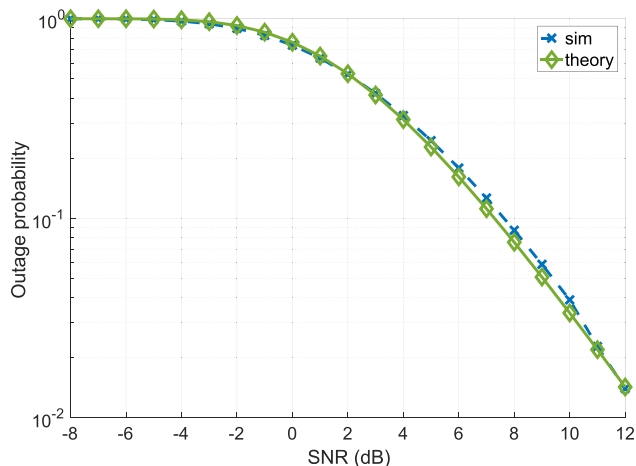
FIGURE 10. Analytical results of the outage probability for DA − HRS closely match the simulation results.

FIGURE 11. DTMC of a 2-hop network consisting of $K = 2$ relays with buffers of size $L = 3$. The transition probability matrix $\mathbf{A} \in \mathbb{R}^{16 \times 16}$ for DDA − max − link can be deduced from the DTMC.

thus, $p + \bar{p} = 1$). Therefore, for DA − HRS the transition matrices are

$$\mathbf{A}_1 = \begin{bmatrix} \bar{p}^2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ p_1 & \bar{p}^2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ p_1 & 0 & \bar{p}^2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & p\bar{p} & 0 & \bar{p} & 0 & 0 & 0 & 0 & 0 \\ 0 & p & p & 0 & \bar{p}^2 & 0 & 0 & 0 & 0 \\ 0 & 0 & p\bar{p} & 0 & 0 & \bar{p} & 0 & 0 & 0 \\ 0 & 0 & 0 & p & p_1 & 0 & \bar{p} & 0 & 0 \\ 0 & 0 & 0 & 0 & p_1 & p & 0 & \bar{p} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & p & p & 1 \end{bmatrix}$$

and

$$\mathbf{A}_2 = \begin{bmatrix} 1 & p & p & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \bar{p} & 0 & p & p_1 & 0 & 0 & 0 & 0 \\ 0 & 0 & \bar{p} & 0 & p_1 & p & 0 & 0 & 0 \\ 0 & 0 & 0 & \bar{p} & 0 & 0 & p\bar{p} & 0 & 0 \\ 0 & 0 & 0 & 0 & \bar{p}^2 & 0 & p & p & 0 \\ 0 & 0 & 0 & 0 & 0 & \bar{p} & 0 & p\bar{p} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \bar{p}^2 & 0 & p_1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \bar{p}^2 & p_1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \bar{p}^2 \end{bmatrix},$$

where $p_1 = \frac{1-\bar{p}^2}{2}$. Note that the DTMC of HRS and DA − HRS are different, due to priorities set; for example, in $\mathbf{A}_1$ from S_2 it would not matter if the next state is S_4 or S_5, whereas in our scheme, priority is given to S_5. Note also that the probability of outage of the states at each of the two timeslot differs. The validity of the theoretical results with respect to simulations for DA − HRS is demonstrated in Figure 10.

B. DDA − max − link

As it is the case with the DA − HRS, DDA − max − link follows a similar pattern. The validity of the theoretical design is demonstrated via an illustrative example.

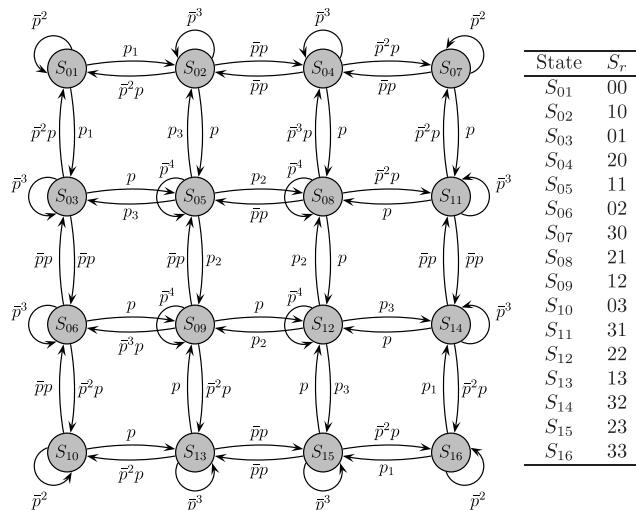*Example:* Consider the case of 2 relays with a buffer of size 3 each, i.e., $K = 2, L = 3$. Since the transition

State	S_r
S_{01}	00
S_{02}	10
S_{03}	01
S_{04}	20
S_{05}	11
S_{06}	02
S_{07}	30
S_{08}	21
S_{09}	12
S_{10}	03
S_{11}	31
S_{12}	22
S_{13}	13
S_{14}	32
S_{15}	23
S_{16}	33

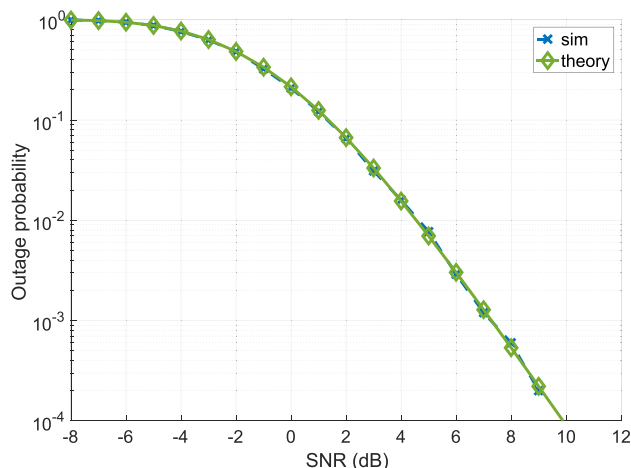**FIGURE 12.** Analytical results of the outage probability for DDA − max − link match the simulation results.

probability matrix $\mathbf{A} \in \mathbb{R}^{16 \times 16}$ is quite big, we omit it, but it can be easily deduced from the DTMC in Figure 11.

Note that $p_2 = \frac{p(1+\bar{p})}{2}$ and $p_3 = \bar{p}^2 p_2$. Again, the outage probability, as derived from the theoretical analysis of DDA − max − link matches the results of the simulations, as shown in Figure 12.

VII. ASYMPTOTIC PERFORMANCE

In this section, we use the theoretical framework from Section VI in order to characterize the asymptotic behavior (high SNR regime) of DA − HRS and DDA − max − link in terms of average delay.

A. DA − HRS

First, we construct the DTMC with the admissible states that the DA − HRS algorithm reaches. More specifically, it can be easily deduced that at high SNR regimes, outages due to the lack of data in the queues are avoided by having one packet
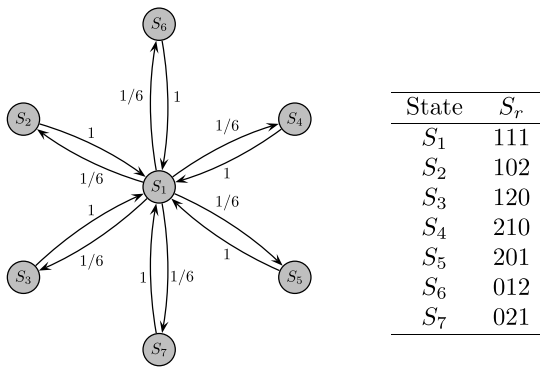
FIGURE 13. The DTMC at the high SNR regime (outage probability is negligible) of a network using the DA − HRS algorithm, consisting of 3 relays.

in each data queue, such that there are transmissions to and from the relay and the state of the buffer after each time-frame returns to the one at the beginning of the time-frame (recall that each time-frame consists of two time-slots).

Figure 13 shows an example of the DTMC at the high SNR regime of a network using the DA − HRS algorithm for a network with 3 relays. The state transition matrix is given by

$$\mathbf{A} = \begin{bmatrix} 0 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1/6 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1/6 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1/6 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1/6 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1/6 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1/6 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix},$$

and the steady state distribution is

$$\pi = \begin{bmatrix} 1/2 & 1/12 & 1/12 & 1/12 & 1/12 \end{bmatrix}.$$

Hence, the average queue length at relay R_j is

$$\mathbb{E}[L_j] = \sum_{r=1}^{7} \pi_r Q_j^{(r)}$$

$$= 1 \times \frac{1}{2} + (0 + 1 + 2)\left(2 \times \frac{1}{12}\right) = 1. \quad (13)$$

By Little's law, the average delay is given by $\mathbb{E}[d_j] = 1 + 1/(1/6) = 7$, where the 1 is added due to the fact that one extra time-slot is required for the packet to reach the destination.

From the example of 3 relays, one can easily generalize the results to the case of a network with K relays. More specifically, it can be shown by the construction of the DTMC that the steady state distribution becomes

$$\pi = \begin{bmatrix} 1/2 & 1/2K & 1/2K & \dots & 1/2K \end{bmatrix}. \quad (14)$$

Additionally, similarly to Eq. (13), it is shown that for any number of relays, the average queue length at relay R_j is $\mathbb{E}[L_j] = 1$. By Little's law again, the average delay is

$$\mathbb{E}[d_j] = 1 + \frac{1}{1/2K} = 2K + 1. \quad (15)$$

Note that in the high SNR regime the average delay is independent of the buffer size L. This is expected since the state transition matrix does not depend on the buffer size. The theoretical results are justified in Figure 2, Section III-B where for $K = 5$ and different buffer sizes the average delay converged to $2 \times 5 + 1 = 11$.

Remark 3: Note that in the asymptotic regime, the queue sizes will be balanced. The number of packets in the buffer will depend on the initial condition. If, for example, we start with $\hat{S}_1 = \begin{bmatrix} 2 & 2 & 2 \end{bmatrix}$, then there will be again 7 states all together. It is obvious that for buffers with $L \geq 4$, full diversity is guaranteed, since no full or empty buffers will exist in the network.

B. DDA − max − link

First, we provide the average delay of max − link. This is done in two steps. First, we find the throughput of each relay; the selection of a relay is equiprobable, and hence, the average throughput at any relay R_j is ρ/K, where $\rho = 1/2$ due to half-duplexity. As a result, $\mathbb{E}[T_j] = 1/2K$. Second, we find the average queue length at relays; it can be easily deduced that the average queue length is $\mathbb{E}[L_j] = \frac{L}{2}$. By Little's law,

$$\mathbb{E}[d_j] = \mathbb{E}[d] = KL. \quad (16)$$

From Eq. (16), it is observed that as either the number of relays or the buffer size increases, the average delay of the max − link algorithm increases, which is undesirable in delay-intolerant applications. The derivation of the average delay for max − link at the high SNR regime is given in [33].

Next, the average delay of the DDA − max − link is derived for the high SNR regime. We show that it is independent of the buffer size L and for $L \geq 4$, the average delay of DDA − max − link is smaller than that of max − link, for any number of relays.
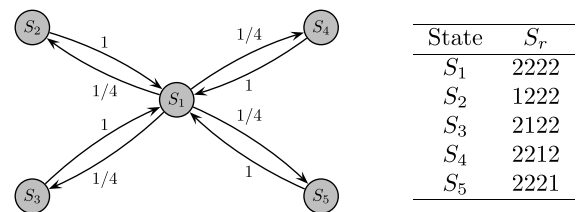

FIGURE 14. DTMC of a network consisting of 4 relays at the high SNR regime, where the outage probability is negligible.

First, as it was the case for the DA − HRS algorithm, the DTMC with the admissible states of DDA − max − link in the high SNR regime is constructed. Our proposed algorithm aims at having 2 packets in each relay. At the high SNR regime, when one packet from a relay is transmitted to the destination, in the next time-slot a packet is transmitted from the source to that relay to recover the desired queue size. As a result, the number of admissible states is limited. To demonstrate this, an example of the DTMC for a network with 4 relays at the high SNR regime is given in Figure 14.

For a network consisting of 4 relays, the number of states is 5. If we had an additional relay, then we would have an additional state; hence, the number of states is always $K + 1$.

The state transition matrix is given by

$$\mathbf{A} = \begin{bmatrix} 0 & 1 & 1 & 1 & 1 \\ 1/4 & 0 & 0 & 0 & 0 \\ 1/4 & 0 & 0 & 0 & 0 \\ 1/4 & 0 & 0 & 0 & 0 \\ 1/4 & 0 & 0 & 0 & 0 \end{bmatrix},$$

and, therefore, the steady state is given by

$$\pi = \begin{bmatrix} 1/2 & 1/8 & 1/8 & 1/8 & 1/8 \end{bmatrix}.$$

Thus, the average queue length at relay R_j is given by

$$\mathbb{E}[L_j] = \sum_{r=1}^{5} \pi_r Q_j^{(r)} = 2 \times \frac{1}{2} + 3\left(2 \times \frac{1}{8}\right) + 1 \times \frac{1}{8} = \frac{15}{8}.$$

So, by Little's law, the average delay is given by

$$\mathbb{E}[d_j] = \frac{15/8}{1/8} = 15.$$

For a network of K relays it can be easily deduced by the construction of the DTMC that the steady state distribution is given by $\pi = \begin{bmatrix} 1/2 & 1/2K & 1/2K & \ldots & 1/2K \end{bmatrix}$, and, hence, the average queue length at relay R_j is

$$\mathbb{E}[L_j] = \frac{4K - 1}{2K}.$$

Hence, by Little's law, the average delay is given by

$$\mathbb{E}[d_j] = \frac{(4K - 1)/2K}{1/2K} = 4K - 1. \qquad (17)$$

Note that, similarly to DA $-$ HRS, in the high SNR regime the average delay is independent of the buffer size L. The theoretical results are justified via the simulations in Section V-B.

Remark 4: From Eq. (16) and (17), it can be deduced that for $L \geq 4$, the average delay of DDA $-$ max $-$ link *is lower than that of* max $-$ link *for any size of network (i.e., $4K - 1 \leq KL$). In reality, buffers have a much larger capacity than $L = 4$, suggesting that* DDA $-$ max $-$ link *should be preferred in practice over the* max $-$ link.

Remark 5: By choosing to have at least 2 packets in the queue is to guarantee high diversity, provided the size of the buffers satisfies $L \geq 3$. If $L \geq 3$, then full diversity is guaranteed, since no full or empty buffers will exist in the network. Note that for DA $-$ HRS, *a buffer of size $L \geq 4$ is required for full diversity; see Remark 3.*

VIII. COMPARISONS

In this section, we compare the *two* main policies proposed in this paper; namely the DA $-$ HRS and the DDA $-$ max $-$ link algorithms. In both policies, we considered the delay and the diversity jointly while aiming to reduce the average packet delay of the system. While the
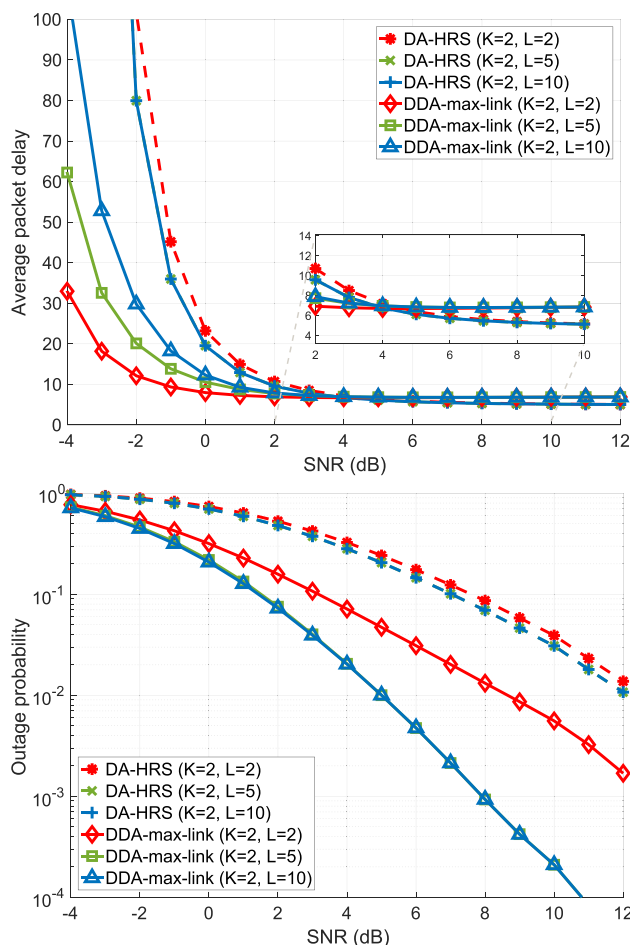

FIGURE 15. Average delay (top) and outage probability (bottom) for the DA $-$ HRS and the DDA $-$ max $-$ link algorithms for $K = 2$ and $L = 2, 5, 10$.

average packet delay as a metric might not be minimized, the joint consideration of delay and diversity reduces the delay considerably and at the same time, it reduces the outage probability; this is evident from the examples shown so far. In what follows, we compare the two main schemes in terms of *average delay* and *outage probability* in order to assess which one is better to use and under which circumstances. Furthermore, the outage performance of DA $-$ HRS and DDA $-$ max $-$ link with outdated CSI is investigated in order to assess the robustness of each policy when the CSI for relay selection might differ from the one during the transmission, a condition which is often the case in realistic implementations.

A. PERFECT CSI

In Figure 15, we have the average delay (top) and outage probability (bottom) for the DA $-$ HRS and the DDA $-$ max $-$ link algorithms for $K = 2$ and $L = 2, 5, 10$ with perfect CSI. At low SNR, the DDA $-$ max $-$ link algorithm has lower delay, since it does not require both $\{S \rightarrow R\}$ and $\{R \rightarrow D\}$ channels to be feasible for transmissions. However, as the SNR becomes better, the performance
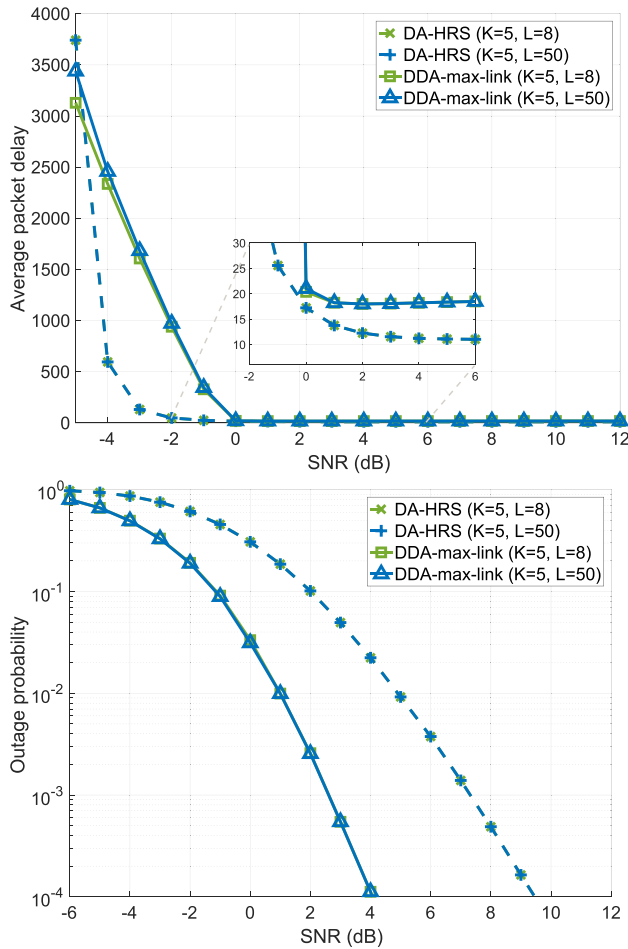
FIGURE 16. Average delay (top) and outage probability (bottom) for the DA − HRS and the DDA − max − link algorithms for *K* = 5 and *L* = 8, 50.

FIGURE 17. Outage probability for *K* = 2 and *L* = 8 (top) and *K* = 5 and *L* = 8 (bottom) for DA − HRS and DDA − max − link with perfect and outdated CSI with ρ = 0.9 and ρ = 0.99.

of DA − HRS improves and for high SNR, the average packet delay becomes lower than that of DDA − max − link. The outage probability of the DA − HRS is higher than that of DDA − max − link, because it requires both {$S{\rightarrow}R$} and {$R{\rightarrow}D$} channels to be feasible for a transmission to take place.

In Figure 16, we have the average delay (top) and outage probability (bottom) for the DA − HRS and the DDA − max − link algorithms for *K* = 5 and *L* = 8, 50. It is evident that for low SNR, DDA − max − link is more preferable whereas for high SNR, DA − HRS performs better. From both comparisons it is evident that a policy providing the properties of both would be beneficial, i.e., a modified version of DDA − max − link that in high SNR enforces the conventional two-slot operation, as in BRS, HRS and DA − HRS. Also, note that *the steady-state average delay* coincides with the theoretical average delay for the high SNR regime derived in the analysis, and it is, as expected, independent of the queue size *L*.

B. OUTDATED CSI
In the next comparison, the practical case of outdated CSI is considered. In this case, the actual channel response h_{ij},
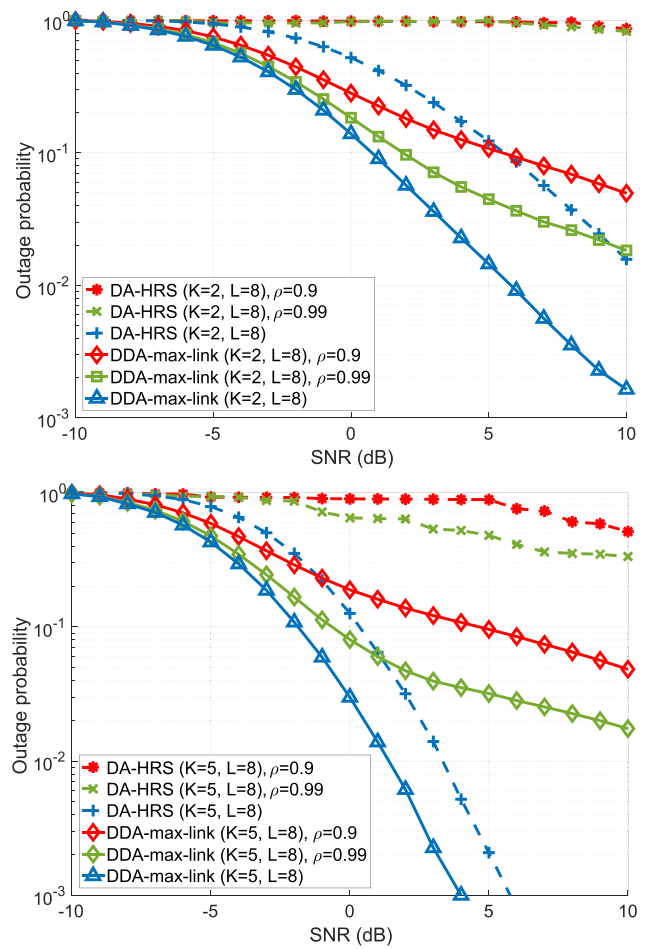
conditioned on the channel response $\hat{h}_{ij}$ that was estimated in the {$i{\rightarrow}j$} link, during the selection period, is given by [31]

$$h_{ij}|\hat{h}_{ij} \sim \mathcal{CN}(\rho_i\hat{h}_{ij}, 1 - \rho_i^2), \qquad (18)$$

where $\rho_i \in [0, 1)$ denotes the correlation coefficient between h_{ij} and $\hat{h}_{ij}$. By adopting the Jakes' model [36], 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.

Figure 17 depicts the outage probability for *K* = 2, *L* = 8 (top) and *K* = 5, *L* = 8 (bottom) for DA − HRS and DDA − max − link with perfect and outdated CSI, when ρ = 0.9 and ρ = 0.99. From this comparison, it can be observed that DA − HRS is severely affected by outdated CSI, as during a frame, two selection processes are performed and the probability that one or both relays being in outage increases. Nonetheless, DDA − max − link, due to its single relay selection is more robust against outdated CSI and its performance improves when *K* increases for low and medium SNR. However, as shown in [31], a diversity order equal to one is obtained, independently of *K*.

Moreover, the performance degrades to that of single relay networks or to random relay selection, even when $\rho_i \approx 1$ for asymptotically high SNR.

IX. CONCLUSIONS AND FUTURE DIRECTIONS

A. CONCLUSIONS

This work presented various relay selection policies, aiming to improve the delay performance of BA relaying, in order to enable applications characterized by delay-sensitivity. The comparisons of the policies showed that adopting the diversity- and delay-aware policy provides improved overall performance, although the policies that do not maintain the network's diversity offer lower average delay. Each policy was investigated through theoretical analysis, numerical and simulation results and their comparisons outline their efficiency. Finally, $DDA - max - link$ has been observed to provide robustness against outdated CSI for low and medium SNR.

B. FUTURE DIRECTIONS

While proposed relay selection mechanisms in the literature, as well as our proposed policies, are shown to improve the performance in terms of delays, there is an interplay between delay and diversity. This is clearly indicated in our proposed $DDA - max - link$, where large diversity, especially in high SNR, increases delays unnecessarily. Part of ongoing research is to develop policies that adaptively choose the number of relays that need to have packets in their buffers (and, subsequently, the diversity) based on the channel conditions.

In case the source and possibly (some of) the relays have stochastic arrival of packets, back-pressure mechanisms [37] should be employed to establish stability of the ingress buffer (i.e., the buffer corresponding to the source where traffic is input to the network) [38], while at the same time, delays and divergence are considered. Furthermore, real-time and critical applications necessitate packets to meet hard per-packet deadline constraints. Towards this direction, part of ongoing research focuses on (i) the evaluation of our proposed framework and (ii) the development of advanced protocols in scenarios with hard per-packet deadline constraints, where packets are forwarded based on the delays they have encountered (as in [39]).

Finally, another fertile research area is the integration of Non-Orthogonal Multiple Access (NOMA) in BA relay networks. Recently, relevant works have emerged [40]–[43] focusing on selecting the optimal transmission strategy when adaptive link selection is available. Nonetheless, algorithms maintaining the diversity of multi-user networks, while employing hybrid NOMA/OMA transmissions should be devised.

REFERENCES

[1] "Cisco visual networking index: Global mobile data traffic forecast update, 2014–2019," Cisco Syst. Inc., San Jose, CA, USA, White Paper, Feb. 2015. [Online]. Available: https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/mobile-white-paper-c11-520862.html

[2] P. Jonsson *et al.*, "Ericsson mobility report," Ericsson, Stockholm, Sweden, Tech. Rep., Jun. 2018. [Online]. Available: https://www.ericsson.com/assets/local/mobility-report/documents/2018/ericsson-mobility-report-june-2018.pdf

[3] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3062–3080, Dec. 2004.

[4] A. Bletsas, A. Khisti, D. P. Reed, and A. Lippman, "A simple cooperative diversity method based on network path selection," *IEEE J. Sel. Areas Commun.*, vol. 24, no. 3, pp. 659–672, Mar. 2006.

[5] D. Michalopoulos and G. Karagiannidis, "Performance analysis of single relay selection in Rayleigh fading," *IEEE Trans. Wireless Commun.*, vol. 7, no. 10, pp. 3718–3724, Oct. 2008.

[6] N. Nomikos *et al.*, "A survey on buffer-aided relay selection," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 2, pp. 1073–1097, 2nd Quart., 2016.

[7] N. Zlatanov, A. Ikhlef, T. Islam, and R. Schober, "Buffer-aided cooperative communications: Opportunities and challenges," *IEEE Commun. Mag.*, vol. 52, no. 4, pp. 146–153, Apr. 2014.

[8] A. Bletsas, H. Shin, and M. Z. Win, "Cooperative communications with outage-optimal opportunistic relaying," *IEEE Trans. Wireless Commun.*, vol. 6, no. 9, pp. 3450–3460, Sep. 2007.

[9] A. Ikhlef, D. S. Michalopoulos, and R. Schober, "Max-max relay selection for relays with buffers," *IEEE Trans. Wireless Commun.*, vol. 11, no. 3, pp. 1124–1135, Mar. 2012.

[10] I. Krikidis, T. Charalambous, and J. S. Thompson, "Buffer-aided relay selection for cooperative diversity systems without delay constraints," *IEEE Trans. Wireless Commun.*, vol. 11, no. 5, pp. 1957–1967, May 2012.

[11] T. Charalambous, N. Nomikos, I. Krikidis, D. Vouyioukas, and M. Johansson, "Modeling buffer-aided relay selection in networks with direct transmission capability," *IEEE Commun. Lett.*, vol. 19, no. 4, pp. 649–652, Apr. 2015.

[12] N. Zlatanov and R. Schober, "Buffer-aided relaying with adaptive link selection—fixed and mixed rate transmission," *IEEE Trans. Inf. Theory*, vol. 59, no. 5, pp. 2816–2840, May 2013.

[13] W. Wicke, N. Zlatanov, V. Jamali, and R. Schober, "Buffer-aided relaying with discrete transmission rates for the two-hop half-duplex relay network," *IEEE Trans. Wireless Commun.*, vol. 16, no. 2, pp. 967–981, Feb. 2017.

[14] M. Oiwa, C. Tosa, and S. Sugiura, "Theoretical analysis of hybrid buffer-aided cooperative protocol based on max–max and max–link relay selections," *IEEE Trans. Veh. Technol.*, vol. 65, no. 11, pp. 9236–9246, Nov. 2016.

[15] A. A. M. Siddig and M. F. M. Salleh, "Balancing buffer-aided relay selection for cooperative relaying systems," *IEEE Trans. Veh. Technol.*, vol. 66, no. 9, pp. 8276–8290, Sep. 2017.

[16] B. R. Manoj, R. K. Mallik, and M. R. Bhatnagar, "Performance analysis of buffer-aided priority-based max-link relay selection in DF cooperative networks," *IEEE Trans. Commun.*, vol. 66, no. 7, pp. 2826–2839, Jul. 2018.

[17] Z. Tian, Y. Gong, G. Chen, Z. Chen, and J. Chambers, "Buffer-aided link selection with network coding in multihop networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 9, pp. 7195–7206, Sep. 2016.

[18] D. Q. Qiao and M. C. Gursoy, "Buffer-aided relay systems under delay constraints: Potentials and challenges," *IEEE Commun. Mag.*, vol. 55, no. 9, pp. 168–174, Sep. 2017.

[19] D. Poulimeneas, T. Charalambous, N. Nomikos, I. Krikidis, D. Vouyioukas, and M. Johansson, "A delay-aware hybrid relay selection policy," in *Proc. IEEE Int. Conf. Telecomm. (ICT)*, May 2016, pp. 1–5.

[20] S. L. Lin and K. H. Liu, "Relay selection for cooperative relaying networks with small buffers," *IEEE Trans. Veh. Technol.*, vol. 65, no. 8, pp. 6562–6572, Aug. 2016.

[21] P. Xu, Z. Ding, I. Krikidis, and X. Dai, "Achieving optimal diversity gain in buffer-aided relay networks with small buffer size," *IEEE Trans Veh. Technol.*, vol. 65, no. 10, pp. 8788–8794, Oct. 2016.

[22] W. Raza, N. Javaid, H. Nasir, N. Alrajeh, and N. Guizani, "Buffer-aided relay selection with equal-weight links in cooperative wireless networks," *IEEE Commun. Lett.*, vol. 22, no. 1, pp. 133–136, Jan. 2018.

[23] D. Poulimeneas, T. Charalambous, N. Nomikos, I. Krikidis, D. Vouyioukas, and M. Johansson, "Delay- and diversity-aware buffer-aided relay selection policies in cooperative networks," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, Apr. 2016, pp. 1–6.

[24] Z. Tian, Y. Gong, G. Chen, and J. A. Chambers, "Buffer-aided relay selection with reduced packet delay in cooperative networks," *IEEE Trans. Veh. Technol.*, vol. 66, no. 3, pp. 2567–2575, Mar. 2017.

[25] M. Oiwa and S. Sugiura, "Reduced-packet-delay generalized buffer-aided relaying protocol: Simultaneous activation of multiple source-to-relay links," *IEEE Access*, vol. 4, pp. 3632–3646, Jun. 2016.

[26] N. Nomikos, T. Charalambous, D. Vouyioukas, and G. K. Karagiannidis, "Low-complexity buffer-aided link selection with outdated CSI and feedback errors," *IEEE Trans. Commun.*, vol. 66, no. 8, pp. 3694–3706, Aug. 2018.

[27] M. Oiwa, R. Nakai, and S. Sugiura, "Buffer-state-and-thresholding-based amplify-and-forward cooperative networks," *IEEE Wireless Commun. Lett.*, vol. 6, no. 5, pp. 674–677, Oct. 2017.

[28] R. Nakai, M. Oiwa, K. Lee, and S. Sugiura, "Generalized buffer-state-based relay selection with collaborative beamforming," *IEEE Trans. Veh. Technol.*, vol. 67, no. 2, pp. 1245–1257, Feb. 2018.

[29] N. Zlatanov, V. Jamali, and R. Schober, "Achievable rates for the fading half-duplex single relay selection network using buffer-aided relaying," *IEEE Trans. Wireless Commun.*, vol. 14, no. 8, pp. 4494–4507, Aug. 2015.

[30] B. Zhou, Y. Cui, and M. Tao, "Stochastic throughput optimization for two-hop systems with finite relay buffers," *IEEE Trans. Signal Process.*, vol. 63, no. 20, pp. 5546–5560, Oct. 2015.

[31] J. L. Vicario, A. Bel, J. Lopez-Salcedo, and G. Seco, "Opportunistic relay selection with outdated CSI: Outage probability and diversity analysis," *IEEE Trans. Wireless Commun.*, vol. 8, no. 6, pp. 2872–2876, Jun. 2009.

[32] B. Hajek, A. Krishna, and R. O. LaMaire, "On the capture probability for a large number of stations," *IEEE Trans. Commun.*, vol. 45, no. 2, pp. 254–260, Feb. 1997.

[33] Z. Tian, G. Chen, Y. Gong, Z. Chen, and J. A. Chambers, "Buffer-aided max-link relay selection in amplify-and-forward cooperative networks," *IEEE Trans. Veh. Technol.*, vol. 64, no. 2, pp. 553–565, Feb. 2015.

[34] D. P. Bertsekas and R. Gallager, *Data Networks*. Upper Saddle River, NJ, USA: Prentice-Hall, 1992.

[35] M. S. Neiman, "The principle of reciprocity in antenna theory," *Proc. IRE*, vol. 31, no. 12, pp. 666–671, Dec. 1943.

[36] A. Goldsmith, *Wireless Communications*. Cambridge, U.K.: Cambridge Univ. Press, 2005.

[37] L. Tassiulas and A. Ephremides, "Stability properties of constrained queueing systems and scheduling policies for maximum throughput in multihop radio networks," *IEEE Trans. Autom. Control*, vol. 37, no. 12, pp. 1936–1948, Dec. 1992.

[38] L. B. Le, E. Modiano, and N. B. Shroff, "Optimal control of wireless networks with finite buffers," *IEEE/ACM Trans. Netw.*, vol. 20, no. 4, pp. 1316–1329, Aug. 2012.

[39] B. Ji, C. Joo, and N. B. Shroff, "Delay-based back-pressure scheduling in multihop wireless networks," *IEEE/ACM Trans. Netw.*, vol. 21, no. 5, pp. 1539–1552, Oct. 2013.

[40] Q. Zhang, Z. Liang, Q. Li, and J. Qin, "Buffer-aided non-orthogonal multiple access relaying systems in Rayleigh fading channels," *IEEE Trans. Commun.*, vol. 65, no. 1, pp. 95–106, Jan. 2017.

[41] S. Luo and K. C. Teh, "Adaptive transmission for cooperative NOMA system with buffer-aided relaying," *IEEE Commun. Lett.*, vol. 21, no. 4, pp. 937–940, Apr. 2017.

[42] N. Nomikos, T. Charalambous, D. Vouyioukas, G. K. Karagiannidis, and R. Wichman, "Relay selection for buffer-aided non-orthogonal multiple access networks," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2017, pp. 1–6.

[43] H. Cao, J. Cai, S. Huang, and Y. Lu, "Online adaptive transmission strategy for buffer-aided cooperative NOMA systems," *IEEE Trans. Mobile Comput.*, to be published.

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