Received 11 April 2021; accepted 28 April 2021. Date of publication 3 May 2021; date of current version 10 May 2021.

Digital Object Identifier 10.1109/OJCOMS.2021.3077036

LoLa4SOR: Leveraging Successive Transmissions for Low-Latency Buffer-Aided Opportunistic Relay Networks

NIKOLAOS NOMIKOS [1] **(Senior Member, IEEE),**
THEMISTOKLIS CHARALAMBOUS [2] **(Senior Member, IEEE), NIKOLAOS PAPPAS** [3] **(Member, IEEE),**
DEMOSTHENES VOUYIOUKAS [4] **(Senior Member, IEEE), AND RISTO WICHMAN** [2] **(Member, IEEE)**

[1] IRIDA Research Centre for Communication Technologies, Department of Electrical and Computer Engineering, University of Cyprus, 1678 Nicosia, Cyprus

[2] School of Electrical Engineering, Aalto University, 02150 Espoo, Finland

[3] Department of Science and Technology, Linköping University (Campus Norrköping), 60174 Norrköping, Sweden

[4] Department of Information and Communication Systems Engineering, University of the Aegean, 83200 Samos, Greece

CORRESPONDING AUTHOR: T. CHARALAMBOUS (e-mail: themistoklis.charalambous@aalto.fi)

The work of Themistoklis Charalambous was supported by the Academy of Finland under Grant 317726. The work of Nikolaos Pappas was supported in part by the Center for Industrial Information Technology (CENIIT). A preliminary version of this work has been published in [1]. In this paper, we additionally introduce the low-complexity distributed implementation framework for LoLa4SOR (herein called d-LoLa4SOR) we provide analysis for the proposed schemes using Markov chains, as well as asymptotic analysis, extracting the diversity gain, while conducting extensive simulations and comparisons for both proposed methods (LoLa4SOR and d-LoLa4SOR).

ABSTRACT Buffer-aided (BA) relaying improves the diversity of cooperative networks often at the cost of increasing end-to-end packet delays. This characteristic renders BA relaying unsuitable for delay-sensitive applications. However, the increased diversity makes BA relaying appealing for ultra-reliable communications. Towards enabling ultra-reliable low-latency communication (URLLC), we aim at enhancing BA relaying for supporting delay-sensitive applications. In this paper, reliable full-duplex (FD) network operation is targeted and for this purpose, hybrid relay selection algorithms are formulated, combining BA successive relaying (SuR) and delay- and diversity-aware (DDA) half-duplex (HD) algorithms. In this context, a hybrid FD DDA algorithm is presented, namely LoLa4SOR, switching between SuR and HD operation. Additionally, a low-complexity distributed version is given, namely d-LoLa4SOR, providing a trade-off among channel state information requirements and performance. The theoretical analysis shows that the diversity of LoLa4SOR equals to two times the number of available relays K, i.e., $2K$, when the buffer size L is greater than or equal to 3. Comparisons with other HD, SuR and hybrid algorithms reveal that LoLa4SOR offers superior outage and throughput performance while, the average delay is reduced due to SuR-based FD operation and the consideration of buffer state information for relay-pair selection. d-LoLa4SOR, as one of the few distributed algorithms in the literature, has a reasonable performance that makes it a more practical approach.

INDEX TERMS Buffer-aided relaying, diversity, full-duplex communication, low-latency, relay selection, successive relaying.

I. INTRODUCTION

A. BACKGROUND

THE RAPID increase of mobile data traffic and the emerging Internet-of-Things (IoT) applications [2] accelerate the need for developing low-complexity algorithms offering reliable connectivity and low end-to-end latency [3]. In this context, sixth generation (6G) mobile networks are envisioned to support dense small cells where coexisting user devices and machines will compete for wireless resources [4]. 6G promises tremendous rate gains through full-duplex (FD) communications, offering simultaneous transmission and reception on the same spectral and temporal resources [5]–[9]. Meanwhile, buffer-aided (BA) cooperative relaying, whose potential was first revealed in the seminal work in [10], is capable of improving the wireless conditions through increased diversity, thus resulting in reduced outages, delays and better throughput; see related surveys in [11]–[13]. Focusing on BA opportunistic relay selection (ORS) algorithms, the survey in [12] presents several cases where half-duplex (HD) relay networks adopt successive relaying (SuR) to achieve FD operation, showing that significant gains can be harvested when hybrid algorithms are adopted, efficiently combining the benefits of all the available relaying modes. Also, in multi-antenna BA relay networks, further flexibility for combining FD, SuR and HD transmissions has shown promising throughput gains, without compromising the reliability of the transmission [14].

Ikhlef *et al.* [15] proposed a hybrid relay selection (HRS) scheme, in which each frame is divided into two time-slots: one for each of the $\{S \rightarrow R\}$ and $\{R \rightarrow D\}$ transmissions. Subsequently, unlike HRS, a scheme, called $\max - \text{link}$, was proposed that leveraged the diversity gain offered by the buffering capability at the relays and scheduled transmissions only through the strongest available link, obtaining a diversity twice the number of relays [16]. In topologies where only a single relay is available, adaptive link selection was examined by Zlatanov and Schober in [17], highlighting the performance gains of data buffering at the relay and revealing that HD relaying can outperform ideal FD relaying, as long as the number of antennas at the source and destination is larger than or equal to the number of antennas at the relay.

Several delay-aware (DA) extensions to HRS and $\max - \text{link}$ have been proposed. In [18], HRS and $\max - \text{link}$ were modified to keep non-empty and balanced queues by choosing the links offered by relays having the smallest (largest) buffer length, among the feasible $\{S \rightarrow R\}$, $\{R \rightarrow D\}$ links, respectively. Moreover, a delay- and diversity-aware (DDA) version of $\max - \text{link}$, exploiting BSI to avoid cases of buffer starvation or overflow was presented. The analysis showed that $\text{DDA} - \max - \text{link}$ is capable of providing reduced outages and delay, compared to $\max - \text{link}$ for $L \geq 3$ packets. A similar approach has been considered in Oiwa *et al.* [19] where the selection algorithm activated relays that were not on the brink of starvation, in order to preserve the diversity of the network. Tian *et al.* [20] enabled the prioritization of $\{R \rightarrow D\}$ transmissions, leading to a DA version of $\max - \text{link}$, where the average packet delay converged to two time-slots, without being affected by neither the number of relays nor the buffer size. Furthermore, buffer state information (BSI) was exploited by Luo and Teh in [21] for choosing the best relay, as long as buffers were neither empty nor full. The theoretical analysis showed that compared to $\max - \text{link}$, a buffer size $L \geq 3$ packets provided lower packet delay, and improved outage performance. In networks where relays are equipped with small buffers, Lin and Liu in [22] proposed the combined relay selection (CRS) algorithm, activating for reception, the relay with the minimum number of packets and for transmission, the relay with the maximum number of packets. So, when CRS was compared to HRS and $\max - \text{link}$, it was shown that the average delay can be significantly reduced. Then, Raza *et al.* in [23], introduced a controlling parameter, namely the buffer limit, indicating the level of buffer occupancy. It was concluded that by adjusting the value of the buffer limit, outage performance gains can be traded with the improvement of the average end-to-end delay. In a two-hop HD multi-relay network where relays are able to perform adaptive rate transmissions, Zlatanov *et al.* in [24] derived the achievable rate expressions of adaptive link selection. Both centralized and distributed operation were discussed, while a heuristic method to bound the transmission delay was proposed, relying only on the knowledge of the average queue length and the average arrival rate at each relay.

Looking to BA relaying from a perspective towards increasing the throughput of the network, several works showed that spectral efficiency gains can be leveraged by developing hybrid algorithms with FD capabilities. If the HD relays are not replaced by FD relays, FD operation can be facilitated by means of SuR. In such algorithms, buffers enable hybrid HD/SuR transmissions, thus increasing the reliability of the transmission, since inter-relay interference (IRI) causes error floors in high rate scenarios, as shown by Li *et al.* in [25]. In Ikhlef *et al.* [26], HD BA relay selection was combined with SuR in an IRI-free topology with isolated relays. The authors studied both adaptive and fixed-rate transmission cases, showing that the proposed space full-duplex (SFD) max-max relay selection (MMRS) is able to offer twice the capacity of HD schemes with adaptive rate transmission, while achieving a coding gain for fixed-rate transmission and a diversity gain equal to the number of the available relays. Then, in a topology where relays were not isolated and performed interference cancelation (IC), BA successive opportunistic relaying (BASOR) was investigated in [27]. More specifically, BASOR selected the best relay-pair by evaluating the IRI channel conditions, aiming at interference avoidance or cancelation. In cases where SuR failed, $\max - \text{link}$ was employed and it was shown that switching among BASOR and $\max - \text{link}$ provided resiliency against outages and improved throughput compared to other HD and FD algorithms. Furthermore, SuR with two relays was examined in [28], [29]; the proposed optimal scheduling policy was integrated with delay-awareness, as well as IRI mitigation based on either dirty paper coding or successive IC. In networks with multi-antenna nodes, Kim and Bengtsson in [30] recovered the loss of HD relaying through joint relay selection and beamforming to suppress the IRI due to successive transmissions, showing that almost ideal FD operation can be obtained. Finally, in SuR networks with a multi-antenna BA source and multiple

BA single-antenna relays, it was shown that joint precoding design and relay-pair selection alleviated IRI for both fixed and adaptive rate cases when channel state information (CSI) was available [31].

B. CONTRIBUTIONS

It is evident that hybrid BA relay selection algorithms can improve the performance of multi-hop cooperative networks by increasing the degrees of freedom of the selection process. However, until now, the integration of delay-awareness in hybrid FD BA relay selection algorithms has not been investigated. In this paper, we aim to shed light on the benefits that can be offered to the network through DA hybrid FD relay selection. The considered setup is mapped to scenarios where data relaying takes place through user devices, as it is the case in device-to-device networks [32], [33]. For this reason, relays are assumed to be HD single-antenna devices with low processing capabilities. In this context, we aim at achieving FD network operation, recovering the multiplexing loss of HD relaying by simultaneous activating the source and a selected relay to transmit at each time-slot. More specifically, the contributions in this work are as follows.

- A hybrid FD BA relay selection algorithm with DA characteristics, namely LoLa4SOR, is proposed. LoLa4SOR switches among HD and FD operation through SuR and aims at reducing the average delay, while avoiding the diversity losses of other BA DA algorithms.
- A low-complexity distributed version of LoLa4SOR is proposed, herein named d-LoLa4SOR, in which the performance is compromised in order to reduce CSI overheads, but still, significant throughput gains are provided compared to HD algorithms.
- A theoretical analysis using Markov chains is presented and the diversity gain of LoLa4SOR is derived, showing that the buffer size determines the diversity order of the wireless transmission.
- The performance of LoLa4SOR is evaluated, in terms of outage probability, throughput, and average delay and comparisons with other relevant algorithms are given. The results show that FD operation through LoLa4SOR offers reduced outages and increased throughput, while its delay is significantly reduced compared to HD relaying.

C. ORGANIZATION

The structure of this paper is as follows. In Section II, we introduce the system model and necessary preliminaries for developing of our study. In Section III, we first give the centralized version for LoLa4SOR, the low-latency algorithm for buffer-aided successive opportunistic relaying then, Section IV presents the details of the distributed framework for its low-complexity operation. Subsequently, theoretical analysis is conducted and the diversity gain of LoLa4SOR is extracted for different buffer sizes in Section V. Next, the performance of the proposed algorithms is given in Section VI, as well as comparisons with other state-of-the-art solutions. Finally, conclusions and future directions are provided in Section VII.

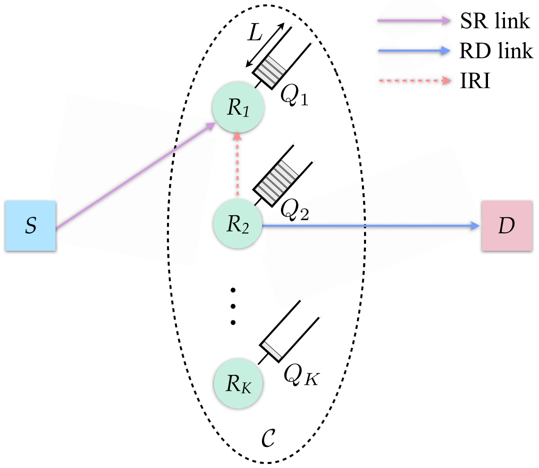


FIGURE 1. A two-hop wireless network where a source node S communicates with a single destination D via a cluster of relays $R_k \in \mathcal{C}$, $k \in \{1, \ldots, K\}$.

II. SYSTEM MODEL

A two-hop cooperative network comprising a source node S, a destination D, and a cluster $\mathcal{C}$ consisting of K decode-and-forward (DF) relays $R_k \in \mathcal{C}$ $(1 \leq k \leq K)$ is considered. Each relay is equipped with a single antenna and operates in HD mode and thus, simultaneous transmission and reception of signals at the same relay, is not possible.[1] It is considered that direct transmissions from the source towards the destination are not possible due to severe fading conditions and communication can be performed only through the relays [34]. At every relay node R_k there is a buffer of length L_k (number of packets), where it can store packets that were successfully received and can be forwarded to the destination. Initially, each relay buffer has Q_k data elements, while some buffers might be empty (i.e., $Q_k = 0$ for some k). For simplicity of exposition, it is assumed that all the buffers have the same length, i.e., $L_k = L, \forall\, k \in \{1, 2, \ldots, K\}$. The vector summarizing the buffer sizes of all relays is denoted by $Q \triangleq (Q_1, Q_2, \ldots, Q_K)$. Figure 1 shows an instance of the two-hop BA wireless relay network. This simple setup is emblematic of a wide range of wireless communication applications.

The network applies time division duplexing to allocate radio resources between uplink and downlink direction. Time is divided in time-slots where the source node S and (possibly) a selected relay R_k transmit using fixed power levels P_S and P_{R_k}, respectively. A saturated source is assumed, having always data for transmission, while the

---

[1] We have chosen HD relays to perform SuR, in order to show the benefit of SuR for our objectives of minimizing the delay while taking into account the diversity. The use of FD relays can of course further enhance the performance, with minimal changes in our proposed algorithms.

information rate is equal to r_0. Retransmissions rely on an Acknowledgment/Negative-Acknowledgment (ACK/NACK) mechanism, where the receivers (either the activated relay or the destination) broadcast short-length error-free packets via a separate narrow-band link, informing the network on whether or not, the packet transmission was successful. As the relays have buffering capabilities, it is likely that the transmitting relay will forward a packet received in a previous time-slot, which is different from the preceding one. Thus, the destination might perform packet reordering, ensuring correct information decoding. This process is necessary in all BA relay networks and can be achieved with low-complexity by including a sequence number in each packet, thus enabling the destination to put the packets in the appropriate order. Furthermore, the wireless channel quality is degraded by Additive White Gaussian Noise (AWGN) and frequency flat Rayleigh block fading, following a complex Gaussian distribution characterized by 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. Also, the channel gains $g_{ij} \triangleq |h_{ij}|^2$ are exponentially distributed [35, Appendix A].

The vectors $b_{SR} \triangleq (b_{SR_1}, b_{SR_2}, \ldots, b_{SR_K})$ and $b_{RD} \triangleq (b_{R_1D}, b_{R_2D}, \ldots, b_{R_KD})$ consist of binary elements capturing 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 are able to accurately estimate the CSI. Similarly, vectors $q_{SR} \triangleq (q_{SR_1}, q_{SR_2}, \ldots, q_{SR_K})$ and $q_{RD} \triangleq (q_{R_1D}, q_{R_2D}, \ldots, q_{R_KD})$, represent in a binary form, the feasible links, due to the fulfillment of the buffer conditions (i.e., for non-full queues in $\{S \to R\}$ links and for non-empty queues 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. If $b_{ij} = 0$ or $q_{ij} = 0$, a transmission on link ij is not attempted and consequently, this link is considered to be in *outage*.

Since SuR is employed in the network, it is possible that simultaneous transmissions by the source and a selected relay might take place, during the same time-slot. The SuR mode of operation involves two relays, since the source is transmitting a packet to one relay, while another relay is forwarding a previously received packet to the destination. In this way, the HD loss of conventional relays is surpassed. As a result, the destination receives one packet per time-slot with the exclusion of the first time-slot. Nonetheless, SuR introduces IRI and the selection algorithm must take into consideration the interference power that the candidate receiving relay will experience by the relay activated for transmission. Here, it is assumed that the source and the relays use fixed power levels, P_S and $P_{R_{\text{tx}}}$, respectively, when transmitting. In an arbitrary time-slot, a packet is successfully forwarded from the transmitting relay R_{tx} towards the destination D if the Signal-to-Noise Ratio (SNR), denoted by $\text{SNR}_{R_{\text{tx}}D}$, is greater than or equal to a threshold γ_0, called the capture ratio, i.e.,

$$\frac{g_{R_{\text{tx}}D}P_{R_{\text{tx}}}}{n_D} \geq \gamma_0, \quad R_{\text{tx}} \in \mathcal{F_{RD}}, \tag{1}$$

where n_j denotes thermal noise variance at the receiver j, which is considered to be AWGN as stated earlier. A packet transmission from source S to the receiving relay R_{rx} is successful, if the Signal-to-Interference-and-Noise Ratio (SINR) at the receiving relay, denoted by $\text{SINR}_{SR_{\text{rx}}}$ is greater than or equal to γ_0, i.e.,

$$\frac{g_{SR_{\text{rx}}}P_S}{g_{R_{\text{tx}}R_{\text{rx}}}P_{R_{\text{tx}}}\mathbb{I}(R_{\text{tx}}, R_{\text{rx}}) + n_{R_{\text{rx}}}} \geq \gamma_0, \;\; R_{\text{rx}} \in \mathcal{F_{SR}} \setminus R_{\text{tx}}, \tag{2}$$

where $\mathbb{I}(R_{\text{tx}}, R_{\text{rx}})$ is a factor indicating whether or not, IC can be performed. When IC is feasible, a fact expressed by $\mathbb{I}(R_{\text{tx}}, R_{\text{rx}}) = 0$, the interfering signal is first decoded and then subtracted at the relay before decoding the source signal. So, in this case, the outage probability is not affected by the IRI. The strong interference regime was studied in various works [29], [36]–[38]. More specifically, $\mathbb{I}(R_{\text{tx}}, R_{\text{rx}})$ is described by

$$\mathbb{I}(R_{\text{tx}}, R_{\text{rx}}) = \begin{cases} 0, & \text{if } \frac{g_{R_{\text{tx}}R_{\text{rx}}}P_{R_{\text{tx}}}}{g_{SR_{\text{rx}}}P_S + n_{R_{\text{rx}}}} \geq \gamma_0, \\ 1, & \text{otherwise.} \end{cases} \tag{3}$$

However, when IC cannot be performed, R_{rx} tries to directly decode the desired signal by examining if the $\text{SINR}_{SR_{\text{rx}}}$ is above the capture ratio γ_0, thus treating the IRI as noise. In this case, the successful transmission probability will be given by [39]:

$$\begin{aligned} \mathbb{P}(\text{SINR}_{SR_{\text{rx}}}) &= 1 - F_{g_{SR_{\text{rx}}}P_S - \gamma_0 g_{R_{\text{tx}}D}P_{R_{\text{tx}}}}\left(\gamma_0 \sigma^2_{n_{R_{\text{rx}}}}\right) \\ &= \frac{P_S\lambda}{P_S\lambda + \gamma_0 P_{R_{\text{tx}}}\mu} \exp\left(-\mu \frac{\gamma_0 \sigma^2_{n_{R_{\text{rx}}}}}{P_S}\right), \end{aligned} \tag{4}$$

where $F_W(w)$ denotes the cumulative distribution function (cdf) of a random variable W, $g_{SR_{\text{rx}}} \sim \text{Exp}(\mu)$ and $g_{R_{\text{tx}}R_{\text{rx}}} \sim \text{Exp}(\lambda)$, $\lambda, \mu > 0$.

We denote by $\mathcal{F}_{\text{pairs}}$ the set of relay pairs that can perform SuR. However, in case the successive transmission is infeasible, the transmission switches to single link selection, where the time-slot is allocated for the transmission of a packet by the source or a relay, following a similar procedure to [16]. In this way, IRI is avoided and the probability of a complete network outage is significantly reduced.

III. LOLA4SOR: LOW-LATENCY ALGORITHM FOR HYBRID BUFFER-AIDED OPPORTUNISTIC RELAYING

Several DA BA algorithms have relied on prioritizing the transmission in the $\{R \to D\}$ links, in order to avoid overflowing the buffers with large numbers of packets [20]. Unfortunately, it has been observed that although the latency can be reduced, $\{R \to D\}$ prioritization has a negative impact on the number of available relays, since buffers tend to starve. Here, a low-latency selection algorithm for hybrid BA SOR/HD (LoLa4SOR) is proposed, employing two distinct relaying techniques, offering low latency without compromising the diversity. Below, the main steps of LoLa4SOR are described and the details are provided in Algorithm .

- At first, the possibility for SOR is examined, where a link-pair $\{S \to R_i, R_j \to D\}$, denoted by (R_i, R_j), is selected at each time-slot, as long as the level of IRI is not high enough to cause outage or IRI can be successfully canceled through IC. In order to maintain small queue sizes and at the same time, retain diversity, similarly to other algorithms in the literature (see $\text{DDA}-\max-\text{link}$ algorithm [18]), it is more beneficial to activate the relays with the largest queues for transmission and the relays with the smallest queues for reception. It must be noted that prior to link-pair activation, the selection criterion is more complicated, as the combination of relays is considered. In this work, we follow an approach emphasizing on maintaining diversity, while aiming at reducing the delay. To this end, at the start of each time-slot, a link-pair among all the feasible link-pairs for SOR, i.e., $(R_i, R_j) \in \mathcal{F}_{\text{pairs}}$ is selected, through the following optimization problem:

$$\left(R_{i^\star}, R_{j^\star}\right) = \arg \max_{(R_i,R_j)\in\mathcal{F}_{\text{pairs}}} \left\{(L-Q_i)^2 + Q_j^2\right\}, \tag{5}$$

where $(R_{i^\star}, R_{j^\star})$ denotes the optimal link-pair (R_i, R_j), i.e., the link-pair achieving the maximum utility of the optimization problem. If the relays are FD, then $i^\star$ and $j^\star$ can be the same. In such cases, link-pair selection should consider the different characteristics of the self-interference channel model, compared to the inter-relay channels of the SuR mode [40]–[42]. In case two or more link-pairs provide the same utility, then by prioritizing the diversity of the network, between the set of link-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 link-pair with the maximum utility of the $\{S \rightarrow R\}$ link is selected, i.e.,

$$\left(R_{i^o}, R_{j^o}\right) = \arg \max_{(R_{i^\star},R_{j^\star})\in\mathcal{F}^\star_{\text{pairs}}} \left\{(L-Q_i)^2\right\}. \tag{6}$$

In case two or more link-pairs still have the same maximum utility, denoted by $\mathcal{F}^o_{\text{pairs}}$ (i.e., $|\mathcal{F}^o_{\text{pairs}}| > 1$), it means that they have the same buffer state, and one of them is randomly activated.

- Moreover, in instances where SOR is infeasible, the efficient $\text{DDA}-\max-\text{link}$ algorithm of [18] is adopted. It must be underlined that $\text{DDA}-\max-\text{link}$ avoids the selection of relays whose buffers are at the edge of underflowing or overflowing and it only activates such relays to avoid a network outage. The details of $\text{DDA}-\max-\text{link}$ algorithm are described in Algorithm 1.

The details of the proposed selection policy are provided in Algorithm 1.

Remark 1: Unlike other approaches that use SuR in BA relay networks, such as [27], in this paper, we propose a delay- and diversity-aware approach in both modes of operation.

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 $\text{DDA}-\max-\text{link}$ algorithm:
    if $\mathcal{F}_{SR} = \emptyset$ and $\mathcal{F}_{RD} = \emptyset$ then
        No packet transmission takes place.
    else
        if $\mathcal{F}_{SR} = \emptyset$ then
            $j = \arg\max_{m\in\mathcal{F}_{RD}} Q_m$                    ($\{R \rightarrow D\}$ 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
                $i = \arg\min_{m\in\widetilde{\mathcal{F}}_{SR}} Q_m$            ($\{S \rightarrow R\}$ 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
                    $j = \arg\max_{\ell\in\widetilde{\mathcal{F}}_{RD}} Q_\ell$        ($\{R \rightarrow D\}$ link)
                else
                    $\hat{\mathcal{F}}_{SR} \triangleq \{m : m \in \mathcal{F}_{SR}, Q_m \geq 2\}$
                    $i = \arg\min_{m\in\hat{\mathcal{F}}_{SR}} Q_m$        ($\{S \rightarrow R\}$ link)
                end if
            end if
        end if
    end if
end if
output Links $\{R_j \rightarrow D\}$ and $\{S \rightarrow R_i\}$, or, link $\{R_j \rightarrow D\}$,
    or, link $\{S \rightarrow R_i\}$ for transmission.
```

IV. DISTRIBUTED LOLA4SOR

For the implementation of LoLa4SOR, CSI of all the $\{S \rightarrow R\}$ and $\{R \rightarrow D\}$ is required, as well as the inter-relay channel conditions between a transmitting and a receiving relay. Such a CSI acquisition procedure is often undesirable or even infeasible to have, especially when the number of available relays is large. In order to facilitate the adoption of LoLa4SOR in different networking environments, in which CSI availability is limited, a distributed implementation approach should be facilitated. As already discussed, LoLa4SOR first aims for SuR and if no link-pair can be selected, the HD $\text{DDA}-\max-\text{link}$ is deployed. The distributed implementation of LoLa4SOR, herein called d-LoLa4SOR, can be divided in the following phases:

- In the *first phase*, the source broadcasts a pilot sequence, prompting the K relays to estimate the $\{S \rightarrow R\}$ CSI.
- Next, in the *second phase*, the destination transmits pilot signals to the relays, with which the relays derive the $\{R \rightarrow D\}$ CSI, assuming that channel reciprocity holds [43]. By the end of the second phase, considering that the relays are aware of the source's transmit

power, P_S, they can assess whether or not they belong in $\mathcal{F}_{SR}$ and/or $\mathcal{F}_{RD}$. However, in order to be able to infer whether there exist relays that are able to transmit and receive in pairs, performing SOR, the relays should estimate the level of IRI. For doing so, they should have estimated the channel conditions between the relays (i.e., the $\{R_j \rightarrow R_i\}$ links), which requires a substantial communication overhead and coordination.

- In the *third phase*, aiming at reduced end-to-end delay, d-LoLa4SOR prioritizes the transmitting relays, and so, from the relays in $\mathcal{F}_{RD}$, the one with the largest queue is selected. This can be performed via a distributed method suggested in [18] (which builds on the idea of distributed timers proposed in the seminal paper [34]) in which, each candidate transmitting relay, R_k, sets its timer to be inversely proportional to a number which is the summation of the number of packets residing in its buffer, Q_k, plus a random number $v_k \in (-1/2, 1/2)$ (in order to avoid collisions). The relay with the largest queue, say R_j, has its timer expire first and broadcasts a flag (distress signal), denoting its activation as the transmitting relay for that time-slot.
- Once the relay for transmission, R_j, is selected, in the *fourth phase*, a pilot sequence is broadcasted by R_j, prompting the $|\mathcal{F}_{SR}|-1$ *remaining* relays to estimate the $\{R_i \rightarrow R_j\}$ CSI (assuming again that channel reciprocity holds). Then, provided that the transmit power of that relay P_j is fixed and predetermined, IRI levels can be evaluated by the relays of the $|\mathcal{F}_{SR}|$ relays and thus, they are able to know whether they can receive a packet from the source or not, while R_j is transmitting. A relay that can successfully receive a packet from the source belongs to set $\mathcal{F}_{j,SR}$. Note that if $\mathcal{F}_{RD} = \emptyset$, then $\mathcal{F}_{j,SR} \equiv \mathcal{F}_{SR}$, i.e., all the relays are considered for receiving a packet from the source, irrespective of whether or not, a transmitting relay is assigned.
- In the *fifth phase*, the relays in $\mathcal{F}_{j,SR}$ compete in the same way as the relays in the third phase, with the difference that this time, these relays set their timers to be proportional to a number that is the number of packets in their buffer plus a random number.
- Once the receiving relay is also selected, SuR is performed. Nonetheless, if $\mathcal{F}_{j,SR}$ is empty, i.e., SuR is infeasible for the selected transmitting relay R_j, then no relay will broadcast any signal during the allocated contention time. In this case, only the selected relay for transmissions will be activated.

In conclusion, d-LoLa4SOR requires that each relay acquires the CSI of the $\{S \rightarrow R\}$ and $\{R \rightarrow D\}$ links, thus the source and the destination broadcast pilot sequences. Then, each relay which is able to transmit to the destination, i.e., having a non-empty queue and an $\{R \rightarrow D\}$ link that is not in outage, sets its timer value inversely proportional to the number of packets residing in its queue. When the timer of the relay with the smallest value expires that relay is selected as the transmitting one. In the last step, the transmitting relay broadcasts a pilot sequence, helping the rest $K-1$ relays to acquire their $\{R \rightarrow R\}$ link CSI. Finally, in order to provide a spherical view on network coordination overheads, Table 1 summarizes the CSI and BSI requirements of different BA relaying protocols.

Algorithm 2 d-LoLa4SOR - Algorithm That Relay R_j Follows

```
input $Q_j$, $P_S$, $P_i$ for all relays $R_i$ in the network, fixed parameter $\lambda_1$ and $\lambda_2$ for the timers
phase 1: A pilot sequence is broadcasted by the source. $R_j$ estimates the $\{S \rightarrow R\}$ CSI and checks whether it belongs to $\mathcal{F}_{SR}$.
phase 2: A pilot sequence is broadcasted by the destination. $R_j$ estimates the $\{R \rightarrow D\}$ CSI and checks whether it belongs to $\mathcal{F}_{RD}$.
if $R_j \in \mathcal{F}_{RD}$ then
    phase 3: $R_j$ sets up a timer with $\tau_j = \lambda_1/(Q_j + v_j)$, $v_j \sim U(-1/2, 1/2)$ and claims the $\{R \rightarrow D\}$ link.
    if $\tau_j < \tau_i \ \forall \ R_i \in \mathcal{F}_{RD}$ then
        $R_j$ becomes the transmitting relay for the slot, i.e., $R_{\text{tx}} = R_j$.
        phase 4: $R_j$ broadcasts a pilot sequence.
    end if
end if
if $R_j \in \mathcal{F}_{SR}$ and $R_j \neq R_{\text{tx}}$ then
    phase 4: $R_j$ checks whether it belongs to set $\mathcal{F}_{\text{tx,SR}}$.
    if $R_j \in \mathcal{F}_{\text{tx,SR}}$ then
        phase 5: $R_j$ sets up a timer with $T_j = \lambda_2(Q_j + w_j)$, $w_j \sim U(-1/2, 1/2)$, and claims the $\{S \rightarrow R\}$ link.
        if $T_j < T_i \ \forall \ R_i \in \mathcal{F}_{\text{tx,SR}}$ then
            $R_j$ becomes the receiving relay for the slot, i.e., $R_{\text{rx}} = R_j$.
        end if
    end if
end if
output Find whether $R_j = R_{\text{tx}}$ or $R_j = R_{\text{rx}}$.
```

The details of the proposed distributed selection policy for each relay R_j, at every time frame, are provided in Algorithm 2.

Remark 2: Note that in LoLa4SOR there exist $K \times (K-1)$ possible relay-pairs and thus, the complexity of selection is $\mathcal{O}(K^2)$. On the contrary, d-LoLa4SOR entails a complexity equal to $\mathcal{O}(K)$ as each time, only $K-1$ relays are examined when R_j is activated. The trade-off between performance and complexity among the two versions is shown at Section VI.

Remark 3: There are various timer-based distributed methods for relay selection, relying on the approach of [34]. For example, in [24], a distributed method for relay and link selection in HD networks is proposed, prompting the relays to negotiate which one should be activated in each time-slot. However, our work is the first one to present a distributed method for achieving FD operation under the SuR paradigm, incorporating both BSI and CSI in the relay-pair selection process.

TABLE 1. Required overheads of LoLa4SOR, d-LoLa4SOR, $\max-\text{link}$, SFD-MMRS and BASOR/$\max-\text{link}$ at each time-slot.

	Pilot transmissions			CSI estimations			Data transmissions from relay nodes			
	S	R_j	D	S	R_j	D	$\{S\to R\}$ CSI	$\{R\to D\}$ CSI	$\{R\to R\}$ CSI	buffer states
LoLa4SOR	1	1	1	0	$K+1$	0	K	K	$K(K-1)$	K
d-LoLa4SOR	1	1^*	1	0	$3^\dagger$	0	0	0	0	0
$\max-\text{link}$ [16]	1	1	0	0	1	K	K	K	0	K
SFD-MMRS [26]	1	0	1	0	2	0	K	K	0	K
BASOR/$\max-\text{link}$ [27]	1	1	1	0	$K+1$	0	K	K	$K(K-1)$	K

$^*R_j$ refers to the activated transmitting relay R_{tx}.
$^\dagger R_j$ refers to the remaining $|\mathcal{F}_{SR}|-1$ receiving relays.

V. THEORETICAL ANALYSIS

A. MODELING USING DISCRETE-TIME, HOMOGENEOUS MARKOV CHAINS

Such cooperative systems consisting of relays equipped with buffers (of finite or infinite size) are usually modeled using discrete-time, homogeneous Markov chains (MC); e.g., Krikidis *et al.* [16] proposed a general framework, to analyze the performance of the $\max-\text{link}$, that has been adopted in several subsequent works in the field that proposed buffer-aided relay selection mechanisms in order to analyze their performance.

In this framework, a state of the MC represents a state of the buffers, i.e., for a network with K relays of buffer size L, there exist $(L+1)^K$ possible buffer states, which comprise the states of the MC. The MC state is denoted by $S_r \triangleq (Q_1^{(r)}Q_2^{(r)}\dots Q_K^{(r)})$, $r\in\{1,2,\dots,(L+1)^K\}$. The transition between the states (and hence the transition probabilities of the Markov chain) are determined by the probabilities of successful/unsuccessful transmissions of packets in the network (on the $\{S\to R\}$ link only, on the $\{R\to D\}$ link only, or on both links). These transition probabilities are summarized in the matrix of transition probabilities of the MC, denoted by $\mathbf{A}\in\mathbb{R}^{(L+1)^K\times(L+1)^K}$. Each entry $\mathbf{A}_{i,j}=\mathbb{P}(S_j\to S_i)$ is the probability to transit from state S_j at time t to state S_i at time $t+1$, i.e.,

$$\mathbf{A}_{i,j}=\mathbb{P}(S_j\to S_i)=\mathbb{P}(X_{t+1}=S_i|X_t=S_j). \tag{7}$$

To be able to construct the transition matrix $\mathbf{A}$, we need to compute the transition probabilities between the different states of the buffers. Towards this end, we observe that, at each time slot, the buffers state may be changed in the following ways:

(i) the queue size of a relay's buffer increases by one, if the source node transmits a packet to that relay is successfully;
(ii) the queue size of a relay's buffer decreases by one, if the relay node transmits a packet (to the destination) successfully, and
(iii) the queue size of a relay's buffer remains unchanged when none of the $\{S\to R\}$ and $\{R\to D\}$ links transmits a packet successfully.

Note that in SuR, we have both *(i)* and *(ii)* taking place at each time frame. Let $\mathcal{C}_r$ denote the set of "active" links (i.e., those links that are not excluded from transmission because of having empty or full buffers) at a specific state r. Then, the outage probability, $\bar{p}_r$, at state r is given by

$$\bar{p}_r=\prod_{\ell\in\mathcal{C}_r}\left(1-\exp\left(-\frac{\gamma_0\eta_{j(\ell)}}{P_{i(\ell)}}\right)\right), \tag{8}$$

where $P_{i(\ell)}$ is the transmit power level of transmitter i on communication link ℓ, and $\eta_{j(\ell)}$ is the noise level at receiver j on link ℓ. Such formulation allows the consideration of asymmetric links, but in this work, for simplicity of exposition, we consider the case of symmetric links only, in which the outage probability at state r is simplified to

$$\bar{p}_r=\left(1-\exp\left(-\frac{\gamma_0\eta}{P}\right)\right)^{|\mathcal{C}_r|}. \tag{9}$$

As a result, the probability of having at least one link not being in outage among the active links at state r is given by

$$p_r=\frac{1}{|\mathcal{C}_r|}\left[1-\left(1-\exp\left(-\frac{\gamma_0\eta}{P}\right)\right)^{|\mathcal{C}_r|}\right]. \tag{10}$$

Since we consider buffers of finite size in this work, the number of states of the MC are finite. The transition probability matrix can be represented by a strongly connected directed graph which justifies the irreducibility of the MC. The existence of outages (and hence self-loops in the states), justifies the aperiodicity of the MC. Hence, it can be easily deduced that the MC is Stationary, Irreducible, and Aperiodic. As a result, there exists a stationary distribution $\boldsymbol{\pi}\in\mathbb{R}^{(L+1)^K}$ which satisfies $\mathbf{A}\boldsymbol{\pi}=\boldsymbol{\pi}$. From the structured MC one can compute the outage probability of the system as follows [16]

$$p_{\text{out}}=\sum_{r=1}^{(L+1)^K}\boldsymbol{\pi}_r\bar{p}_r=\text{diag}(\mathbf{A})\boldsymbol{\pi}. \tag{11}$$

Remark 4: The proposed selection algorithm shares the same analytical framework with other BA algorithms in the literature, such as [20], [21], [23], [27]. So, in this work, we rather focus on the theoretical derivation of the diversity order that, to the best of the authors' knowledge, has not appeared before for low-latency successive relay networks with buffers.

B. DIVERSITY ORDER ANALYSIS

The diversity order[2] practically embodies the maximum number of independent links between a source and a destination [45]. The more the distinguishable links between the source and the destination, the higher the probability that a link with a high enough SNR will be selected, thus leading to a lower outage probability. Note that in this work the outage probability is defined as the probability that none of the relays has a successful transmission or reception of packets.

The expression (11) for the outage probability as it stands does not facilitate the computation of the diversity gain of our system. In what follows, a simplified formula will be derived for the outage probability in order to obtain the diversity order achieved by our proposed scheme. Before deriving the diversity order of LoLa4SOR, we state Proposition 1, which shows that if the maximum powers $P_S^{\max}$ and $P_{R_{\text{tx}}}^{\max}$ are not imposing any limitations/constraints for each feasible (in terms of queue feasibility) pair of relays R_{rx} and R_{tx}, then there exist power levels that satisfy the interference cancelation conditions and, as a consequence, the outage probability tends to zero.

Proposition 1 [27, Proposition 1]: Let $P_S^{\max} \rightarrow \infty$ and $P_{R_{\text{tx}}}^{\max} \rightarrow \infty$. For each pair of relays R_{rx} and R_{tx}, there exist P_S and $P_{R_{\text{tx}}}$ such that $\mathbb{I}(R_{\text{tx}}, R_{\text{rx}}) = 0$, $\text{SNR}_{R_{\text{tx}}D} \geq \gamma_0$ and $\text{SINR}_{SR_{\text{rx}}} \geq \gamma_0$. The minimum power levels P_S^* and $P_{R_{\text{tx}}}^*$ are achieved when $\text{SNR}_{R_{\text{tx}}D} = \text{SINR}_{SR_{\text{rx}}} = \gamma_0$, and are given by

$$P_S^* = \frac{\gamma_0 n_{R_{\text{rx}}}}{g_{SR_{\text{rx}}}}, \tag{12a}$$

$$P_{R_{\text{tx}}}^* = \max\left\{\frac{\gamma_0 n_D}{g_{R_{\text{tx}}D}}, \frac{n_{R_{\text{rx}}}\gamma_0(\gamma_0+1)}{g_{R_{\text{tx}}R_{\text{rx}}}}\right\}. \tag{12b}$$

Proposition 1 will be useful in our subsequent diversity analysis, in which we allow the power (or SNR) to tend to infinity. Then, as the power levels tend to infinity we can assume that the probability of outage of both the $\{S \rightarrow R\}$ and the $\{R \rightarrow D\}$ communication links tends to zero. As a result, we can simply assume that for high SNR the $\{S \rightarrow R\}$ and $\{R \rightarrow D\}$ links do not experience any interference. Hence, the outage probability of the network (either when there is SuR or a single link transmission) is exponentially distributed and, for the case of symmetric i.i.d. channels, is written analytically as

$$\mathbb{P}_{\text{out}} = \varepsilon^{2K}, \tag{13}$$

where $\varepsilon \triangleq 1 - \exp(-\gamma_0/\phi)$ and ϕ is the power of the transmitting node (either the source or the transmitting relay).

It was proved in [16] that, for the max − link relay selection protocol, as the size of the buffer, L, approaches infinity, the states where no full or empty relays exist are dominant[3] and, hence, max − link can achieve diversity order of $2K$. Nevertheless, when L is small, the probability of being at an empty or full buffer is nonzero, irrespective of how large the power (ϕ) is. Unlike max − link and similar to other works in the literature (see, e.g., [18], [44]), LoLa4SOR takes into account the queue size of the buffers and can, therefore, prevent each buffer to be either full or empty. As a result, a larger diversity order can be obtained for buffers of small size/capacity L than with max − link.

Lemma 1: The diversity order of LoLa4SOR is given by

$$d = \begin{cases} K, & \text{if } L = 1 \\ 2K-2, & \text{if } L = 2 \\ 2K, & \text{if } L \geq 3. \end{cases} \tag{14}$$

Proof: See the Appendix. ■

VI. PERFORMANCE EVALUATION

Here, the performance of both LoLa4SOR versions is evaluated in terms of outage probability, average throughput and average delay and comparisons with three categories of selection algorithms are given. The first category consists of HD algorithms and more specifically, max − link and DDA − max − link. Then, the second category includes BASOR, while a hybrid HD/SOR algorithm is considered for the third category, based on BASOR/max − link (H-BASOR). Moreover, a topology with i.i.d. channels, modeled as zero-mean complex Gaussian random variables with variances $\sigma_{g_{SR}}^2 = \sigma_{g_{RD}}^2 = \sigma_{g_{RR}}^2$ is simulated and performance is evaluated, under varying transmit SNR values in each link, corresponding to the ratio of the transmit power at each transmitter over the noise power. Moreover, $K = 3$ relays, with a buffer size of $L = 5$ packets are assumed, unless otherwise stated, while the transmission rate is equal to 1 bps/Hz. This topology allows us to study the impact of inter-relay interference, contrary to other works which assume relays to be isolated (e.g., [26]). On the other hand, it does not provide any favorable conditions for interference cancelation, as it would be the case with closely located relays.

A. OUTAGE PROBABILITY

Fig. 2 shows the outage probability of LoLa4SOR for $K = 3$ and varying buffer size L. As it has been proven in Lemma 1, the negative effect of using $L < 3$ on the diversity performance is evident. More specifically, when $L = 1$ a diversity equal to K is observed, as buffers are often full and relays can only be selected for HD operation, while successive relaying often fails, especially for low and medium SNR, as receiving relays are not available. Then, for $L = 2$, diversity improves, reaching a diversity order equal to $2K - 2$. Nonetheless, for $L \geq 3$, the diversity order tends to $2K$, as SNR increases. Moreover, the cases of $L = 3$ and $L = 5$ exhibit similar diversity, while a coding gain is observed throughout the SNR range for $L = 5$. These results comply with the diversity order provided in Lemma 1.

The outage probability performance for various algorithms for $K = 3$, $L = 5$ is shown in Fig. 3. It is observed that BASOR exhibits the worst outage performance, affected by IRI, as HD operation is absent. Reduced diversity

---

[2] The diversity order (or diversity gain) is the gain in spatial diversity, that is used for improving the reliability of a communication link and it is defined by: $d = -\lim_{\text{SNR}\rightarrow\infty} \frac{\log \mathbb{P}_{\text{out}}(\text{SNR})}{\log \text{SNR}}$.

[3] By dominant we mean the states for which the stationary distribution is greater than zero.

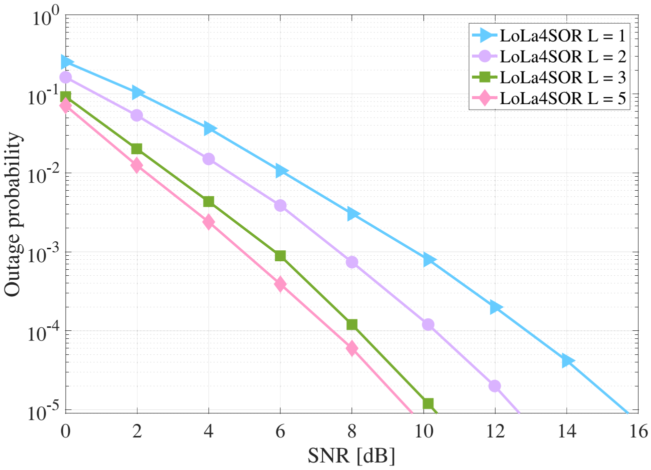


FIGURE 2. **Outage probability of LoLa4SOR for $K = 3$ and varying L.**

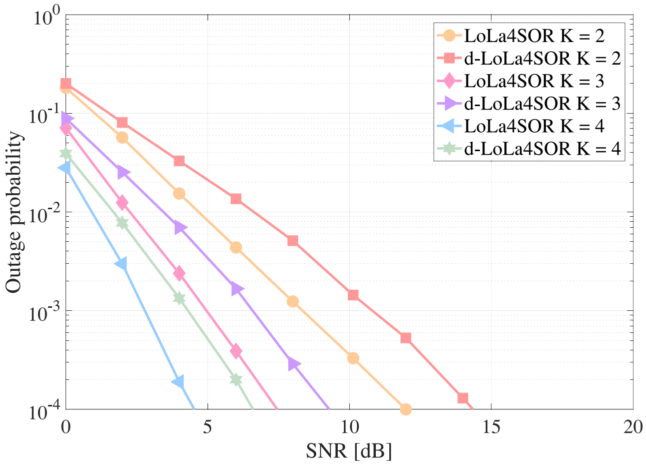


FIGURE 4. **Outage probability for varying K, $L = 5$ and various algorithms.**

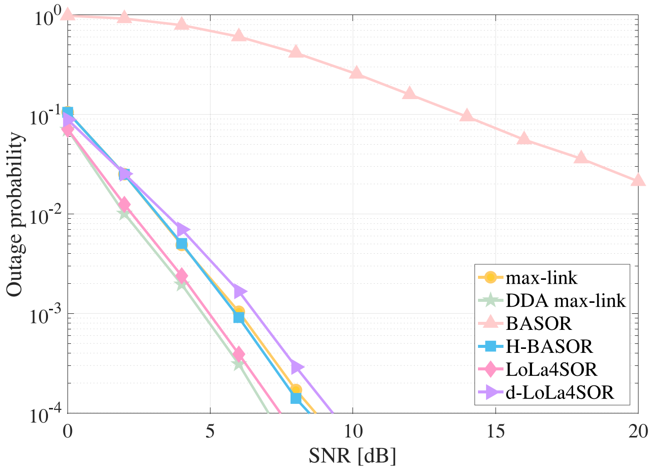


FIGURE 3. **Outage probability for $K = 3$, $L = 5$ and various algorithms.**

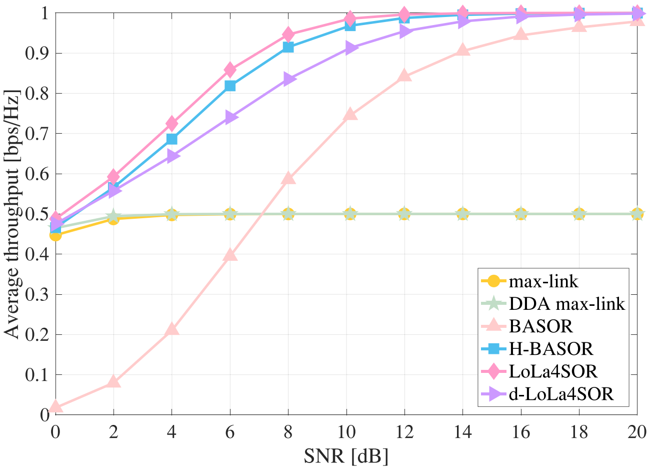


FIGURE 5. **Average throughput for $K = 3$, $L = 5$ and various algorithms.**

is provided by d-LoLa4SOR, since $\{R \to D\}$ prioritization increases the instances of empty buffers. Still, d-LoLa4SOR performs closer to DDA algorithms than to BASOR, leading to a desirable trade-off, considering its low-complexity implementation. Overall, the best performance is provided by $\mathrm{DDA}-\max-\mathrm{link}$ and LoLa4SOR, both preserving the diversity of the network when it is possible. Finally, H-BASOR offers adequate outage performance due to the adoption of $\max-\mathrm{link}$, exploiting its increased diversity.

Next, Fig. 4 includes outage results for the two versions of LoLa4SOR for $L = 5$ and varying K. As more relays become available, the outage probability reduces. Overall, the centralized version of LoLa4SOR outperforms its distributed version. This behavior stems from the different link-pair selection process. More specifically, centralized LoLa4SOR checks all the possible link-pairs, according to (5). On the contrary, d-LoLa4SOR selects a pair after activating a transmitting relay with the maximum buffer size and, thus, the reduced degrees of freedom lead to worse outage performance.

B. AVERAGE THROUGHPUT

The average throughput comparisons are included in Fig. 5. Here, the performance can be classified in three categories. Firstly, reduced end-to-end throughput is offered by the HD algorithms, reaching the upper bound of 0.5 bps/Hz after 2 dB. Then, the BASOR offers the worst performance in the low and medium SNR regime, while after 7 dB it outperforms the HD algorithms. It is obvious that due to IRI, fixed transmit power and absence of HD operation, BASOR falls short of the throughput upper-bound. On the contrary, the combination of SOR and HD algorithms is beneficial, as depicted by the throughput performance of the hybrid algorithms. Among the hybrid algorithms, LoLa4SOR has the best performance, as IRI is avoided by activating HD operation when link-pair selection is infeasible. Moreover, diversity is maintained due to $\mathrm{DDA}-\max-\mathrm{link}$, compared to H-BASOR, where delay and diversity awareness is not integrated, neither in its SOR nor in its HD operation. Regarding d-LoLa4SOR, it can be seen that although it entails slightly increased complexity compared to the

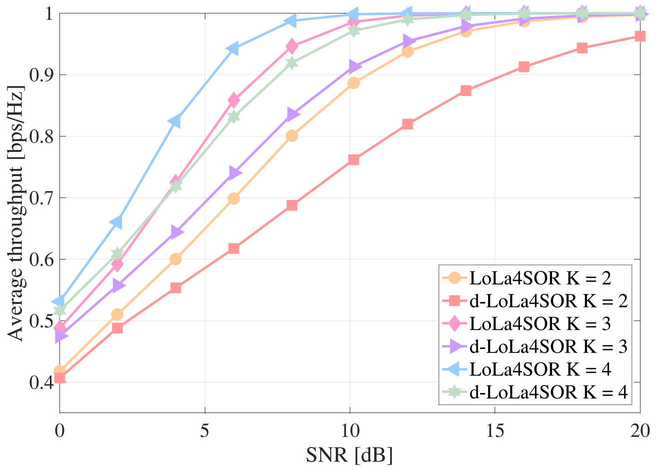


FIGURE 6. **Average throughput for varying K, $L = 5$ and various algorithms.**

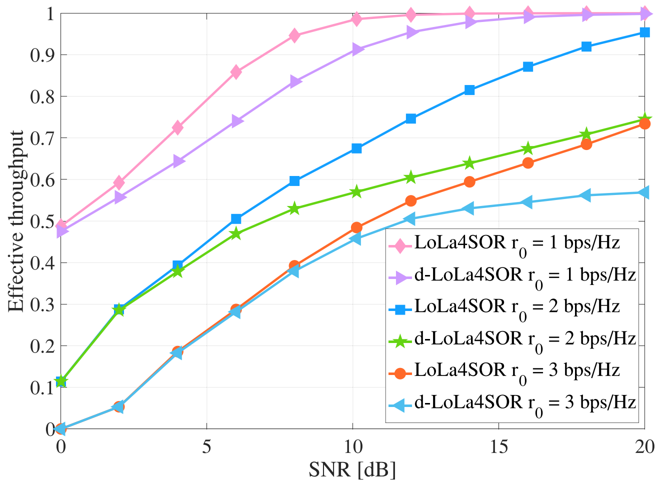


FIGURE 7. **Effective throughput for $K = 3$, $L = 5$ and varying r_0 values.**

HD algorithms, it leads to significantly superior throughput performance.

Fig. 6 depicts the average throughput for both versions of LoLa4SOR and different K. It can be seen that even for $K = 2$, d-LoLa4SOR surpasses the throughput upper bound of HD algorithms after 2 dB. In general, throughput improves by increasing the number of available relays. Moreover, the centralized version of LoLa4SOR, independently of K achieves the upper bound of the FD transmission. More importantly, in topologies with increased numbers of relays, d-LoLa4SOR can progressively reach the FD upper bound, as shown for $K = 3$ and $K = 4$, thus revealing an important trade-off between coordination overheads and performance.

In order to better depict the performance of LoLa4SOR and d-LoLa4SOR under different cases of fixed rate r_0, Fig. 7 illustrates the effective throughput performance. Here, the effective throughput is defined as the ratio of the number of packets, successfully decoded in the destination over the

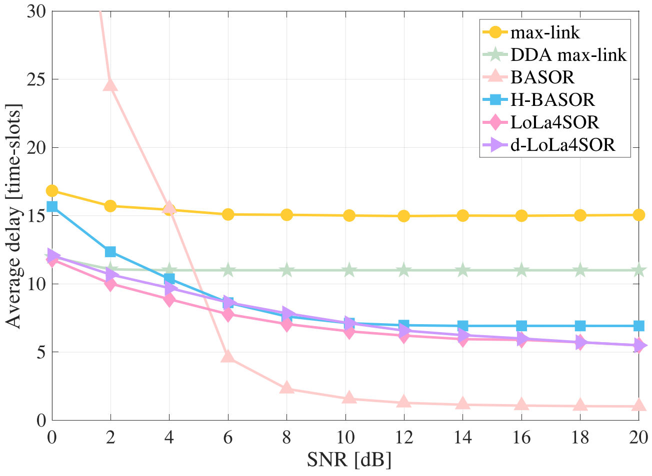


FIGURE 8. **Average delay for $K = 3$, $L = 5$ and various algorithms.**

number of packets transmitted by the saturated source, during the whole transmission period. Since both algorithms perform SuR, a new packet can be transmitted by the source at each time-slot, using a pre-defined fixed rate level. From the results, it can be seen that as r_0 increases, the effective throughput decreases, since the chances for IC at the relay are reduced, and due to higher capture ratio values, outages in the network increase.

C. AVERAGE DELAY

The results in Fig. 8 present the average delay performance of the different selection categories. It can be seen that the BASOR algorithm achieves packet transmission with the lowest delay. Unfortunately, as already observed in the outage and throughput results, significantly less packets are transmitted, compared to LoLa4SOR, d-LoLa4SOR and H-BASOR. Between the three hybrid algorithms, LoLa4SOR achieves the lowest delay, while H-BASOR provides the worst delay performance, but still, it outperforms the two HD algorithms while transmitting more packets. At the same time, d-LoLa4SOR stays behind its centralized version and surpasses H-BASOR throughout the SNR range. However, among the hybrid algorithms, d-LoLa4SOR transmits the least number of packets. As for $\max-\text{link}$ and $\text{DDA}-\max-\text{link}$, their performance follows the results of the delay analysis in [18], highlighting an average delay equal to KL and $4K-1$ for high SNR, respectively and thus, they are outperformed by LoLa4SOR, d-LoLa4SOR and H-BASOR.

VII. CONCLUSION AND FUTURE DIRECTIONS

A. CONCLUSION

The efficient operation of 5G networks depends on cooperative schemes that can support a broad range of applications with diverse requirements. Such schemes should provide robustness against outages without neglecting the throughput and delay performance. In this work, we combined the merits of successive and half-duplex relaying, targeting to reduce the average delay of two-hop buffer-aided relay networks. Thus, LoLa4SOR, a low-latency successive opportunistic relay selection algorithm was proposed, achieving reduced packet delays, without suffering diversity losses that are inherent in delay-aware buffer-aided relay selection algorithms. LoLa4SOR is the first successive relaying algorithm leveraging buffer state information during relay-pair selection and offering delay improvement. Also, a distributed framework for LoLa4SOR was presented, promoting low-complexity implementation. Then, LoLa4SOR was evaluated in terms of diversity gain, showing that a diversity gain equal to $2K$ can be achieved. Comparisons with other algorithms suggested that LoLa4SOR can provide reduced outages and increased throughput, while keeping a low average packet delay.

B. FUTURE DIRECTIONS

Currently, LoLa4SOR does not perform power adaptation, which would allow additional link-pairs to be formed, improving the performance of the network. Another interesting area with practical interest is the study of outdated CSI on the operation of hybrid SOR/HD algorithms, as well as FD relaying on top of LoLa4SOR. Also, the effect of erroneous ACK/NACK feedback channel should be examined in order to overcome performance degradation due to duplicate packets in real-world setups. Moreover, the integration of LoLa4SOR in millimeter wave (mmWave) communications can be investigated, as some early studies present the effect of cooperative relaying on improving both reliability and delay performance [46]. Finally, cases where multiple users are served through non-orthogonal multiple access (NOMA) [47]–[50] can further enhance the connectivity.

APPENDIX
PROOF OF LEMMA 1

The proof of Lemma 1, relies on the context of the simplified MC introduced in [44], in which each link is selected according to a weight associated with the buffer state. However, the analysis in [44] does not take into consideration successive relaying (affects the transition probabilities and structure of the MC). Also, the diversity order obtained in our case for $L = 2$ is different.

First, we aggregate the MC introduced in Section V-A into K+1 states as follows: state $\tilde{S}_j$ includes all the states S_i in which exactly j buffers are either full or empty. As a result, $\tilde{S}_j$ has $2K - j$ available links. Hence, the outage probability (11) can be expressed as

$$p_{\text{out}} = \sum_{r=1}^{(L+1)^K} \boldsymbol{\pi}_r \bar{p}_r = \sum_{j=0}^{K} \tilde{\boldsymbol{\pi}}_j \varepsilon^{2K-j}, \tag{15}$$

where $\tilde{\boldsymbol{\pi}}_j$ is the steady-state probability for being in state $\tilde{S}_j$ and it is given by

$$\tilde{\boldsymbol{\pi}}_j = \sum_{i:S_i \in \tilde{S}_j} \boldsymbol{\pi}_i. \tag{16}$$

Let the transition probability matrix of the new MC be denoted by $\tilde{\mathbf{A}} \in \mathbb{R}^{(K+1)\times(K+1)}$. As before, each entry $\tilde{\mathbf{A}}_{i,l} = \mathbb{P}(\tilde{S}_j \to \tilde{S}_l)$ represents the probability of transition from state $\tilde{S}_j$ at one time slot to state $\tilde{S}_l$ at the next time slot. To construct transition matrix $\tilde{\mathbf{A}}$, we need to determine the transition probabilities of the new MC.

First, for the case of $L = 1$, each buffer has either 1 or 0 packets. So, each relay has only one link available and, hence, the diversity order is K. To prove the rest of Lemma 1, we consider two special cases: $L = 2$ and $L = 3$. For $L = 2$, we show that the diversity order is equal to $2K - 1$, while for $L = 3$, the diversity order is equal to $2K$. Subsequently, since the outage probability decreases with L, it can be easily deduced that the diversity order does not change for $L > 3$.

A. DIVERSITY ORDER FOR L = 2

When $L = 2$, we have the following transitions:

1) State $\tilde{S}_j$ will remain in $\tilde{S}_j$ if either no transmission is feasible or one relay with a single packet in its buffer becomes full or empty while another from empty or full stays with one packet in its buffer.
2) State $\tilde{S}_j$ will move to $\tilde{S}_{j+1}$ if a relay with a single packet in its buffer is selected to transmit/receive a packet and no other relay with a full (empty) buffer is selected to transmit (receive) at the same time.
3) State $\tilde{S}_j$ will move to $\tilde{S}_{j-1}$ if a relay with a full (empty) buffer is selected to transmit (receive) a packet and no other relay with one packet is selected to transmit/receive at the same time.
4) State $\tilde{S}_j$ will move to $\tilde{S}_{j+2}$ if a relay with a single packet in its buffer is selected to transmit and another relay with one packet is selected to receive.
5) State $\tilde{S}_j$ will move to $\tilde{S}_{j-2}$ if a relay with a full buffer is selected to transmit and another relay with an empty is selected to receive.

Unlike [44], our MC may have transitions of 2 steps, thus complicating the analysis of the MC. Since we are interested about the diversity analysis, we concentrate on the MC at the high SNR regime of a network using LoLa4SOR. For $L = 2$, the MC at the high SNR regime for a network with 3 relays is depicted in Figure 9.

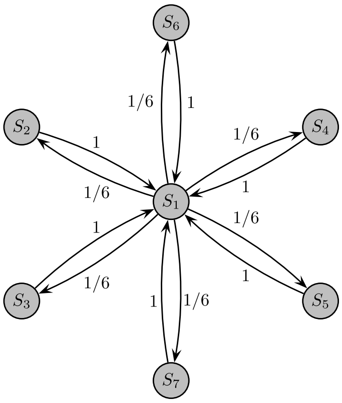
The state transition matrix is, thus, given by

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

The stationary distribution is easily computed as

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

Transforming this MC to the simplified one, we get the following states: $\tilde{S}_0 = \{S_1\}$, $\tilde{S}_2 = \{S_2, S_3, S_4, S_5, S_6, S_7\}$, and



State	S_r
S_1	111
S_2	102
S_3	120
S_4	210
S_5	201
S_6	012
S_7	021

FIGURE 9. **The MC at the high SNR regime (outage probability is negligible) of a network for $K = 3$ and $L = 2$.**

$\tilde{S}_1 = \tilde{S}_3 = \emptyset$, with $\tilde{\boldsymbol{\pi}}_0 = 1/2$ and $\tilde{\boldsymbol{\pi}}_2 = 1/2$. Therefore, the outage probability (15) is given by

$$p_{\text{out}} = \sum_{j=0}^{3} \tilde{\boldsymbol{\pi}}_j \varepsilon^{6-j} = \tilde{\boldsymbol{\pi}}_0 \varepsilon^6 + \tilde{\boldsymbol{\pi}}_2 \varepsilon^4 = \frac{\varepsilon^4}{2}\Big(\varepsilon^2 + 1\Big).$$

The diversity order is then

$$\begin{aligned} d &= -\lim_{\phi\to\infty} \frac{\log p_{\text{out}}}{\log \phi} \\ &= -\lim_{\phi\to\infty} \frac{4\log\varepsilon + \log(\varepsilon^2+1) - \log 2}{\log\phi} \\ &\overset{(a)}{=} -\lim_{\phi\to\infty} \frac{4\log\varepsilon}{\log\phi} \overset{(b)}{=} 4, \end{aligned}$$

where (a) stems from the fact that the 2 terms are not scaling with ϕ and (b) stems from the fact that $\varepsilon \triangleq 1 - \exp(-\gamma_0/\phi)$ and for small values of x, $1 - \exp(-x) \approx x$.

From the example with $K = 3$ relays, the results can be generalized to that of a network consisting of K relays. Specifically, it can be easily deduced by the construction of the MC that the stationary distribution generalizes to

$$\boldsymbol{\pi} = \Big[1/2 \quad 1/2K \quad 1/2K \quad \ldots \quad 1/2K\Big]. \tag{17}$$

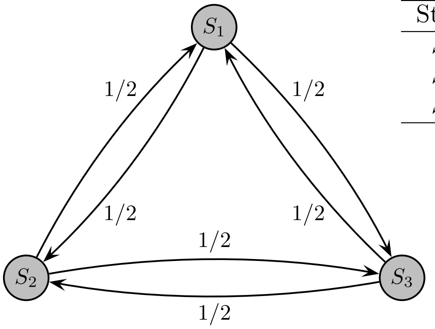
Transforming this MC to the simplified one, we get the following states:

$$\begin{aligned} &\tilde{S}_0 = \{S_1\}, \\ &\tilde{S}_2 = \mathcal{C} \setminus S_1, \\ &\tilde{S}_1 = \tilde{S}_3 = \ldots = \tilde{S}_K = \emptyset, \end{aligned}$$

with $\tilde{\boldsymbol{\pi}}_0 = 1/2$ and $\tilde{\boldsymbol{\pi}}_2 = 1/2$. Therefore, the outage probability (15) is given by

$$p_{\text{out}} = \tilde{\boldsymbol{\pi}}_0 \varepsilon^{2K} + \tilde{\boldsymbol{\pi}}_2 \varepsilon^{2K-2} = \frac{\varepsilon^{2K-2}}{2}\Big(\varepsilon^2 + 1\Big),$$

and, hence, the diversity order is



State	S_r
S_1	221
S_2	122
S_3	212

FIGURE 10. **The MC at the high SNR regime (where the outage probability is negligible) of a network for $K = 3$ and $L = 3$.**

$$\begin{aligned} d &= -\lim_{\phi\to\infty} \frac{\log p_{\text{out}}}{\log \phi} \\ &= -\lim_{\phi\to\infty} \frac{(2K-2)\log\varepsilon + \log(\varepsilon^2+1) - \log 2}{\log\phi} \\ &= 2K - 2. \end{aligned}$$

Note that the diversity order for $L = 2$ in [44] is $2K - 1$ due to the fact that they have single transmissions per frame. Our scheme sacrifices diversity for the sake of higher throughput.

B. DIVERSITY ORDER FOR L $\geq$ 3

When $L = 3$, we have similar transitions as it is the case for $L = 2$; the details are omitted here for simplicity of exposition. Due to the relay selection policy at the high SNR regime the states of the relays will converge to the case in which no relay is either empty or full. For example, for a network with $K = 3$ relays Figure 10 shows the behavior of the MC at the high SNR regime.

The state is either one of S_1, S_2 or S_3 with equal probability due to the symmetry of the MC. All states belong to $\tilde{S}_0$ in the simplified MC and hence $\tilde{\boldsymbol{\pi}}_0 = 1$.

It is easily deduced that this is the case for any number of relays K. Therefore, the outage probability (15) is given by

$$p_{\text{out}} = \tilde{\boldsymbol{\pi}}_0 \varepsilon^{2K} = \varepsilon^{2K},$$

and, hence, the diversity order is

$$d = -\lim_{\phi\to\infty} \frac{\log p_{\text{out}}}{\log\phi} = 2K.$$

Thus, since the outage probability decreases with L, it can be deduced that the diversity order does not change for $L > 3$.

REFERENCES

[1] N. Nomikos, T. Charalambous, N. Pappas, D. Vouyioukas, and R. Wichman, "LoLA4SOR: A low-latency algorithm for successive opportunistic relaying," in *Proc. IEEE Int. Conf. Comput. Commun. (INFOCOM) Workshop*, Apr. 2019, pp. 1–6.

[2] (Nov. 2020). *Ericsson Mobility Report*. [Online]. Available: https://www.ericsson.com/4adc87/assets/local/mobility-report/documents/2020/november-2020-ericsson-mobility-report.pdf

[3] O. L. A. Lopez, N. H. Mahmood, H. Alves, C. M. Lima, and M. Latva-Aho, "Ultra-low latency, low energy, and massiveness in the 6G era via efficient CSIT-limited scheme," *IEEE Commun. Mag.*, vol. 58, no. 11, pp. 56–61, Nov. 2020.

[4] M. Z. Chowdhury, M. Shahjalal, S. Ahmed, and Y. M. Jang, "6G wireless communication systems: Applications, requirements, technologies, challenges, and research directions," *IEEE Open J. Commun. Soc.*, vol. 1, pp. 957–975, 2020.

[5] M. Heino *et al.*, "Recent advances in antenna design and interference cancellation algorithms for in-band full duplex relays," *IEEE Commun. Mag.*, vol. 53, no. 5, pp. 91–101, May 2015.

[6] Z. Zhang, X. Chai, K. Long, A. V. Vasilakos, and L. Hanzo, "Full duplex techniques for 5G networks: Self-interference cancellation, protocol design, and relay selection," *IEEE Commun. Mag.*, vol. 53, no. 5, pp. 128–137, May 2015.

[7] D. Korpi, T. Riihonen, A. Sabharwal, and M. Valkama, "Transmit power optimization and feasibility analysis of self-backhauling full-duplex radio access systems," *IEEE Trans. Wireless Commun.*, vol. 17, no. 6, pp. 4219–4236, Jun. 2018.

[8] M. Mohammadi, B. K. Chalise, H. A. Suraweera, H. Q. Ngo, and Z. Ding, "Design and analysis of full-duplex massive antenna array systems based on wireless power transfer," *IEEE Trans. Commun.*, vol. 69, no. 2, pp. 1302–1316, Feb. 2021.

[9] Y. Jiang *et al.*, "Toward URLLC: A full duplex relay system with self-interference utilization or cancellation," *IEEE Wireless Commun.*, vol. 28, no. 1, pp. 74–81, Feb. 2021.

[10] A. K. Sadek, K. J. R. Liu, and A. Ephremides, "Cognitive multiple access via cooperation: Protocol design and performance analysis," *IEEE Trans. Inf. Theory*, vol. 53, no. 10, pp. 3677–3696, Oct. 2007.

[11] 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.

[12] 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.

[13] 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.

[14] N. Nomikos, T. Charalambous, D. Vouyioukas, and G. K. Karagiannidis, "When buffer-aided relaying meets full duplex and NOMA," *IEEE Wireless Commun.*, vol. 28, no. 1, pp. 68–73, Feb. 2021.

[15] 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.

[16] 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.

[17] 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, Mar. 2013.

[18] 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, 2018.

[19] 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.

[20] 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.

[21] 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.

[22] 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.

[23] W. Raza, N. Javaid, H. Nasir, K. Aurangzeb, Z. A. Khan, and S. I. Haider, "BTRS: Buffer-threshold based relay selection scheme for cooperative wireless networks," *IEEE Access*, vol. 7, pp. 23089–23099, 2018.

[24] 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.

[25] Q. Li, M. Yu, A. Pandharipande, X. Ge, J. Zhang, and J. Zhang, "Performance of virtual full-duplex relaying on cooperative multi-path relay channels," *IEEE Trans. Wireless Commun.*, vol. 15, no. 5, pp. 3628–3642, May 2016.

[26] A. Ikhlef, J. Kim, and R. Schober, "Mimicking full-duplex relaying using half-duplex relays with buffers," *IEEE Trans. Veh. Technol.*, vol. 61, no. 7, pp. 3025–3037, Sep. 2012.

[27] N. Nomikos, T. Charalambous, I. Krikidis, D. N. Skoutas, D. Vouyioukas, and M. Johansson, "A buffer-aided successive opportunistic relay 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.

[28] R. Simoni, V. Jamali, N. Zlatanov, R. Schober, L. Pierucci, and R. Fantacci, "Buffer-aided diamond relay network with block fading," in *Proc. IEEE Int. Conf. Commun. (ICC)*, London, U.K., Jun. 2015, pp. 1982–1987.

[29] R. Simoni, V. Jamali, N. Zlatanov, R. Schober, L. Pierucci, and R. Fantacci, "Buffer-aided diamond relay network with block fading and inter-relay interference," *IEEE Trans. Wireless Commun.*, vol. 15, no. 11, pp. 7357–7372, Nov. 2016.

[30] S. M. Kim and M. Bengtsson, "Virtual full-duplex buffer-aided relaying in the presence of inter-relay interference," *IEEE Trans. Wireless Commun.*, vol. 15, no. 4, pp. 2966–2980, Apr. 2016.

[31] T. Charalambous, S. M. Kim, N. Nomikos, M. Bengtsson, and M. Johansson, "Relay-pair selection in buffer-aided successive opportunistic relaying using a multi-antenna source," *Ad Hoc Netw.*, vol. 84, pp. 29–41, Mar. 2019.

[32] G. I. Tsiropoulos, A. Yadav, M. Zeng, and O. A. Dobre, "Cooperation in 5G HetNets: Advanced spectrum access and D2D assisted communications," *IEEE Wireless Commun.*, vol. 24, no. 5, pp. 110–117, Oct. 2017.

[33] C.-Y. Chen, C.-A. Sung, and H.-H. Chen, "Optimal mode selection algorithms in multiple pair device-to-device communications," *IEEE Wireless Commun.*, vol. 25, no. 4, pp. 82–87, Aug. 2018.

[34] 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.

[35] D. Tse and P. Viswanath, *Fundamentals of Wireless Communications*. Cambridge, U.K.: Cambridge Univ. Press, 2005.

[36] H. Sato, "The capacity of the Gaussian interference channel under strong interference (Corresp.)," *IEEE Trans. Inf. Theory*, vol. IT-27, no. 6, pp. 786–788, Nov. 1981.

[37] M. H. Costa and A. E. Gamal, "The capacity region of the discrete memoryless interference channel with strong interference (Corresp.)," *IEEE Trans. Inf. Theory*, vol. IT-33, no. 5, pp. 710–711, Sep. 1987.

[38] Y. Fan, C. Wang, J. S. Thompson, and H. V. Poor, "Recovering multiplexing loss through successive relaying using repetition coding," *IEEE Trans. Wireless Commun.*, vol. 6, no. 12, pp. 4484–4493, Dec. 2007.

[39] N. Nomikos, T. Charalambous, D. Vouyioukas, R. Wichman, and G. K. Karagiannidis, "Power adaptation in buffer-aided full-duplex relay networks with statistical CSI," *IEEE Trans. Veh. Technol.*, vol. 67, no. 8, pp. 7846–7850, Aug. 2018.

[40] S. N. Venkatasubramanian, C. Zhang, L. Laughlin, K. Haneda, and M. A. Beach, "Geometry-based modeling of self-interference channels for outdoor scenarios," *IEEE Trans. Antennas Propag.*, vol. 67, no. 5, pp. 3297–3307, May 2019.

[41] G. J. González, F. H. Gregorio, J. Cousseau, T. Riihonen, and R. Wichman, "Generalized self-interference model for full-duplex multicarrier transceivers," *IEEE Trans. Commun.*, vol. 67, no. 7, pp. 4995–5007, Jul. 2019.

[42] A. T. Abusabah, L. Irio, R. Oliveira, and D. B. da Costa, "Approximate distributions of the residual self-interference power in multi-tap full-duplex systems," *IEEE Wireless Commun. Lett.*, vol. 10, no. 4, pp. 755–759, Apr. 2021.

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

[44] 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.

[45] A. Ribeiro, X. Cai, and G. B. Giannakis, "Symbol error probabilities for general cooperative links," *IEEE Trans. Wireless Commun.*, vol. 4, no. 3, pp. 1264–1273, May 2005.

[46] C. Tatino, N. Pappas, I. Malanchini, L. Ewe, and D. Yuan, "On the benefits of network-level cooperation in millimeter-wave communications," *IEEE Trans. Wireless Commun.*, vol. 18, no. 9, pp. 4408–4424, Sep. 2019.

[47] 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.
[48] M. Mohammadi *et al.*, "Full-duplex non-orthogonal multiple access for next generation wireless systems," *IEEE Commun. Mag.*, vol. 57, no. 5, pp. 110–116, May 2019.
[49] N. Nomikos, T. Charalambous, D. Vouyioukas, G. K. Karagiannidis, and R. Wichman, "Hybrid NOMA/OMA with buffer-aided relay selection in cooperative networks," *IEEE J. Sel. Topics Signal Process.*, vol. 13, no. 3, pp. 524–537, Jun. 2019.
[50] 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.

NIKOLAOS NOMIKOS (Senior Member, IEEE) received the Diploma degree in electrical engineering and computer technology from the University of Patras, Greece, in 2009, and the M.Sc. and Ph.D. degrees from the Information and Communication Systems Engineering Department, University of the Aegean, Samos, Greece, in 2011 and 2014, respectively. He is currently a Research Associate with the IRIDA Research Centre for Communication Technologies, Department of Electrical and Computer Engineering, University of Cyprus. His research interest is focused on cooperative communications, nonorthogonal multiple access, full-duplex communications, and machine learning for wireless networks optimization. He is a member of the IEEE Communications Society and the Technical Chamber of Greece.

THEMISTOKLIS CHARALAMBOUS (Senior Member, IEEE) received the B.A. degree in electrical and information sciences from Trinity College, the M.Eng. degree in electrical and information sciences from Cambridge University in 2005, and the Ph.D. degree in control laboratory from Engineering Department, Cambridge University in 2010. He joined the Human Robotics Group, Imperial College London as a Research Associate form September 2009 to September 2010. From September 2010 to December 2011, he worked as a Visiting Lecturer with the Department of Electrical and Computer Engineering, University of Cyprus. From January 2012 to January 2015, he worked with the Department of Automatic Control, School of Electrical Engineering, Royal Institute of Technology as a Postdoctoral Researcher. From April 2015 to December 2016, he worked as a Postdoctoral Researcher with the Department of Electrical Engineering, Chalmers University of Technology. In January 2017, he joined the Department of Electrical Engineering and Automation, School of Electrical Engineering, Aalto University as a Tenure-Track Assistant Professor. Since September 2018, he has been nominated Research Fellow of the Academy of Finland and since July 2020 he has been a Tenured Associate Professor. His primary research targets the design and analysis of (wireless) networked control systems that are stable, scalable, and energy efficient.

NIKOLAOS PAPPAS (Member, IEEE) received the B.Sc. degree in computer science, the M.Sc. degree in computer science, the B.Sc. degree in mathematics, and the Ph.D. degree in computer science from the University of Crete, Greece, in 2005, 2007, 2012, and 2012, respectively. From 2005 to 2012, he was a Graduate Research Assistant with the Telecommunications and Networks Laboratory, Institute of Computer Science, Foundation for Research and Technology-Hellas, and a Visiting Scholar with the Institute of Systems Research, University of Maryland, College Park, College Park, MD, USA. From 2012 to 2014, he was a Postdoctoral Researcher with the Department of Telecommunications, Supélec, France. Since 2014, he has been with Linköping University, Norrköping, Sweden, as a Marie Curie Fellow (IAPP), where he is currently an Associate Professor of Mobile Telecommunications with the Department of Science and Technology. His main research interests include the field of wireless communication networks with emphasis on the stability analysis, energy harvesting networks, network-level cooperation, age-of-information, network coding, and stochastic geometry. From 2013 to 2018, he was an Editor of IEEE COMMUNICATIONS LETTERS. He is currently an Editor of IEEE TRANSACTIONS ON COMMUNICATIONS, IEEE/KICS JOURNAL OF COMMUNICATIONS AND NETWORKS, and IEEE OPEN JOURNAL OF COMMUNICATIONS SOCIETY. He is also a Guest Editor of IEEE INTERNET OF THINGS JOURNAL for the Special Issue Age of Information and Data Semantics for Sensing, Communication and Control Co-Design in IoT.

DEMOSTHENES VOUYIOUKAS (Senior Member, IEEE) received the five-year Diploma and Ph.D. degrees in electrical and computer engineering, and the Joint Engineering-Economics M.Sc. degree from the National Technical University of Athens in 1996, 2003, and 2004, respectively. He is currently a Professor and the Director of the Computer and Communication Systems Laboratory, Department of Information and Communication Systems Engineering, University of the Aegean, Greece. In this area, he has over 120 publications in scientific journals, books, book chapters, and international conference proceedings. His research interests include mobile and wireless communication systems, channel characterization and propagation models, performance modeling of wireless networks, cooperative wideband systems with relays, UAV and aerial communications, UWB indoor localization techniques, next generation mobile, and satellite networks and 5G and beyond technologies. He is member of IEEE Communication Society of the Greek Section, IFIP, an ACM, and the Technical Chamber of Greece.

RISTO WICHMAN (Member, IEEE) received the M.Sc. and D.Sc.(Tech.) degrees in digital signal processing from the Tampere University of Technology, Finland, in 1990 and 1995, respectively. From 1995 to 2001, he worked with Nokia Research Center as a Senior Research Engineer. In 2002, he joined the Department of Signal Processing and Acoustics, School of Electrical Engineering, Aalto University, Finland, where he has been a Full Professor since 2008. His research interest includes signal processing techniques for wireless communication systems.