Capacity Improvement through Buffer-Aided Successive Opportunistic Relaying

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***Abstract*—In this work, we propose a buffer-aided successive opportunistic relaying scheme that aims to improve the average capacity of the network when inter-relay interference arises between relays that are selected for transmission and reception. In order to exploit the benefits of buffering at the relays, we propose a relay-pair selection policy that decouples the receiving relay at the previous time slot from being the transmitting relay at the next slot. Furthermore, we impose an interference cancellation threshold allowing the relay that is selected for reception, to decode and subtract the inter-relay interference. The proposed relaying scheme selects the relaying pair that maximizes the average capacity of the relay network. The performance of the proposed scheme is evaluated via simulation and comparisons with other state-of-the-art half and full-duplex relay selection schemes, in terms of outage probability, average capacity and average delay. The results reveal the need for a tradeoff between improving the outage on the cost of reduced capacity and increased delay, and vice versa. Finally, conclusions are drawn and future directions are discussed, including the need for a hybrid scheme incorporating both half and full-duplex characteristics.**

I. Introduction

Cooperative communications are a major element of next generation wireless networks. Among these techniques, relaying has been a very active research area with works covering its various aspects and the gains introduced to the network. By offering alternative and independent transmission paths, relaying increases the diversity gain of the network as multipath fading is mitigated [1]. In order to reduce the complexity of such topologies when multiple relay nodes are employed, relay selection has been suggested [2]. More specifically, the best relay is selected based on the end-to-end channel quality of each relay candidate without sacrificing the outage performance.

Earlier works studied relaying without considering the effect of buffering. As a result, relay selection was based on the $\max-\min$ criterion and its variations [2]–[4]. In these works the source and the selected relay were assumed to be transmitting in orthogonal time-slots and as a result the end-to-end rate was reduced by one-half. Different approaches have been proposed to recover the half-duplex loss [5]. One of them is to allow the source and the relay to transmit simultaneously resulting in a full-duplex operation but with inter-relay interference (IRI). This successive relaying operation has been the subject of various studies. In [6], [7] the capacity region for networks with two relays supporting successive relaying were given in the absence of a source-destination (*SD*) link and with the availability of a *SD* link, correspondingly. The work in [8] extended [7] and instead of interference subtraction, IRI was decoded and by employing superposition coding it was forwarded to the destination in a scenario where the inter-relay channels are strong. In this way, improved diversity-multiplexing tradeoff (DMT) was achieved. In [9] the IRI was canceled at the relays for cases of strong interference resulting in gains in outage probability and average capacity. An extension of this work employed relays with multiple interfaces [10] where in addition to IRI cancellation, out-of-band transmissions allowed successive transmissions without the interference deteriorating the network performance.

In recent studies, the addition of buffering at the relays has been suggested as a way to further improve the diversity of the network and novel relay selection policies have been suggested. Ikhlef *et al.* [11] proposed the $\max-\max$ relay selection (MMRS) in which the relay with the best source-relay (*SR*) link is selected for reception and the relay with the best relay-destination (*RD*) link is selected for transmission. Also, hybrid relay selection (HRS) was suggested when the relays are not available for selection due to buffers being full or empty, resulting in a combination of $\max-\min$ and $\max-\max$ policies. Furthermore, MMRS was proposed for a successive relaying topology [12] with isolated relays with weak inter-relay links and negligible IRI. In the cases where relay buffers are full or empty, a hybrid scheme that combines $\max-\max$ and $\max-\min$ is discussed. In [13] an additional degree of freedom is offered to the network. As a part of the proposed $\max-\text{link}$ policy, the best link is selected among the available *SR* and *RD* ones. In the analysis it is shown that as the buffer size tends to infinity, diversity order reaches twice the number of relays. In a similar fashion, adaptive link selection is proposed by [14] in a single relay network. Also, in [15] half-duplex relaying has been shown to outperform ideal full-duplex relaying when MIMO techniques are employed at the relay.

In this work we present an extension to the successive opportunistic relaying scheme of [9] by providing the relays with buffering capabilities. In this setting, at each time-slot, a relay-pair is selected: one relay receives the source signal

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and one forwards a previously received packet to the destination. By canceling the inter-relay interference introduced by successive transmissions, when the inter-relay link is strong, we mitigate the IRI to a significant degree. The operation of our buffer-aided successive opportunistic relaying scheme (called BA-SOR hereafter) is demonstrated and its complexity is discussed. More specifically, the contributions of this work are the following:

(i) A buffer-aided successive opportunistic relay selection scheme is proposed taking advantage of the buffering at the relays, thus offering increased freedom in relay selection since the relay that received the current source signal is not necessarily the one that will forward it to the destination in the next time-slot, as was the case with [9]. This scheme not only offers the opportunity for selecting a better *RD* channel, but also it does not require to acquire any further knowledge of the channel in the next time slot.

(ii) A threshold in rate, above which interference cancellation can be performed, is imposed at the relays in order to mitigate the degrading effect of inter-relay interference. Based on this approach the effect of IRI is further studied and a scheme is proposed that takes advantage of interference cancellation (IC). Hence, our model is more realistic compared to that proposed in [12] where relays are considered isolated.

(iii) Comparisons are performed with half and full-duplex schemes achieving performance gains in both average capacity and average delay, compared to half-duplex relaying; our scheme also reduces the performance gap compared to the scheme of [12] which is considered as a bound to the performance of our scheme.

The structure of this paper is as follows. In Section II, we present the system model while Section III describes in detail the proposed BA-SOR scheme. After, Section IV includes the performance evaluation of the proposed scheme and the comparisons with half and full-duplex relaying. Finally, conclusions and the future work are discussed 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 nodes are characterized by the half-duplex constraint and therefore, they cannot transmit and receive simultaneously. A direct link between the source and the destination does not exist and communication can be established only via relays [2]. Each relay R_k holds a buffer (data queue) Q_k of capacity L (number of data elements) where it can store source data that has been decoded at the relay and can be forwarded to the destination. The parameter $l_k \in \mathbb{Z}_+$, $l_k \in [0, L]$ denotes the number of data elements that are stored in buffer Q_k; at the beginning, each relay buffer is empty (i.e., $l_k = 0$ for all k). We denote by $\mathcal{T}$ all the relays for which their buffer is not empty, i.e., $\mathcal{T} = \{R_k : l_k > 0\}$, $\mathcal{T} \subseteq \mathcal{C}$.

Time is considered to be slotted and at each time-slot the source S and one of the relays R_k transmit with power P_S

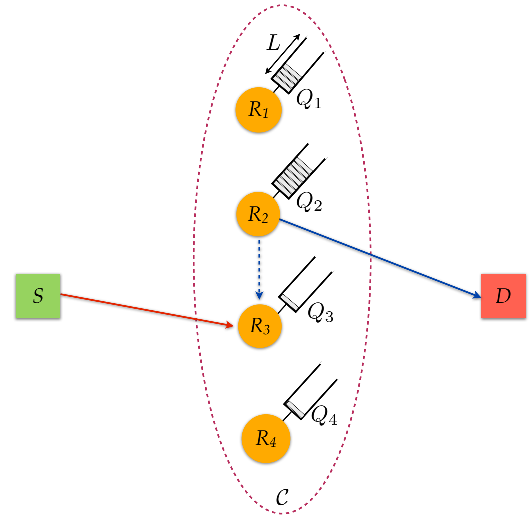

Fig. 1. A simple relay network that exemplifies the system model: Source S communicates with Destination D via a cluster of 4 relays $R_k \in \mathcal{C}$, $k \in [1, 4]$.

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 bits per channel use (BPCU). 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 of that packet's reception status.

All wireless links exhibit fading and additive white Gaussian noise (AWGN). The fading is assumed to be stationary, with frequency non-selective Rayleigh block fading. This means that the fading coefficients h_{ij} (for the $i \rightarrow j$ link) remain constant during one slot, but change independently from one slot to another according to a circularly symmetric complex Gaussian distribution with zero mean and unit variance. The channel gains are $g_{ij} = |h_{ij}|^2$ and exponentially distributed, taking values in the range $(0, \sigma_{ij}^2)$. The noise N denotes the circular symmetric complex Gaussian noise with zero mean and variance n (i.e., $N \sim \mathcal{CN}(0, n)$) and, for simplicity, is assumed to be equal at each receiver.

It is worth noting that our focus is to investigate the performance of buffer-aided successive opportunistic relay selection scheme under a global channel state information (CSI) assumption and hence, the implementation issues are beyond the scope of this work. Note, however, that conventional centralized/distributed half-duplex relay selection approaches can be applied for the implementation of the proposed scheme (e.g., [2]).

Since we implement successive relaying, we have concurrent transmissions by the source and one relay taking place at the same time-slot. This results in IRI and as a result the proposed algorithm has to consider its effect on the relay that receives the source signal. More specifically, in an arbitrary time-slot q the signal that the destination receives from the transmitting relay R_t is expressed as

$$y_D = h_{R_tD} x_p + N \ , \quad (1)$$

where x_p is the signal received in a previous time-slot p and stored in the buffer of R_t. It must be noted that x_p was not necessarily received in the $q-1$ time-slot (i.e., $p \leq q-1$).

At the same time, the reception of the source's signal by relay R_r is interfered from the transmission of R_t which forwards a previous signal x_p to the destination, thus R_r receives

$$y_{R_r} = h_{SR_r} x_q + h_{R_tR_r} x_p + N \ . \quad (2)$$

Assuming a Gaussian input distribution and an information theoretic capacity achieving channel coding scheme, the instantaneous capacities are expressed correspondingly as

$$r_{R_tD} \triangleq \log_2 \left(1 + \frac{g_{R_tD} P_{R_t}}{n}\right) \ , \quad (3)$$

and

$$r_{SR_r} \triangleq \log_2 \left(1 + \frac{g_{SR_r} P_S}{g_{R_tR_r} P_{R_t} + n}\right) \ . \quad (4)$$

The condition that allows IC to be performed between a possible relay pair is that the received signal from the transmitting relay R_t can be successfully decoded from the receiving relay R_r. We say that the signal is successfully decoded if the rate[1] is above a certain threshold r_0. This is depicted by

$$r_{R_tR_r} \triangleq \log_2 \left(1 + \frac{g_{R_tR_r} P_{R_t}}{g_{SR_r} P_S + n}\right) \geq r_0 \ , \quad (5)$$

where P_{R_t} is the power of the transmitting relay, $g_{R_tR_r}$ is the channel gain of the inter-relay channel, g_{SR_r} is the channel gain of the *SR* channel, n is the noise at the receiving relay. In this work, we assume that the power with which a packet is transmitted is fixed to its maximum (due to battery limitations) and equal to P. Hence, equation (5) becomes

$$r_{R_tR_r} = \log_2 \left(1 + \frac{g_{R_tR_r} P}{g_{SR_r} P + n}\right) \geq r_0 \ . \quad (6)$$

III. Buffer-aided successive opportunistic relaying

Here we describe in detail, the operation of BA-SOR. As we have concurrent transmissions, relay selection does not depend merely on the quality of the *SR* and *RD* channel conditions. On the contrary, the IRI is the defining factor in the proposed relay selection policy. More specifically, BA-SOR performs relay-pair selection. By examining one-by-one the possible relay-pairs, first we calculate the power of the signal received at *D* which is $P_D = g_{R_tD} P + n_D$ for an arbitrary relay R_t with non-empty buffer. After, BA-SOR requires that the relay selected for reception has a non-full buffer and is different from the transmitting one. For each candidate relay for reception we perform a *feasibility check*, i.e., to examine whether IC is feasible. If IC can be performed, this relay, denoted by R_i, enters the competition with a value equal to its *SR* channel gain, g_{SR_i}. On the other hand if the IC condition cannot be fulfilled, then R_i enters the competition with a value equal to $g_{SR_i}/g_{R_tR_i}$. As we target capacity maximization in each time-slot, we calculate the end-to-end capacity that each relay pair can achieve. Finally, the selected pair of relays will be the one offering the maximum capacity to the network in that specific time-slot. Thus, the proposed relay selection policy is formulated as

$$\max_{t \in \mathcal{T}} \left\{ \min \left[\max_{i \in \mathcal{C}-\{t\}} \left(\frac{g_{SR_i}}{g_{R_tR_i} \left(1 - \mathbb{I}(R_tR_i)\right) + \mathbb{I}(R_tR_i)} \right), g_{R_tD} \right] \right\}$$

where $\mathbb{I}(R_tR_i)$ is an indicating factor that shows whether interference cancellation has taken place; it is described by

$$\mathbb{I}(R_tR_i) = \begin{cases} 0, & \text{if (6) is not satisfied,} \\ 1, & \text{otherwise.} \end{cases} \quad (7)$$

From the description of the proposed scheme, we observe that prior to pair selection, BA-SOR examines each relay and compares its effect on the other $K-1$ so in total the possible pairs are equal to $K(K-1)$. Thus, the complexity of the proposed relay selection policy is equal to $\mathcal{O}(K^2)$.

Remark 1. *Note that in the case where all the relays are available for selection (i.e., all buffers are neither full nor empty), and the IRI is negligible (either because the relays are isolated or too close resulting in IRI cancellation), the BA-SOR coincides with the selection bound suggested in [12]. In this specific case, all the relays can be selected for either transmission or reception and hence, the diversity gain[2] becomes equal to the number of relays in the network.*

Remark 2. *In [6], [7] the capacity region for networks with two relays supporting successive relaying were given. Although the derivation of the exact capacity region for a buffer-aided successive opportunistic network is not in the scope of this work, it is an interesting area for research. Here, we aim at a fixed rate threshold r_0 below which an outage is observed. As a result, the presented results offer an insight on the capacity improvement that our scheme can offer either through interference cancellation or through interference avoidance, coupled with relay-pair selection and buffering at the relays.*

IV. Numerical Results

In order to evaluate the performance of the proposed BA-SOR scheme we perform comparisons with half-duplex buffer-aided schemes including the scheme that combines the

[1] In general, we do not need to make any assumptions on the function that maps the Signal-to-Interference-and Noise (SINR) ratio at a receiver to the rate achieved on the corresponding link, except that it is non-decreasing. For simplicity, in this work we consider that on any link-i, the rate is well approximated by Shannon's formula, $r_i = \log_2(1 + SINR)$.

[2] The diversity gain is the gain in spatial diversity, used to improve the reliability of a link.

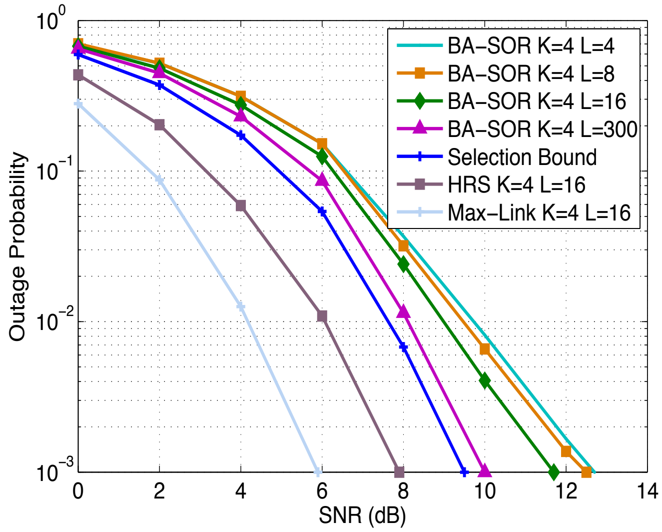

Fig. 2. Outage probability for increasing transmit SNR

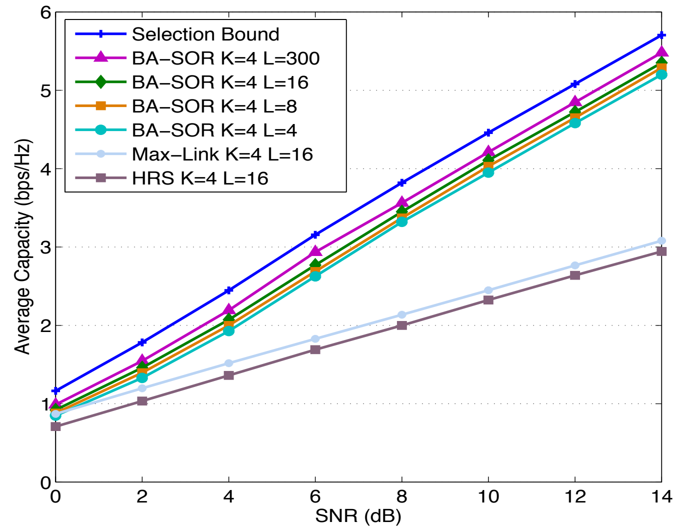

Fig. 3. Average capacity for increasing transmit SNR and various buffer sizes

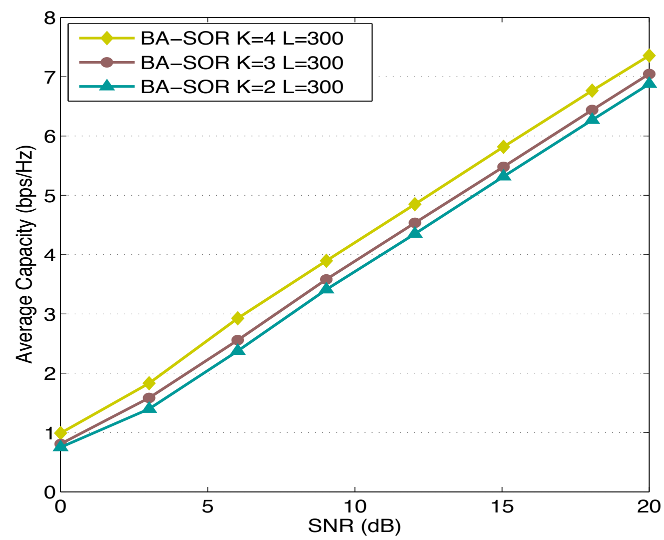

Fig. 4. Average capacity for increasing transmit SNR and various numbers of relays

$\max-\max$ and $\max-\min$ selection criteria, denoted as HRS [11], the adaptive link selection scheme denoted as $\max-\text{link}$ [13] and the successive scheme of [12] which is also the performance bound for our scheme since IRI is not considered. Results were obtained in terms of (i) outage probability, (ii) average capacity and (iii) average delay. In the scenarios discussed below, the capacity threshold r_0 is equal to 2 bps/Hz.

In Fig. 2 the outage behavior for the considered relay selection schemes is presented. Each scheme has $K = 4$ relays and a buffer size $L = 16$ except for BA-SOR which is depicted for additional buffer-sizes, since we want to examine the effect of L on the proposed scheme's performance. It is observed that $\max-\text{link}$ has the lowest outage probability as diversity order scales with twice the number of relays [13], due to the fact that adaptive link selection is possible and IRI does not exist. The second half-duplex scheme is $\max-\max$ and it clearly outperforms all the full-duplex successive schemes in this comparison but it is surpassed by the $\max-\text{link}$. In the set of successive relaying curves, the selection bound is not matched due to two reasons: first, relays are isolated and IRI is negligible and second, there is no constraint on the queues and the relays are always available for selection since they are never full or empty. In the high transmit SNR regime and assuming equal power allocation, we observe from (6) that interference cancellation depends only on the ratio of the inter-relay channel gain with the channel gain of the source and the relay considered for reception

$$\lim_{P\to\infty} \log_2\left(1+\frac{g_{R_iR_j}P}{g_{SR_j}P+n}\right) = \log_2\left(1+\frac{g_{R_iR_j}}{g_{SR_j}}\right) \geq r_0 \,.$$

As a result, the proposed scheme even for $L = 300$ has a 0.5 dB performance gap but achieves the same diversity order equal to $K = 3$. For small buffer sizes, BA-SOR faces difficulties in managing the cases of full or empty buffers and relays are often excluded from selection, thus reducing the diversity of the network.

Fig. 3 illustrates the average capacity performance for each scheme. We calculate the average end-to-end capacity achieved by each selection scheme, while having r_0 as the rate threshold of the system. In the results we evaluate the capability of each relay selection scheme to offer improved throughput, if adaptive rate transmissions are employed at the source and the transmitting relay.

The full-duplex schemes which employ two simultaneous transmissions during the whole period of a time-slot have a clear advantage. Again, the selection bound is not achieved as IRI is not always subtracted and in some cases the buffers are either full or empty. For high transmit SNR, the capacity of the successive schemes is almost twice the capacity offered by the half-duplex schemes, thus justifying the adoption of successive transmissions when increased capacity is needed in the network. Moreover, an increase in buffer size does not offer big gains in capacity indicating that this metric depends mostly on the number of relays.

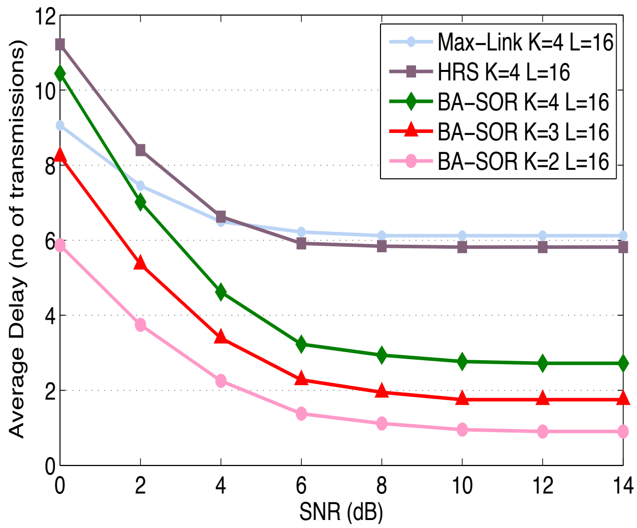

Fig. 5. Average delay for increasing transmit SNR

Fig. 4 reveals the relationship between the number of relays and the possible gain in average capacity. We set $L = 300$ in order to clearly examine the effect of relay addition. We see that as the number of relays increases, so does the average capacity. The noteworthy element in this comparison is that the achieved gain of employing $K = 4$ relays compared to $K = 3$ is larger than increasing to $K = 3$ relays compared to $K = 2$. This is reasonable since the possible relay-pairs increase from 2, in the case of $K = 2$, to 6 for $K = 3$ and finally, to 12 for $K = 4$, since each time BA-SOR performs $K(K-1)$ searches to find the optimal relay-pair. So, the average capacity gain scales according to this fact.

The final set of comparisons examines the average delay for each transmitted packet and it is shown in Fig. 5. The first observation is the increased delay of the half-duplex schemes. Compared to the corresponding full-duplex case for $K = 4$ relays, the transmitted packets experience delays of about six time-slots in high SNR since each packet requires at least two time-slots to reach the destination. Furthermore, $\max - \max$ achieves slightly better performance compared to $\max - \text{link}$ as the latter's adaptive link selection may cause additional delay. For the BA-SOR, we depict curves for varying K and as the relay number decreases, so does the delay for each transmitted packet. It is expected that when more relays are employed in the network and no delay constraint is imposed, some packets may experience increased delays. More specifically, the possibility of selecting a specific relay decreases as the number of possible candidates increases, thus leading to excess delay for some packets and increased average delay in the network.

V. Conclusions

In this paper, we presented an extension to the successive opportunistic relaying scheme of [9] by considering relays with buffering capabilities. In this relay network, at each time-slot, a relay-pair is selected to be activated; one of the relays receives the source signal while the other simultaneously forwards a previously received packet to the destination. By canceling the IRI introduced by successive transmissions, when the inter-relay link is strong, we mitigate the IRI to a significant degree. Moreover, the operation and the complexity of the proposed BA-SOR scheme were described. Numerical results and comparisons with other half-duplex and full-duplex schemes indicate that a tradeoff has to be made in outage performance in order to improve capacity and delay, and vice versa.

Future directions include the combination of BA-SOR with a more robust half-duplex scheme in order to merge the best of both techniques. In addition, more efficient ways of interference mitigation and exploitation can be examined based on network coding aiming to increase the diversity of the network. Finally, adaptive transmission rates should be employed in order to harvest the gains that were observed in the average capacity domain and at the same time to reduce the average delay.

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