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LoLA4SOR: A Low-Latency Algorithm for Successive Opportunistic Relaying

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***Abstract*—Buffer-aided (BA) relaying has been proposed as an efficient way to improve the diversity of multi-hop networks. Nonetheless, it results in increased end-to-end delay, as packets tend to reside in the relays' buffers for many time-slots. In order to enable the adoption of BA relays in delay-intolerant applications, the combination with successive relaying can increase the number of packets that are transmitted. In this work, hybrid relay selection algorithms are studied, where delay- and diversity aware (DDA) half-duplex algorithms are complemented with successive BA relaying. Moreover, a hybrid DDA algorithm is presented, namely $\mathrm{LoLA4SOR}$ that adapts to the transmit conditions, switching between half-duplex (HD) and successive relaying (SuR). The performance of $\mathrm{LoLA4SOR}$ is compared to several HD, successive and hybrid algorithms, in terms of outage probability, throughput and delay. The results indicate that $\mathrm{LoLA4SOR}$ provides superior outage and throughput performance, while its delay performance is not affected by the buffer size and, as the number of relays increase, its delay reduces due to the high probability for successive transmissions.**

***Index Terms*—Relay selection, buffer-aided relaying, delay, successive opportunistic relaying, low-latency, diversity.**

I. Introduction

The recent unparalleled increase of mobile data traffic [1] necessitates the development of efficient algorithms providing reliable connectivity and low end-to-end latency. Among the fifth generation (5G) technologies, buffer-aided (BA) cooperative relaying has the potential of improving link diversity, thus resulting in less outages and improved throughput [2]. Moreover, low delay can be maintained, as long as the relaying algorithms take into consideration the delay constraint of the application [3]. In addition, the survey in [4] presented several BA opportunistic relay selection (ORS) algorithms, incorporating half-duplex (HD), full-duplex (FD) and successive relaying (SuR) modes of operation, showing that promising results can be harvested when hybrid algorithms are adopted, switching among the possible relaying modes.

In HD networks, BA relay selection algorithms were developed, dividing one time-slot between $\{S\to R\}$ and $\{R\to D\}$ transmissions [5] (hybrid relay selection - HRS) or exploiting the diversity of all the available links for single link ($\max-\mathrm{link}$) selection without [6] and with direct source-destination ($\{S\to R\}$) connectivity [7]. For single relay networks, adaptive link selection was investigated in [8], showing that due to buffering, HD relaying can surpass the performance of ideal FD relaying if the source and the destination have the same number of antennas as the relay or more. The effect on throughput and delay of full-duplex relaying on random access multiuser networks was studied in [9]–[11].

The modification of HRS and $\max-\mathrm{link}$ towards delay-awareness (DA) has been investigated in various works. In [12], HRS was modified to maintain non-empty and balanced queues by activating the links with the smallest (largest) data queue, among the feasible links. Then, Tian *et al*. prioritized $\{R\to D\}$ transmissions, resulting in a DA version of $\max-\mathrm{link}$ [13], where the average delay converges to two time-slots, without depending on either the number of relays or buffer size. Buffer State Information (BSI) was used in [14] to select the best relay, as long as buffers were not empty or full. Compared to $\max-\mathrm{link}$, a buffer size $L\leq 3$ packets resulted in lower delay. For relays with small buffers, the authors in [15] proposed combined relay selection (CRS), selecting the relay having the minimum number of packets, for reception and the relay having the maximum number of packets, for transmission. CRS offers reduced delay, when compared to HRS and $\max-\mathrm{link}$. Furthermore, HRS and $\max-\mathrm{link}$ were evaluated in [16], providing DA extensions, as well as a delay- and diversity-aware (DDA) version of $\max-\mathrm{link}$, exploiting BSI. The analysis showed that DDA $\max-\mathrm{link}$ offers reduced outages and delay, compared to $\max-\mathrm{link}$ for $L\geq 3$ packets. A similar approach has been adopted in [17] selecting relays that were not on the brink of starvation, thus preserving the diversity. A low-delay hybrid HRS/$\max-\mathrm{link}$ selection algorithm was developed in [18], aiming first for HRS and if selection failed, the algorithm searched all the links to avoid outages through $\max-\mathrm{link}$. Recently, broadcasting in the $\{S\to R\}$ links was integrated in BA relay selection [19], reducing the delay without compromising the diversity. Finally, by adopting broadcasting in the $\{S\to R\}$ link and prioritizing $\{R\to D\}$ transmissions, delay was further reduced in [20], while achieving low-complexity and distributed implementation through the $\mathrm{LoCo-Link}$ selection algorithm.

In another line of research, spectral efficiency can be improved by developing hybrid algorithms with FD capabilities through SuR, while using single antenna HD relays. In [21], HD BA relay selection was combined with SuR in a topology with isolated relays. The authors investigated both adaptive

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and fixed-rate transmission, showing that the proposed *Space Full-Duplex* (SFD) max-max relay selection (MMRS) can double the capacity of HD schemes with adaptive rates, while providing a coding gain for fixed-rates. In a topology where relays are not isolated and interference cancellation (IC) can be achieved, BA successive opportunistic relaying (BA-SOR) was investigated in [22], performing close to the upper-bound of [21], where IRI is negligible. BA-SOR was combined with $\max - \text{link}$ in [23], in order to achieve power adaptation under a pre-specified spectral efficiency threshold. It was shown that switching among BA-SOR and $\max - \text{link}$ is taking place, thus providing resiliency against outages and improved throughput. For cases targeting the reduction network coordination overheads in terms of CSI, distributed switch-and-stay combining (DSSC) [24] has been adopted in [25], where the previously selected relay-pair is used again when it is not in outage, thus avoiding a new round of CSI acquisition and exchange.

It is clear that hybrid BA relay selection algorithms are able to improve the performance of relay networks. Nonetheless, until now, the integration of DA characteristics into hybrid BA relay selection has not been investigated. In this work, we aim to shed light on the performance gains that can be harvested by DA hybrid relay selection. More specifically, we propose LoLA4SOR, a low-latency hybrid algorithm, aiming at reducing delay, while avoiding the diversity losses of DA BA relaying. The performance of LoLA4SOR is evaluated in terms of outage probability, throughput and average delay and comparisons with other state-of-the-art algorithms are given. The results show that LoLA4SOR offers reduced outages and increased throughput, while its latency does not increase with the number of available relays nor with the buffer size.

The remainder of this paper is organized as follows. In Section II, we introduce the system model. In Section III, we first present LoLA4SOR, the low-latency algorithm for successive opportunistic relaying, and we provide theoretical analysis of the algorithm. Next, performance evaluation is provided in Section IV, while conclusions and future directions are given in Section V.

II. System Model

We assume a simple cooperative network consisting of one source S, one destination D and a cluster $\mathcal{C}$ with K decode-and-forward (DF) relays $R_k \in \mathcal{C}$ $(1 \leq k \leq K)$. All relays are HD and therefore they cannot transmit and receive signals simultaneously. It is assumed that a direct link between the source and the destination cannot be established due to deep fading and communication can be established only via relays [26]. Each relay R_k holds a buffer (data queue) of length L_k (number of data elements), where it can store source data that has been decoded at the relay and can be forwarded to the destination. At the beginning, each relay buffer has Q_k data elements; some buffers may as well be empty (i.e., $Q_k = 0$ for some k). For simplicity of exposition, we assume that the length of buffers is the same for all relays, i.e., $L_k = L, \forall\, k \in \{1, 2, \ldots, K\}$. The vector summarizing the queue sizes at the

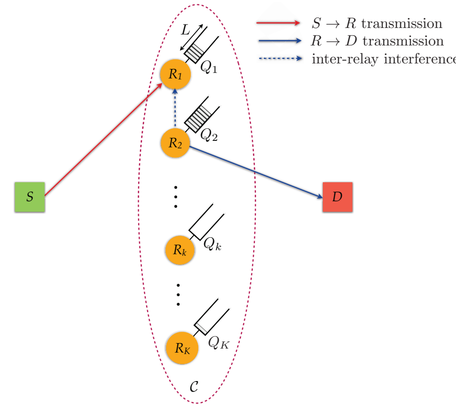

Fig. 1. The system model: Source S communicates with Destination D via a cluster of relays $R_k \in \mathcal{C}$, $k \in \{1, \ldots, K\}$.

buffers of all relays is denoted by $Q \triangleq (Q_1, Q_2, \ldots, Q_K)$. Figure 1 shows an instance of the relay-assisted network.

Time is considered to be slotted and at each time-slot the source S and (possibly) one of the relays R_k transmit with power P_S and P_{R_k}, respectively. The source node is assumed to be saturated (it has always data to transmit) and the information rate is equal to r_0. The retransmission process is based on an Acknowledgment/Negative-Acknowledgment (ACK/NACK) mechanism, in which short-length error-free packets are broadcasted by the receivers (either a relay R_k or the destination D) over a separate narrow-band channel in order to inform the network on whether or not, the packet was successfully received. As the relays have buffering capabilities, it is highly probable that the relay selected for transmission will forward a packet received in a previous transmission phase other than the preceding. As a result, packet reordering might be required at the destination, so that the information is correctly decoded. This can be easily achieved by including a sequence number in each packet, thus allowing the destination to put the packets in order. This is required in all BA relaying protocols. The quality of the wireless channels is degraded by Additive White Gaussian Noise (AWGN) and frequency flat Rayleigh block fading according to a complex Gaussian distribution with zero mean and variance σ_{ij}^2 for the i to j link. For simplicity, the power of the AWGN is assumed to be normalized with zero mean and unit variance. The channel gains are $g_{ij} \triangleq |h_{ij}|^2$ and exponentially distributed [27, Appendix A].

By $b_{SR} \triangleq (b_{SR_1}, b_{SR_2}, \ldots, b_{SR_K})$ and $b_{RD} \triangleq (b_{R_1D}, b_{R_2D}, \ldots, b_{R_KD})$ we capture in a binary form the links that are not in outage (i.e., if transmission on link R_iD is feasible, then $b_{R_iD} = 1$). It is assumed that the receivers can estimate (accurately, if not otherwise stated) the CSI. Similarly, by $q_{SR} \triangleq (q_{SR_1}, q_{SR_2}, \ldots, q_{SR_K})$ and $q_{RD} \triangleq (q_{R_1D}, q_{R_2D}, \ldots, q_{R_KD})$ 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 $\{S \rightarrow R\}$ links and for non-empty buffers in $\{R \rightarrow D\}$ links). Sets $\mathcal{F}_{SR}$ and $\mathcal{F}_{RD}$, contain the feasible $\{S \rightarrow R\}$ and $\{R \rightarrow D\}$ links, respectively. In case $b_{ij} = 0$ or $q_{ij} = 0$, no transmission is attempted on link $\{i \rightarrow j\}$; as a consequence, we say that link $\{i \rightarrow j\}$ is in *outage*.

Since we implement SuR, we (may) have concurrent transmissions by the source and one relay taking place at the same time slot. This relaying strategy requires at least two relays, as the source is sending a frame to one relay, while another relay is transmitting to the destination, thus recovering the HD loss of regular relays. In this way, the destination receives one frame per transmission phase with the exception of the first phase. However, overlapping transmissions result in IRI and the source has to consider the interference power that the candidate relay for reception will receive by the transmitting relay. In this work, we assume that the source and the relays use a constant power, P_S and P_{R_t}, respectively, when transmitting. In an arbitrary frame, a packet is successfully transmitted from the transmitting relay R_t to the destination D if the Signal-to-Noise Ratio (SNR), denoted by SNR_{R_tD}, is greater than or equal to a threshold, called the capture ratio, say γ_0; i.e.,

$$\frac{g_{R_tD}P_{R_t}}{n_D} \geq \gamma_0 \ , \quad R_t \in \mathcal{F}_{\mathcal{RD}} \ , \tag{1}$$

where n_j denotes the variance of thermal noise at the receiver j, which is assumed to be AWGN. A packet is successfully transmitted from source S to the receiving relay R_r, if the Signal-to-Interference-and-Noise Ratio (SINR) at the receiving relay, denoted by SINR_{SR_r} is greater than or equal to γ_0, i.e.,

$$\frac{g_{SR_r}P_S}{g_{R_tR_r}P_{R_t}\mathbb{I}(R_t,R_r)+n_{R_r}} \geq \gamma_0 \ , \quad R_r \in \mathcal{F}_{\mathcal{SR}}, R_r \neq R_t \ , \tag{2}$$

where $\mathbb{I}(R_t,R_r)$ is a factor indicating whether IC can be obtained and it is described by

$$\mathbb{I}(R_t,R_r) = \begin{cases} 0, & \text{if } \dfrac{g_{R_tR_r}P_{R_t}}{g_{SR_r}P_S+n_{R_r}} \geq \gamma_0 \ , \\ 1, & \text{otherwise.} \end{cases} \tag{3}$$

Details about IC feasibility conditions and theoretical analysis for SuR can be found in [23]. We denote by $\mathcal{F}_{\text{pairs}}$ the set of relay pairs that can perform SuR.

If successive transmission is infeasible, the transmission policy reduces to single link selection, where either the source or a relay transmits a packet, following a policy similar to [6]. Successive relaying is combined with opportunistic relaying in order to select which pair of relays will assist the communication in each transmission phase.

III. LoLA4SOR: Low- Latency Algorithm for Successive Opportunistic Relaying

A. *The* LoLA4SOR *algorithm*

Several DA BA algorithms have been based on prioritizing the links $\{R \rightarrow D\}$ to avoid having buffers with a large number of packets [13]. Unfortunately, it has been observed that although the latency is reduced, the number of available relays reduces as well. Here, the low-latency algorithm for SOR (LoLA4SOR) is proposed, adopting two distinct relaying techniques, providing low latency and increased diversity. In what follows, we highlight the main aspects of the proposed algorithm; the details of LoLA4SOR are provided in Algorithm 1.

- Firstly, the possibility for SOR is employed, where a relay-pair is selected at each time-slot, as long as IRI is not high enough to cause outage or its degrading effect can be canceled through IC. In order to keep the queue sizes small and at the same time retain diversity, as it is the case with other algorithms proposed in the literature (cf. $\text{DDA}-\max-\text{link}$ algorithm [16]), it is more beneficial to choose the relays with the largest queues to transmit and the relays with the smallest queues to receive packets. When a pair is considered, the criterion becomes a bit more complicated since the combination of relays is considered. In this work, our approach gives emphasis on maintaining diversity and then aims at reducing the delay. To this end, at the start of each frame a link-pair $\{S \rightarrow R_i, R_j \rightarrow D\}$, denoted by (R_i, R_j), among *all the feasible link-pairs for SOR relaying*, i.e., $(R_i, R_j) \in \mathcal{F}_{\text{pairs}}$, is selected by an optimization problem, given by:

$$(R_{i^\star}, R_{j^\star}) = \arg \max_{(R_i,R_j)\in\mathcal{F}_{\text{pairs}}} \left\{(L-Q_i)^2 + Q_j^2\right\}, \tag{4}$$

  where $(R_{i^\star}, R_{j^\star})$ denote the optimal link-pair (R_i, R_j), i.e., the link-pair for which the maximum utility of the optimization problem is achieved. In case two or more relay pairs have the same utility, then by giving priority to the diversity of the system, among the set of relay pairs with the maximum utility, denoted by $\mathcal{F}^\star_{\text{pairs}}$ (the cardinality of $\mathcal{F}^\star_{\text{pairs}}$ is greater than 1, i.e., $|\mathcal{F}^\star_{\text{pairs}}| > 1$), the relay pair with the maximum utility of the $\{S \rightarrow R\}$ link is chosen, i.e.,

$$(R_{i^o}, R_{j^o}) = \arg \max_{(R_{i^\star},R_{j^\star})\in\mathcal{F}^\star_{\text{pairs}}} \left\{(L-Q_i)^2\right\}. \tag{5}$$

  In case two or more relay pairs still have the same maximum utility, denoted by $\mathcal{F}^o_{\text{pairs}}$ (i.e., $|\mathcal{F}^o_{\text{pairs}}| > 1$), then it means they have the same buffer state, and one of them is chosen at random.
- Moreover, in instances where SOR cannot be performed, the efficient $\text{DDA}-\max-\text{link}$ algorithm, proposed in [16] is deployed. It is emphasized that $\text{DDA}-\max-\text{link}$ avoids the selection of relays with buffers being near underflow or overflow, and activates such relays only to avoid a network outage. The details of $\text{DDA}-\max-\text{link}$ algorithm are included in Algorithm 1.

Remark 1. *Such cooperative systems consisting of relays equipped with finite (and infinite) buffer sizes have been traditionally modeled using Discrete Time Markov Chains (DTMC). For the considered system model, [6] 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 proposed. The theoretical analysis of* LoLA4SOR *follows* mutatis mutandis *those of [23] and [16], but it is omitted herein due to space limitations.*

Algorithm 1 LoLA4SOR

input Q, $\mathcal{F}_{\text{pair}}$, $\mathcal{F}_{SR}$ $\mathcal{F}_{RD}$.
if $\mathcal{F}_{\text{pair}} \neq \emptyset$ **then**
  $(R_{i^\star}, R_{j^\star}) = \arg\max_{(R_i,R_j)\in\mathcal{F}_{\text{pairs}}} \left\{(L-Q_i)^2 + Q_j^2\right\}$
  if $|\mathcal{F}^\star_{\text{pairs}}| > 1$ **then**
    $(R_{i^o}, R_{j^o}) = \arg\max_{(R_{i^\star},R_{j^\star})\in\mathcal{F}^\star_{\text{pairs}}} \left\{(L-Q_i)^2\right\}$
    if $|\mathcal{F}^o_{\text{pairs}}| > 1$ **then**
      Choose a relay pair from $\mathcal{F}^o_{\text{pairs}}$ at random.
    end if
  end if
else
  Apply the $\mathrm{DDA-max-link}$ algorithm:
  if $\mathcal{F}_{SR} = \emptyset$ **and** $\mathcal{F}_{RD} = \emptyset$ **then**
    No packet transmission takes place.
  else
    if $\mathcal{F}_{SR} = \emptyset$ **then**
      $j = \arg\max_{m\in\mathcal{F}_{RD}} Q_m$ ($\{R\to D\}$ link)
    else
      $\widetilde{\mathcal{F}}_{SR} \triangleq \{m : m \in \mathcal{F}_{SR}, Q_m \leq 1\}$
      if $\widetilde{\mathcal{F}}_{SR} \neq \emptyset$ **then**
        $i = \arg\min_{m\in\widetilde{\mathcal{F}}_{SR}} Q_m$ ($\{S\to R\}$ link)
      else
        $\widetilde{\mathcal{F}}_{RD} \triangleq \{\ell : \ell \in \mathcal{F}_{RD}, Q_\ell \geq 2\}$
        if $\widetilde{\mathcal{F}}_{RD} \neq \emptyset$ **then**
          $j = \arg\max_{\ell\in\widetilde{\mathcal{F}}_{RD}} Q_\ell$ ($\{R\to D\}$ link)
        else
          $\hat{\mathcal{F}}_{SR} \triangleq \{m : m \in \mathcal{F}_{SR}, Q_m \geq 2\}$
          $i = \arg\min_{m\in\hat{\mathcal{F}}_{SR}} Q_m$ ($\{S\to R\}$ link)
        end if
      end if
    end if
  end if
end if
Output Links $\{R_j\to D\} and \{S\to R_i\}$, or, link $\{R_j\to D\}$, or, $\{S\to R_i\}$ for transmission.

IV. Performance Evaluation

Next, performance evaluation results are given for LoLA4SOR, as well as comparisons with three categories of selection algorithms, for the outage probability, average throughput and average delay. The first category consists of HD algorithms and more specifically, $\mathrm{max-link}$, $\mathrm{DA-max-link}$ and $\mathrm{DDA-max-link}$. Then, the second category includes BASOR and DA BASOR, where the latter selects the relay with the maximum number of packets to transmit. Finally, hybrid HD/SOR algorithms are considered for the third category, such as hybrid the BASOR/$\mathrm{max-link}$ (H-BASOR), and the hybrid DA-BASOR/$\mathrm{DA-max-link}$ (DA H-BASOR). Regarding the network parameters, a topology with i.i.d. channels, $K = 4$ relays, with a buffer size of $L = 5$ packets is considered, unless otherwise stated, while the transmission rate is equal to 2 bps/Hz.

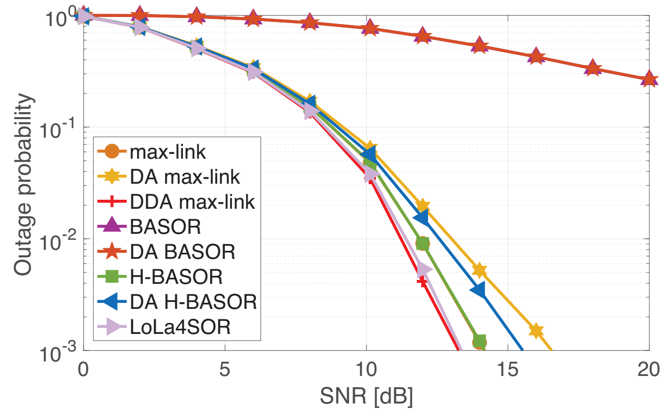

Fig. 2. Outage probability for $K = 4$, $L = 5$ and various algorithms.

A. Outage probability

The outage probability for various algorithms is depicted in Fig. 2. It can be seen that the two SOR algorithms have the worst outage performance due to severe IRI, as the transmitting nodes are assumed to transmit with fixed power. Moreover, they have identical performance, revealing that relay-pair selection is characterized by reduced degrees of freedom and thus, diversity is hard to be maintained by DA-BASOR, even when BSI is considered. Then, the DA schemes experience increased outages, as diversity is compromised by empty buffers, due to the prioritization of the $\{R\to D\}$ transmission. Overall, the best performance is provided by the DDA algorithms, i.e. $\mathrm{DDA-max-link}$ and LoLA4SOR, both maintaining the diversity of the network when it is possible. Finally, H-BASOR performs closely to the DDA algorithms, as for its HD operation, it adopts $\mathrm{max-link}$ resulting in improved diversity.

B. Average throughput

Next, the average throughput comparisons are given in Fig. 3. Here, the performance can be classified in three categories. Firstly, the HD algorithms provide reduced end-to-end throughput, reaching the upper bound of 1 bps/Hz after 10 dB. Next, the two SOR algorithms provide the worst performance for low and medium SNR, while after 15 dB they surpass the performance of HD algorithms. It is evident that due to IRI and fixed transmit power, the SOR algorithms can not provide the maximum throughput, even for asymptotically high SNR. Nonetheless, the combination of SOR and HD algorithms is beneficial, as depicted by the throughput performance of the hybrid algorithms. Among these algorithms, LoLA4SOR has the best performance as IRI is efficiently mitigated by activating $\mathrm{max-link}$ when relay-pair selection can not be performed. Moreover, diversity losses are avoided due to $\mathrm{DDA-max-link}$, compared to H-BASOR and DA H-BASOR, where the latter has significantly worse performance, due to increased instances of empty buffers.

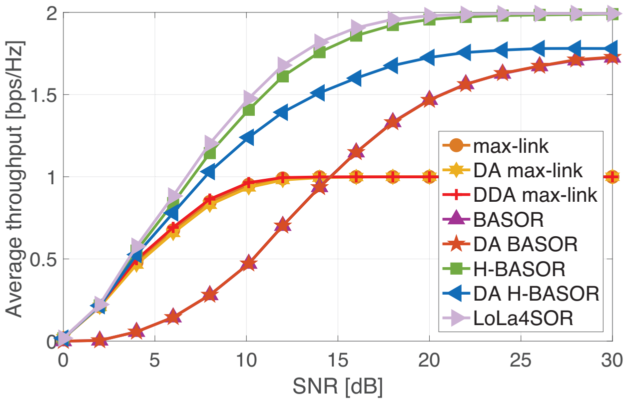

Fig. 3. Average throughput for $K = 4$, $L = 5$ and various algorithms.

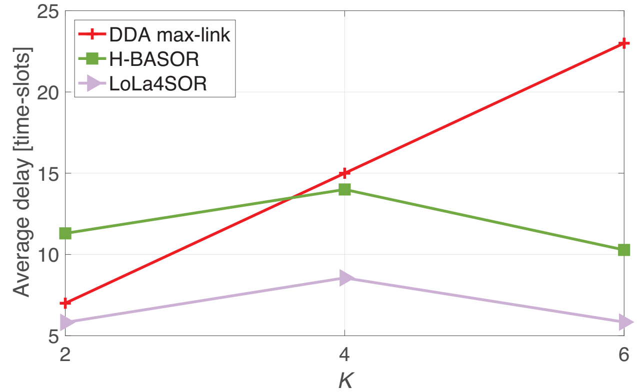

Fig. 5. Average delay for $L = 10$ and transmit SNR equal to 20 dB.

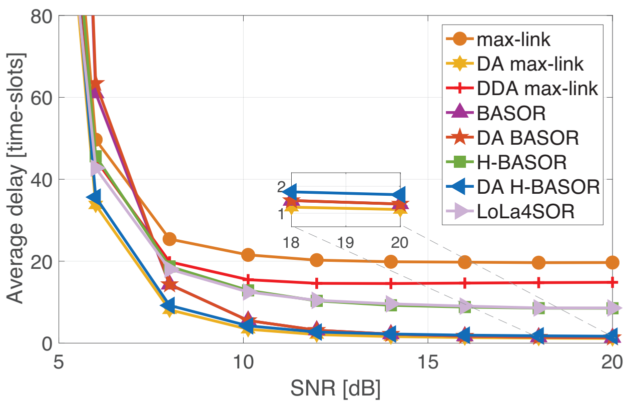

Fig. 4. Average delay for $K = 4$, $L = 5$ and various algorithms.

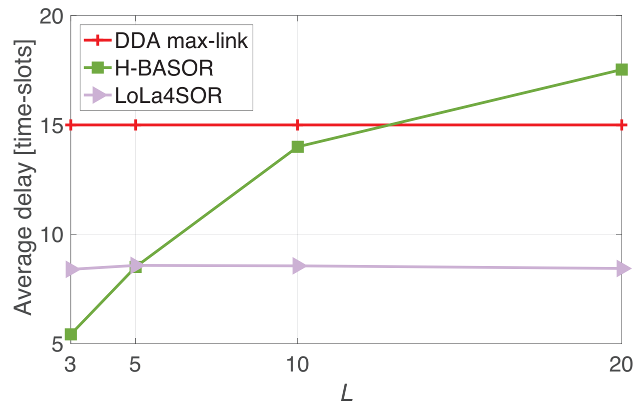

Fig. 6. Average delay for $K = 4$ and transmit SNR equal to 20 dB.

C. Average delay

The results in Fig. 4 present the average delay performance of the three selection categories. It can be observed that the DA and the two SOR algorithms transmit their packets with the lowest delay. Unfortunately, as already seen in the outage and throughput results, they transmit less packets, compared to $\mathrm{LoLA4SOR}$ and H-BASOR. Moreover, $\mathrm{LoLA4SOR}$ and H-BASOR provide similar delay performance in this case, both relying on $\mathrm{max-link}$ for low SNR and SOR for higher SNR values. Regarding $\mathrm{max-link}$ and $\mathrm{DDA-max-link}$, as shown in the delay analysis in [16], they provide a delay equal to KL and $4K-1$ for high SNR, respectively and thus, they perform worse than $\mathrm{LoLA4SOR}$ and H-BASOR.

After, the impact of K on the average delay performance is shown in Fig. 5. In this comparison, larger buffers are considered with $L = 10$ packets, as well as high transmit SNR equal to 20 dB. It can be seen that $\mathrm{DDA-max-link}$ is affected by increasing the number of available relays, providing each time an average delay of $4K-1$. For this L, $\mathrm{LoLA4SOR}$ has improved delay performance, compared to H-BASOR, independently of the number of relays. One may notice that when $K = 4$, the average delay increases, before decreasing again for $K = 6$. This behaviour can be justified by the hybrid nature of both algorithms. More specifically, for $K = 2$, relay-pair selection fails in many instances and HD operation is activated. In this case, a reduced number of packets reaches the destination. Then, for $K = 4$, SOR is more frequently performed, however, HD transmissions are still employed and each algorithm is affected by the increase of K. Finally, for $K = 6$, the SOR mode dominates the network's operation and the average delay reduces, as HD transmissions are rarely adopted.

The final comparison shows the impact of L on the average delay of the network in Fig. 6, for $L = 10$ and transmit SNR equal to 20 dB. Firstly, $\mathrm{DDA-max-link}$ is not affected by increasing the buffer size, providing an average delay of 15 transmissions. It can be seen that H-BASOR provides the lowest delay for small buffer sizes, but for increased L, it is significantly affected, as the delay performance of its HD mode of operation, i.e. $\mathrm{max-link}$ depends on L [16]. Also, when performing SOR, H-BASOR does not use BSI. More importantly, $\mathrm{LoLA4SOR}$ provides an almost stable average delay performance, due to incorporating BSI for relay and relay-pair selection in HD and SOR modes, respectively. So, $\mathrm{LoLA4SOR}$ ends up being the most efficient algorithm in terms of delay for a wide range of buffer sizes.

V. Conclusions and Future Directions

A. Conclusions

In this work, the combination of successive and half-duplex relaying was studied, in order to reduce the latency of two-hop wireless networks. We proposed $\mathrm{LoLA4SOR}$, a low-latency successive opportunistic relay selection algorithm, aiming at reducing packet delays, while avoiding diversity losses that are inherent in delay-aware buffer-aided relaying. LoLA4SOR was evaluated in terms of outage probability, throughput and average delay and comparisons with other algorithms were presented. It was shown that LoLA4SOR provides reduced outages and increased throughput, while its latency does not increase either with the number of available relays or with the buffer size.

B. Future Directions

In the current scheme of LoLA4SOR, we do not use consider power adaptation, which would enable more relay pairs to be formed and potentially improve the performance of the overall system. Furthermore, a scheme can be considered in which the power expenditure is taken into consideration as well.

The effect of LoLA4SOR in mmWave communications will be an interesting directions, since some early studies present the effect of relaying on the reliability and delay [29].

Although successive relaying schemes, such as LoLA4SOR, offer a lot of improvements, they require additional overhead communication for the implementation. It would be interesting to discuss a distributed implementation or approximation of such approaches with reduced overhead communication.

Finally, scenarios where multiple users are served through non-orthogonal multiple access (NOMA) [30]–[33], using hybrid relay selection algorithms is a promising research field.

References

[1] "Ericsson mobility report", June 2018. Available: https://www.ericsson.com/assets/local/mobility-report/documents/2018/ericsson-mobility-report-june-2018.pdf.

[2] 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, April 2014.

[3] 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, Sept. 2017.

[4] N. Nomikos, T. Charalambous, I. Krikidis, D. N. Skoutas, D. Vouyioukas, M. Johansson, C. Skianis, "A survey on buffer-aided relay selection," *IEEE Commun. Surv. & Tut.*, vol. 18, no. 2, pp. 1073-1097, Secondquarter 2016.

[5] A. Ikhlef, D. S. Michalopoulos and R. Schober, "Max-max relay selection for relays with buffers," *IEEE Trans. Wireless Commun.*, vol. 11, pp. 1124–1135, March 2012.

[6] 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, pp. 1957–1967, May 2012.

[7] 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, pp. 649–652, 2015.

[8] N. Zlatanov and R. Schober, "Buffer-aided half-duplex relaying can outperform ideal full-duplex relaying," *IEEE Commun. Lett.*, vol. 17, no. 3, pp. 479–482, March 2013.

[9] N. Pappas, M. Kountouris, A. Ephremides and A. Traganitis, "Relay-Assisted Multiple Access With Full-Duplex Multi-Packet Reception," *IEEE Trans. Wireless Commun.*, vol. 14, no. 7, pp. 3544-3558, July 2015.

[10] I. Dimitriou and N. Pappas, "Performance analysis of a cooperative wireless network with adaptive relays," *Ad Hoc Networks*, vol. 87, pp. 157-173, May 2019.

[11] N. Pappas, I. Dimitriou and Z. Chen, "Network-level Cooperation in Random Access IoT Networks with Aggregators," *Int. Teletraffic Congress (ITC 30)*, Sept. 2018.

[12] D. Poulimeneas, T. Charalambous, N. Nomikos, I. Krikidis, D. Vouyioukas, M. Johansson, "A delay-aware hybrid relay selection policy," *IEEE Int. Conf. on Telecommun., (ICT)*, May 2016.

[13] Z. Tian, Y. Gong, G. Chen and J. Chambers, "Buffer-aided relay selection with reduced packet delay in cooperative networks," *IEEE Trans on Veh. Technol.*, vol. PP, no. 99, pp. 1–1, May 2016.

[14] S. Luo and K. C. Teh, "Buffer state based relay selection for buffer-aided cooperative relaying systems," *IEEE Trans. Wireless Commun.*, vol. 14, no. 10, pp. 5430–5439, Oct. 2015.

[15] 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.

[16] N. Nomikos, D. Poulimeneas, T. Charalambous, I. Krikidis, D. Vouyioukas and M. Johansson, "Delay- and diversity-aware buffer-aided relay selection policies in cooperative networks," *IEEE Access*, vol. 6, pp. 73531–73547, Nov. 2018.

[17] 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.

[18] 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. PP, no. 99, pp.1–1, Jan. 2016.

[19] 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, no., pp. 3632–3646, 2016.

[20] 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.

[21] A. Ikhlef, K. Junsu and R. Schober, "Mimicking full-duplex relaying using half-duplex relays with buffers," *IEEE Trans. Veh. Technol.*, vol. 61, pp. 3025–3037, Sept. 2012.

[22] N. Nomikos, D. Vouyioukas, T. Charalambous, I. Krikidis, P. Makris, D. N. Skoutas, M. Johansson and C. Skianis, "Joint relay-pair selection for buffer-aided successive opportunistic relaying," *Wiley Trans. Emerg. Telecommun. Technol.*, vol. 25, no. 8, pp. 823–834 Aug. 2014.

[23] N. Nomikos, T. Charalambous, I. Krikidis, D. N. Skoutas, D. Vouyioukas and M. Johansson, "A buffer-aided successive opportunistic relaying selection scheme with power adaptation and inter-relay interference cancellation for cooperative diversity systems," *IEEE Trans. Commun.*, vol. 63, no. 5, pp. 1623–1634, May 2015.

[24] D. S. Michalopoulos, A. S. Lioumpas, G. K. Karagiannidis and R. Schober, "Selective cooperative relaying over time-varying channels," *IEEE Trans. Commun.*, vol. 58, no. 8, pp. 2402–2412, Aug. 2010.

[25] N. Nomikos, P. Makris, D. Vouyioukas, D. N. Skoutas and C. Skianis, "Distributed joint relay-pair selection for buffer-aided successive opportunistic relaying," *IEEE Int. Workshop Comp. Aid. Mod. Anal. and Des. (CAMAD)*, pp. 318-322, Berlin, Germany, Sept. 2013.

[26] A. Bletsas, A. Khisti, D. Reed and A. Lippman, "A simple cooperative diversity method based on network path selection," *IEEE J. Sel. Areas Commun.*, vol. 24, pp. 659–672, March 2006.

[27] D. Tse and P. Viswanath, "Fundamentals of wireless communications," *Cambridge University Press*, 2005.

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

[29] C. Tatino, N. Pappas, I. Malanchini, L. Ewe, D. Yuan, "Throughput Analysis for Relay-Assisted Millimeter-Wave Wireless Networks," *IEEE Globecom Workshops*, pp. 1-6, Dec. 2018.

[30] 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, April 2017.

[31] H. Cao, J. Cai, S. Huang and Y. Lu, "Online adaptive transmission strategy for buffer-aided cooperative NOMA systems," IEEE Trans. Mob. Comp. (early access), pp. 1–1, July 2018.

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

[33] 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.