

## RESEARCH ARTICLE

# Joint Relay-Pair Selection for Buffer-Aided Successive Opportunistic Relaying<sup>†\*</sup>

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## ABSTRACT

In this work, we present a buffer-aided successive opportunistic relaying scheme (herein called BA-SOR) that aims at improving the average capacity of the network when inter-relay interference (IRI) arises between relays that are selected for simultaneous transmission and reception. We propose a relay selection policy that, by exploiting the benefits of buffering at the relays, decouples the receiving relay at the previous time slot to be the transmitting relay at the next slot. Furthermore, we impose an interference cancellation (IC) threshold allowing the relay that is selected for reception, to decode and subtract the IRI. The proposed relaying scheme selects the relaying pair that maximizes the average capacity of the relay network. Its performance is evaluated through simulations 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 that a tradeoff has to be made between improving the outage at 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. Copyright © 0000 John Wiley & Sons, Ltd.

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## 1. INTRODUCTION

Cooperative communications are a basic element of next generation wireless networks. Among the major issues, relaying has been a very active research area with works covering its various aspects and the gains introduced to the network [1]. Initial contributions on the information theoretic aspects of relay networks were presented by [2, 3] while the concept of cooperative relaying has been revisited in recent years. By offering alternative and independent transmission paths, relaying increases the diversity gain of the network as multi-path fading is mitigated and reduces the outage probability [4–6]. The authors in [7] investigated the performance of various relaying protocols based on amplify-and-forward, decode-and-forward and decode-and-re-encode for different relay positioning and spectral-efficiency targets, while general expressions for the outage probability of cooperative relaying with varying relay number and selection combining

at the destination were derived in [8]. A more recent work in [9] investigated the outage, throughput and energy efficiency performance of half and full-duplex relaying. It is concluded that the selection among these two strategies depends on the amount of self-interference that full-duplex relaying exhibits which tends to degrade significantly its performance. In order to reduce the complexity of such topologies when multiple relay nodes are employed, relay selection has been suggested as a simple yet powerful way to take advantage of the diversity gain offered by the multiple relays (see, for example, [10] for a simple distributed relay selection policy). More specifically, one “best” relay is selected based on some criterion (e.g., the end-to-end channel quality of each relay candidate) without sacrificing the outage performance.

Earlier works in the literature studied relay selection policies without considering the case for which relays are equipped with buffers. 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. As a result, relay selection was based on the max–min selection criterion and its variations (see, for example, [10–14] and references therein). Extending the two-hop paradigm, the authors in [15] derive closed-form expressions for the outage

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capacity and channel capacity of multi-hop topologies where selection of the optimal path is performed. It is stated that the main disadvantage of multi-hop relaying is the increased complexity and signaling needed in order to select the best end-to-end path. Furthermore, various approaches have been proposed to recover the half-duplex loss [16]; one of them is to allow the source and the selected 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 that we discuss in the sequel. In [17], the capacity region of a network with two relays that alternatively forward the source message is presented. Interference cancellation was proposed as a way to reduce the degrading effects of IRI and it was shown that if the inter-relay channel is strong, in the case of decode-and-forward (DF) relays, cancellation prior to decoding is efficient. Also, in [18] the presence of a direct link offered increased diversity gain and the capacity regions for a successive relaying network were given. In the extension of this work in [19], assuming again that the inter-relay channels are strong, instead of subtracting the interference, IRI is decoded and by employing superposition coding it is forwarded to the destination. In this way, improved diversity-multiplexing tradeoff (DMT) is achieved. In [20] 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 [21] where in addition to IRI cancellation, out-of-band transmissions allowed successive transmissions without deteriorating network performance.

In recent studies, the addition of buffering capability 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.* [22] 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, a 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. The space full-duplex max – max relay selection (SFD-MMRS) was proposed for a successive relaying topology [23] with isolated relays with weak inter-relay links where negligible IRI conditions occur. For fixed transmission rate the outage probability is derived and the diversity gain is proved to be equal to the number of relays due to buffering. In [24] the best link is selected among the available SR and RD ones, as a part of the proposed max – link policy, thus offering an additional degree of freedom to the network. In the analysis it is shown that as the buffer size tends to infinity, diversity order reaches twice the number of relays.

In this work we study successive relaying in an interference-limited environment where the achievable

capacity in the network is limited by the amount of interference that the transmitting relay causes to the other relay that receives the source's signal. This topology is similar to the Z-interference channel [25] which consists of two pairs which communicate at the same time where the receiver of the one pair is interfered from the transmitter of the other pair while the receiver of the other pair does not experience interference. In a more recent work [26] this topology has been studied and the achievable rate regions were presented. Other works, study different relaying topologies where interference arises such as [27], which derived the capacity region in a network where multiple single or multi-hop pairs communicate simultaneously employing different interference mitigation techniques. The authors in [28] extracted the achievable rates for general relay channels and their extensions such as the multi-access relay channels (MARC) and broadcast relay channels (BRC) under different relaying strategies. Furthermore, [29] studied the very strong and strong interference regimes for MARC networks where a single relay facilitates the communication of multiple source-destination pairs.

In this work, we present a buffer-aided successive opportunistic relaying scheme, called BA-SOR, that aims to improve the average capacity of the network when inter-relay interference (IRI) arises between relays that are selected for transmission and reception. It is essentially an extension to the successive opportunistic relaying scheme suggested in [20] with the provision of relays with buffering capabilities. In this setting, at each time-slot, a relay pair is selected: one relay to receive the source signal and one to forward 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 BA-SOR is described and the complexity of this relay selection policy is demonstrated. More specifically, the contributions of this work are the following:

(i) A buffer-aided successive opportunistic relay selection scheme is proposed taking advantage of buffering at the relays, thus offering:

- (a) 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 [20];
- (b) the opportunity for selecting a better RD channel, and
- (c) it does not require to assume or predict any further knowledge of the channel at the next time slot.

(ii) A threshold in capacity – 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 IC. Hence, our model is more realistic

compared to that proposed in [23] 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 [23] which is considered as a bound for our scheme.

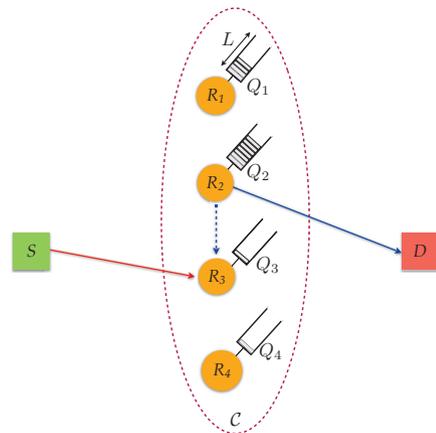
The structure of this paper is as follows. In Section 2, we present the system model while Section 3 presents some relevant relay selection schemes. Section 4 describes in detail the proposed BA-SOR scheme and Section 5 includes the performance evaluation of the proposed scheme and some corresponding remarks. Then, Section 6 shows the numerical results and the comparisons with half and full-duplex relaying. Finally, the paper is concluded in Section 7 with some comments on possible extensions of our results and future directions.

## 2. 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 [10]. 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  $P_S$  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 *instantaneous* channel



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

gains are  $g_{ij} = |h_{ij}|^2$  and are exponentially distributed with parameter  $\lambda_{ij} = (\mathbb{E}\{g_{ij}\})^{-1}$ . In practice,  $g_{ij}$  takes values in the range  $(0, 1]$  (since the channel gain cannot be larger than 1). Noise  $N$  denotes the circular symmetric complex Gaussian noise with zero mean and variance  $n$  (i.e.,  $N \sim \mathcal{C}\mathcal{N}(0, n)$ ) 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., [10]).

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 so, 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

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

where  $x_p$  is the signal received by  $R_t$  in a previous time-slot  $p$ , decoded and stored in its buffer where it remained until  $R_t$ 's transmission. 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 relay  $R_r$  that is receiving the source signal (that is different to the transmitting relay  $R_t$ ) experiences IRI from  $R_t$  that currently is forwarding  $x_p$  to the destination, thus  $R_r$  receives

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

Assuming a Gaussian input distribution and an information theoretic capacity achieving channel coding

scheme, the instantaneous capacities are expressed correspondingly as

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

and

$$r_{SR,r} \triangleq \log_2 \left( 1 + \frac{g_{SR,r} P_S}{g_{R_r,R_r} P_{R_r} + n} \right). \quad (4)$$

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\* is above a certain threshold  $r_0$ . This is depicted by

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

where  $P_{R_t}$  is the power of the transmitting relay,  $g_{R_r,R_r}$  is the channel gain of the inter-relay channel,  $g_{SR,r}$  is the channel gain of the  $SR$  channel,  $n_{R_r}$  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, equations (3), (4) and (5) for the instantaneous capacities become

$$r_{R_r,D} = \log_2 \left( 1 + \frac{g_{R_r,D} P}{n} \right), \quad (6a)$$

$$r_{SR,r} = \log_2 \left( 1 + \frac{g_{SR,r} P}{g_{R_r,R_r} P + n} \right), \quad (6b)$$

$$r_{R_r,R_r} = \log_2 \left( 1 + \frac{g_{R_r,R_r} P}{g_{SR,r} P + n} \right), \quad (6c)$$

respectively. Therefore, inter-relay interference cancellation is achieved when  $r_{R_r,R_r} \geq r_0$ .

### 3. RELAY SELECTION POLICIES

#### 3.1. Max-Min relay selection in successive relaying

The max – min relay selection policy implemented in a successive relaying network takes a different form if the IRI can be canceled at the relays. In [20], a reactive relay selection policy is proposed. More specifically, instead of considering only the  $SR$  and  $RD$  channel gains, the feasibility of IC is also examined. In this way, with a very simple IC condition the following two cases for relay selection are given.

\*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,  $r_i = \log_2(1 + \text{SINR})$ .

- (i) If candidate relay  $R_k$  can perform IC then it may be selected to receive from the source based on the following value:

$$R^* = \arg \max_{R_k \in \mathcal{C}} \min \{g_{S,R_k}, g_{R_k,D}\}. \quad (7)$$

- (ii) On the other hand, if  $R_k$  cannot perform IC then it can be selected after competing with the rest of the relays as below:

$$R^* = \arg \max_{R_k \in \mathcal{C}} \min \left\{ \frac{g_{S,R_k}}{g_{R_r,R_k}}, g_{R_k,D} \right\}. \quad (8)$$

Equations (7) and (8) provide the relay which maximizes the end-to-end throughput for the relay network with and without inter-relay interference cancellation, respectively. This is done by maximizing the minimum throughput between  $SR$  channels for the first time slot and  $RD$  channels for the second time slot, over all possible relay selections. It is obvious that by having two simultaneous transmissions by the source and the transmitting relay reduces the diversity of the network as  $R^*$  can not participate in the selection process due to the half-duplex constraint. On the other hand, if IRI is effectively mitigated, a full-duplex behavior can be achieved and the half-duplex loss is leveraged. However, due to the lack of buffers a large number of relays is required for IC to be either efficiently mitigated or avoided.

#### 3.2. Max-Max Relay Selection (MMRS)

The Max-Max Relay Selection (MMRS) [22] is the first policy that exploits buffering capability at the relay nodes and is used as a reference selection scheme. Given that the relay nodes are equipped with buffers and thus can store the data received from the source, the max – max policy splits the relay selection decision in two parts and selects the relay with the best source-relay link for reception and the relay with the best relay-destination link for transmission. The max – max selection policy respects the conventional two-slot cooperative transmission where the first slot is dedicated for the source transmission and the second slot for the relaying transmission, but the relay node may not be the same for both phases of the protocol. The max – max relay selection policy can be written as

$$R_r^* = \arg \max_{R_k \in \mathcal{C}} \{g_{S,R_k}\}, \quad (9)$$

$$R_t^* = \arg \max_{R_k \in \mathcal{C}} \{g_{R_k,D}\}, \quad (10)$$

where  $R_r^*$  and  $R_t^*$  denote the relay selected for the first phase and the second phase of the cooperative protocol, respectively. Equations (9) and (10) provide the channels which maximize the throughput on the  $SR$  and the  $RD$  links, respectively. It has been proven that the max – max relay selection policy also ensures full diversity equal to the number of the relays and it provides a significant coding gain in comparison to the conventional max – min

selection scheme. However, it is worth noting that the above selection strategy assumes that no relay's buffer can be empty or full at any time and thus all relays have always the option of receiving or transmitting [22, Sec. III. C]. Therefore, the max – max relay selection considered provides the optimal performance that can be achieved by such a scheme, thus yielding the lowest outage bound.

### 3.3. Space Full-Duplex Max-Max Relay Selection (SFD MMRS)

The Space Full-Duplex Max-Max Relay Selection (SFD MMRS) [23] considers a relay network where successive transmissions are performed in each transmission phase in order to recover the half-duplex loss of relaying. The authors suggest the use of different relays for reception and transmission so simultaneously in each phase two links are activated each using a different relay. Equation (11) provides the combined selection of receiving and transmitting relays. The relays are selected if their links are the best among all the available ones. If one relay has both the best *SR* and *RD* links, then the protocol selects different relays for reception and transmission; in this case, the best bottleneck link involving either the second best relay for reception or the best relay for transmission. More specifically, SFD MMRS selects the relay pair based on

$$(R_{\bar{r}_1}, R_{\bar{t}_1}) = \begin{cases} (R_{r_1}, R_{t_1}), & \text{if } r_1 \neq t_1 \\ (R_{r_2}, R_{t_1}), & \text{if } r_1 = t_1 \text{ and } \min(g_{SR_{r_2}}, g_{RD_{t_1}}) \\ (R_{r_1}, R_{t_2}), & \text{otherwise.} \end{cases} \quad (11)$$

where  $r_1, t_1$  are the best relay for reception and transmission respectively while  $r_2, t_2$  are the second best ones. However, SFD MMRS does not take into account the inter-relay interference that arises due to the concurrent transmissions since inter-relay links are considered weak and IRI is negligible. Therefore, practical implementation based on SFD MMRS is suggested in cases where enough isolation is provided to the relays. In these environments, SFD MMRS can achieve a diversity gain equal to the number of the employed relays.

## 4. BUFFER-AIDED SUCCESSIVE OPPORTUNISTIC RELAYING

In this section, we describe in detail the way of operation of BA-SOR. Since we have concurrent transmissions, relay selection does not depend merely on the quality of the *SR* and *RD* channel conditions. On the contrary, the inter-relay interference is the defining factor in the proposed relay selection policy. More specifically, BA-SOR performs a joint selection of a pair of relays. By examining one-by-one the possible relay pairs, first we calculate the power of the signal received at *D* which is  $P_D = g_{R_i D} P + n_D$

for an arbitrary relay  $R_i$  with non-empty buffer. After, the receiving relay must be one that is not selected as the transmitting one and have non-full buffers. 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  $g_{SR_i}/g_{R_i R_i}$ . As we target on 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

$$\max_{i \in \mathcal{R}} \left\{ \min \left[ \max_{i \in \mathcal{C} - \{i\}} \left( \frac{g_{SR_i}}{g_{R_i R_i} (1 - \mathbb{I}(R_i R_i)) + \mathbb{I}(R_i R_i)} \right), g_{R_i D} \right] \right\} \quad (12)$$

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

$$\mathbb{I}(R_i R_i) = \begin{cases} 0, & \text{if (6c) is not satisfied,} \\ 1, & \text{otherwise.} \end{cases} \quad (13)$$

Note that this policy simply maximizes the minimum end-to-end throughput over a single slot, taking into account the fact that inter relay interference cancellation may take place. However, when there is no available relay-pair to support successive relaying it is not possible for a single relay to transmit in the network, either in the *SR* or the *RD* link and this causes an outage to the network. 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 inter-relay interference is negligible (either because the relays are either isolated or too close resulting in IRI cancellation), the BA-SOR coincides with the selection bound suggested in [23]. In this specific case, all the relays can be selected for either transmission or reception and hence, the diversity gain<sup>†</sup> becomes equal to the number of relays in the network.

#### Remark 2

Note that in the case of negligible IRI and for *i.i.d.* fading in the *SR* (i.e.,  $\bar{g}_S \triangleq g_{SR_i}, \forall R_i \in \mathcal{C}$ ) and *RD* (i.e.,  $\bar{g}_D \triangleq g_{R_i D}, \forall R_i \in \mathcal{C}$ ) links, each relay has the same probability of being selected either for transmission or for

<sup>†</sup>The diversity gain is the gain in spatial diversity, used to improve the reliability of a link.

reception. Unlike [23], in this work the end-to-end capacity is not specified by the weakest link (i.e.,  $\min\{\overline{g_S}, \overline{g_D}\}$ ), but the IRI needs to be taken into account. If IRI can be canceled for this simplified scenario, for all instances, then our scheme becomes equivalent to that of [23] and consequently, the end-to-end capacity is equal to the capacity of the weakest link. So, in this case, the source and the relays transmit with a rate corresponding to the end-to-end capacity.

*Remark 3*

In [17, 18] 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. 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  $r_0$  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 joint relay-pair selection and buffering at the relays.

## 5. PERFORMANCE ANALYSIS

In this section, an outage analysis is provided for the BA-SOR scheme based on the system model and the scheme description that were presented previously. In our network the main degrading and limiting factor is the interference between the relays which is introduced by the successive transmissions that allow two nodes to transmit at the same time. Similar interference conditions arise in [30] although in a different network topology. In that work, opportunistic relay selection is employed in a network where a direct source-destination (SD) link is available. As is the case with our network, [30] considers that two transmissions take time simultaneously. In one transmission period the source transmits to the destination while a previously opportunistically selected relay forwards a previous frame to a different destination. In the next period, another relay is selected to forward the source packet to the destination that received directly from the source previously, thus increasing diversity, while the source serves another destination. As a result, the relay interferes in the SD communication and in the reception of other relays that try to decode the source's frame. The difference in our work is that there is no SD link and only one destination is present. Also, interference arises in the SR link and not in the RD link as the selected transmitting relay interferes in the reception of another relay that is selected for reception. Moreover, the proposed BA-SOR scheme performs a joint relay-pair selection which is possible due to the adoption of buffer-aided relays. However, [30] does not consider any buffering and as a result the outage probability depends mostly on the

number of relays that managed to successfully decode the source's frame in the presence of a specific interfering relay. The buffering capability of the relays leads to interesting results in the special case where large buffer sizes and relay numbers are available. More specifically, in this case due to the large buffer size  $L$ , neither relay will be full or empty, thus offering increased degrees of freedom in pair selection.

We distinguish the outage events of each link. The outage event  $A$  denotes the case of experiencing an outage in the SR link when IC is infeasible and is given by

$$\begin{aligned} A &= \left\{ \log_2 \left( 1 + \frac{g_{SR_i} P}{g_{R_i R_i} P + n} \right) < r_0 \right\} \\ &= \left\{ \frac{g_{SR_i} P}{g_{R_i R_i} P + n} < 2^{r_0} - 1 \right\}. \end{aligned}$$

Likewise, the outage event  $A^*$  denotes the case of experiencing an outage in the SR link when IC is possible and is given by

$$\begin{aligned} A^* &= \left\{ \log_2 \left( 1 + \frac{g_{SR_i} P}{n} \right) < r_0 \right\} \\ &= \left\{ \frac{g_{SR_i} P}{n} < 2^{r_0} - 1 \right\}. \end{aligned}$$

Equivalently, for the RD link

$$\begin{aligned} B &= \left\{ \log_2 \left( 1 + \frac{g_{R_i D} P}{n} \right) < r_0 \right\} \\ &= \left\{ \frac{g_{R_i D} P}{n} < 2^{r_0} - 1 \right\}. \end{aligned}$$

*Remark 4*

In the case where a small number of relays is available in the network, events  $A$  and  $B$  are not independent since the selection of a relay for transmission deprives this relay from being selected for reception, and vice versa. So, if we assume that a large number of relays is available we can consider these two events to be independent. Since in every transmission phase, two transmissions occur at the same time, we denote an outage event when one or both transmissions fail.

Following Remark 4, the outage probability for a pair of relays when IC is not possible is given by

$$\begin{aligned} P_{out} &= P(A \cup B) = P(A) + P(B) - P(A \cap B) \\ &= P(A) + P(B) - P(A)P(B) \\ &= 1 - \exp\left(-\lambda_{SR_i} \gamma \frac{n}{P}\right) \left( \frac{\lambda_{R_i R_i}}{\gamma(\lambda_{SR_i} + \lambda_{R_i R_i})} \right) \\ &\quad + 1 - \exp\left(-\lambda_{R_i D} \gamma \frac{n}{P}\right) \\ &\quad - \left[ 1 - \exp\left(-\lambda_{SR_i} \gamma \frac{n}{P}\right) \left( \frac{\lambda_{R_i R_i}}{\gamma(\lambda_{SR_i} + \lambda_{R_i R_i})} \right) \right] \times \\ &\quad \left[ 1 - \exp\left(-\lambda_{R_i D} \gamma \frac{n}{P}\right) \right], \end{aligned}$$

while for a relay pair that achieved IC

$$\begin{aligned} P_{out}^* &= P(A^* \cup B) = P(A^*) + P(B) - P(A^* \cap B) \\ &= P(A^*) + P(B) - P(A^*)P(B) \\ &= \left[1 - \exp\left(-\lambda_{SR_i} \gamma \frac{n}{P}\right)\right] + \left[1 - \exp\left(-\lambda_{R_i D} \gamma \frac{n}{P}\right)\right] \\ &\quad - \left[1 - \exp\left(-\lambda_{SR_i} \gamma \frac{n}{P}\right)\right] \times \left[1 - \exp\left(-\lambda_{R_i D} \gamma \frac{n}{P}\right)\right], \end{aligned}$$

where  $\lambda_{SR_i}$  and  $\lambda_{R_i R_i}$  are the parameters of the exponential distributions followed by the instantaneous channel powers in the corresponding Rayleigh-faded links and  $\gamma \triangleq 2^{r_0} - 1$ .

The total outage probability is formulated as

$$P_{out-tot} = \sum_{i=1}^M P_{out} + \sum_{j=1}^{\bar{M}} P_{out}^*, \quad (14)$$

where  $M$  denotes the number of relay pairs where IC is not possible at the relay of the pair that is selected for reception and  $\bar{M} = K(K-1) - M$  is the number of relay pairs where IC can be performed at the relay of the pair which is selected for reception.

#### Remark 5

In the low SNR regime, the case of having an outage in the  $RD$  link (event  $B$ ) is important in calculating the outage probability of the network. On the contrary, event  $B$  becomes less likely in the high SNR regime as the number of relays increases and hence  $P(B)$  decreases with increasing the number of relays. This is verified by numerical examples, where the performance is shown to be affected by the interference and not the thermal noise. In this case,  $P(B) \approx 0$  and hence (14) becomes,

$$P_{out} = \sum_{i=1}^M P(A) + \sum_{j=1}^{\bar{M}} P(A^*). \quad (15)$$

This approximation is also justified in [30]. Hence, in the high SNR regime the total outage probability can be approximated by

$$\begin{aligned} P_{out-tot} &= \sum_{i=1}^M P(A) + \sum_{j=1}^{\bar{M}} P(A^*) \\ &= \sum_{i=1}^M \left[1 - \exp\left(-\lambda_{SR_i} \gamma \frac{n}{P}\right) \left(\frac{\lambda_{R_i R_i}}{\gamma(\lambda_{SR_i} + \lambda_{R_i R_i})}\right)\right] \\ &\quad + \sum_{j=1}^{\bar{M}} \left[1 - \exp\left(-\lambda_{SR_j} \gamma \frac{n}{P}\right)\right]. \end{aligned}$$

Note that at high SNR regime, if IC is possible (i.e.,  $\bar{M} \neq 0$ ), for the same reasons as before, event  $A^*$  becomes less likely to occur and hence, (15) can be further approximated by  $P_{out} = \sum_{i=1}^M P(A)$ .

#### Remark 6

From the system description and the corresponding analysis, it is obvious that in order for IRI to be canceled

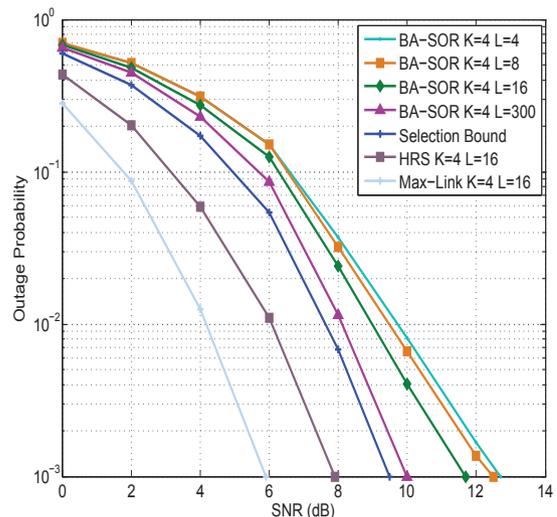


Figure 2. Outage probability for increasing transmit SNR

more efficiently or even to render it negligible in more cases, power adaptation should be considered. However, performing power allocation depending only on the link quality as in [23] is not suitable in many scenarios of practical use where IRI must not be neglected. More specifically, during the previously described relay pair selection, the optimal pair should be chosen based on the required power for successful decoding both at the candidate relay for reception and at the destination. This optimization procedure contains the IRI that the candidate relay for transmission causes to the other relays and by considering a total power constraint optimal results could be obtained even in the power minimization area.

## 6. NUMERICAL RESULTS

In order to evaluate the performance of the proposed BA-SOR scheme we have developed a simulation setup in MATLAB<sup>©</sup> based on the description of the system model in Section 2. Furthermore, we perform comparisons with half-duplex buffer-aided schemes including the scheme that combines the max-max and max-min selection criteria, denoted as HRS [22], the adaptive link selection scheme denoted as max-link [24] and the successive scheme of [23], 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 for the links of the considered relaying schemes and the data elements in the buffers scale according to this value. More specifically, when a transmission is successful the buffer of the relay selected for reception increases by  $r_0$  while the buffer of the relay that transmits to the destination reduces by  $r_0$ .

In Figure 2 the outage behavior for the considered relay selection schemes is presented in order to evaluate the diversity that they offer to the network. 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-link has the lowest outage probability as diversity order scales with twice the number of relays [24], since 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 max-link. In the set of successive relaying curves, the selection bound is not matched due to two reasons: first, we consider that 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. For the high SNR regime and assuming equal power allocation, we can observe from (6c) that the interference cancellation mechanism depends only on whether the inter-relay channel gain is large enough compared to that of the source and the relay selected for reception, to surpass the rate threshold  $r_0$ .

$$\lim_{P \rightarrow \infty} \log_2 \left( 1 + \frac{g_{R_i R_j} P}{g_{S R_j} P + n} \right) = \log_2 \left( 1 + \frac{g_{R_i R_j}}{g_{S R_j}} \right) \geq r_0.$$

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  $K = 4$ . 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. This behavior is more clearly depicted in Figure 3, where the BA-SOR's outage performance with a fixed transmit SNR equal to 10 dB and different numbers of relays is investigated. For  $K = 2$  we see that the increase in buffer size has a more significant effect on the outage probability since this is the worst case for a successive scheme. Similar behavior is observed for the other two cases where the increased  $L$  offers a better insight on the diversity of the network since the relays are rarely excluded from the selection process and each relay can be evaluated both as a possible transmitting or receiving relay. In general, the outage curves reveal a reduction in the gain offered by the increasing buffer size since for  $L > 16$  the occurrences of empty or full relays tend to minimize and the diversity of the network stabilizes.

The effect of relay number on the outage probability is shown in Figure 4. The buffer size  $L$  is equal to 300 in order to isolate the effect of relay number  $K$  on the outage behavior as otherwise some relays would be excluded from being examined both for reception and transmission. The case where  $K = 2$  relays are employed in the network, reveals the difficulty of the proposed relay selection policy to effectively mitigate the IRI when there are not enough relay pairs to be evaluated. We note that for a successive relaying protocol this case is the worst one, since the relay

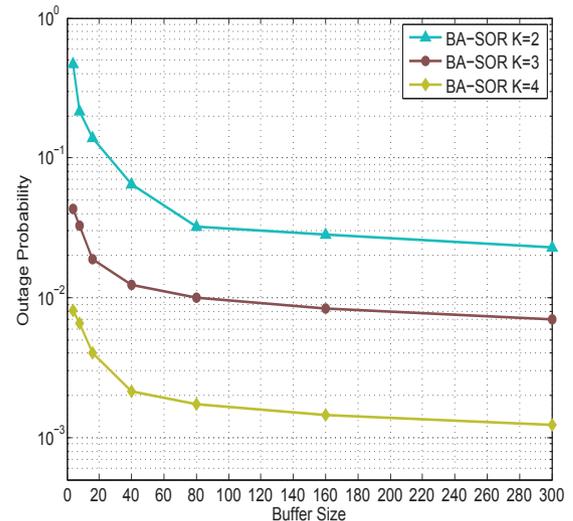


Figure 3. Outage probability for increasing buffer size and fixed transmit SNR equal to 10dB

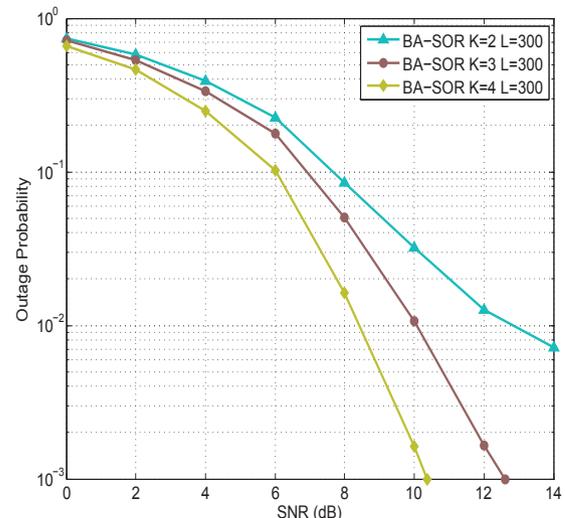
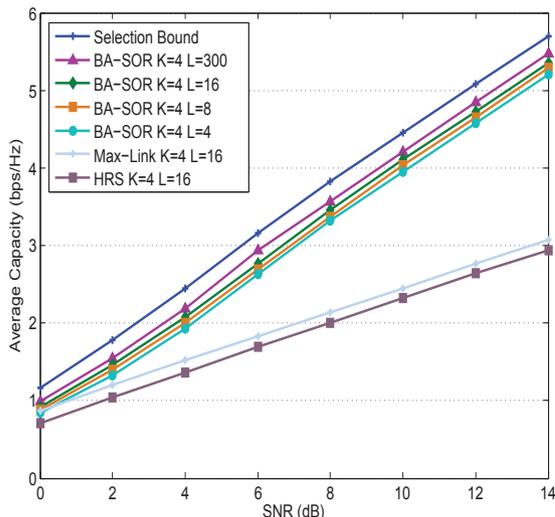


Figure 4. Outage probability for increasing transmit SNR and various numbers of relays

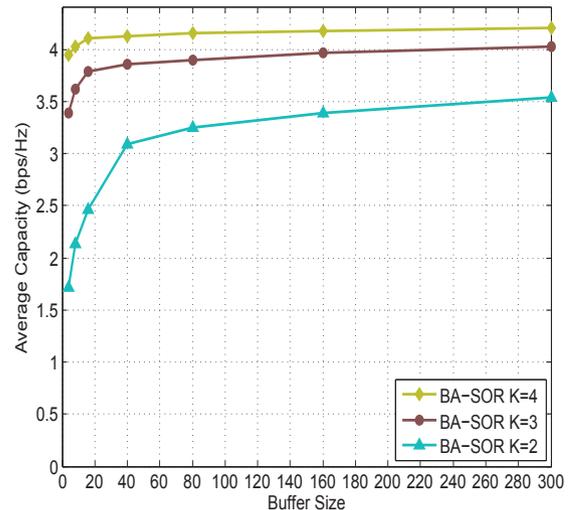
simply alternate roles in every time-slot and practically there is no selection process taking place. On the contrary, when  $K \geq 3$  there is a significant improvement in the diversity of the network since the probability of IC or interference avoidance increases significantly.

Figure 5 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.

As we compare two different families of relay selection policies, we have an obvious advantage of the full-duplex schemes since we perform the two-hop transmission



**Figure 5.** Average capacity for increasing transmit SNR and various buffer sizes



**Figure 6.** Average capacity for increasing buffer size and fixed transmit SNR equal to 10dB

during the whole period of a time-slot. Again, the selection bound is not achieved since IRI is not always subtracted and in some cases the buffers are 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, increasing the buffer size does not lead in big gains in the capacity domain indicating that capacity depends mostly on the number of relay. This is more obvious in Figure 6 where a fixed transmit SNR equal to 10dB is assumed and various numbers of relays are employed in the selection procedure. As is the case with the outage probability, the case of  $K = 2$  experiences a larger gain with the increase of  $L$  compared to the other two cases. The average capacity curve indicates that the gain reduces for  $L > 16$  but still a small increase is observed as the probability of having full or empty relays tend to decrease, thus offering more links where channel conditions offer improved average capacity.

Figure 7 reveals the relationship between the number of relays and the possible gain in average capacity. In this comparison, we have a large buffer size  $L = 300$  in order to clearly examine the effect of relay addition. We see that as the relays increase so does the average capacity. The noteworthy element in this comparison is that the achieved gain of employing 4 relays compared to  $K = 3$  is larger than increasing to 3 relays compared to  $K = 2$ . This is logical as 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 is shown in Figure 8. The first observation is the increased delay of the half-duplex

schemes. Compared to the corresponding full-duplex case of  $K = 4$  relays, the transmitted packets experience delays of about six transmissions 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 – link since the latter’s adaptive link selection may cause additional delay to some packets. For the BA-SOR, we depict curves for varying  $K$  and we see that as the relay number decreases, the delay also increases for each transmitted packet. It is expected that, when more relays are added to 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. This is clearly illustrated in the case of  $K = 2$  where at high SNR each transmitted packet remains for only one time-slot in a relay’s buffer since BA-SOR has only two possible candidates and an alternate selection among these two relays is often the case. On the contrary, the cases of  $K = 3$  and  $K = 4$  provide degraded delay for each transmitted packet. So, if delay sensitivity is required, the selection policy should consider this constraint in order to prioritize packets with excess delay and provide a more robust performance in the delay department.

## 7. DISCUSSION AND CONCLUSIONS

In this work, we let relays be equipped with buffers, thus removing the constraint that the receiving relay during the previous time slot has to become the transmitting relay of the current time slot. In the context of successive transmissions, this feature allows for combinations of relays that provide the best conditions for the relay

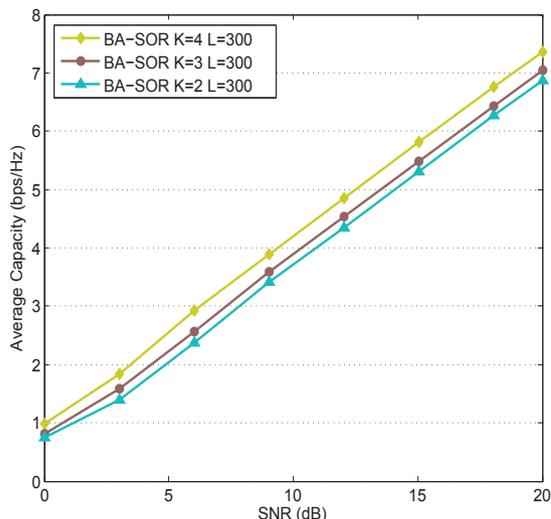


Figure 7. Average capacity for increasing transmit SNR and various numbers of relays

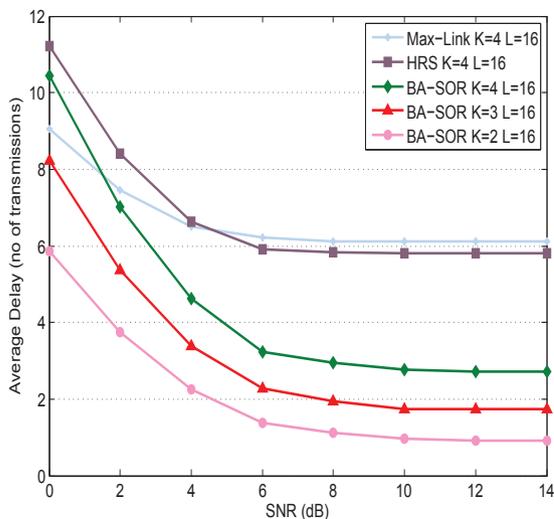


Figure 8. Average delay for increasing transmit SNR

network by choosing not only the best channel gains, but also by including interference mitigation techniques that essentially alleviate the half-duplex constraint of the relays. More specifically, we presented an extension to the successive opportunistic relaying scheme of [20], called the BA-SOR scheme, by considering relays with buffering capabilities. In this setting, we studied a relay network where, at each time-slot, a relay-pair is selected to be activated; one of the relays receive 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.

The benefits of our scheme are as the following:

- (i) Dependency of the current transmission on previous transmission periods is avoided allowing for more

options, thus increasing the diversity of the network. By decoupling the receiving relay at the previous time slot to be the transmitting relay at the next slot, we also make use of a relay based on measurements of its current channel conditions, rather than on predictions of the channel state, based on previous measurements as in the successive opportunistic relaying scheme of [20].

- (ii) Furthermore, the joint relay-pair selection offers either interference cancellation or interference avoidance, thus allowing the network to select the relays that will offer the best possible capacity at each time-slot.

The operation and complexity of BA-SOR have been thoroughly described. Numerical results and comparisons with other half-duplex and full-duplex schemes show that the average delay is decreased while the average capacity is increased, compared to existing state-of-the-art schemes proposed recently in the literature. The results also suggest that a tradeoff has to be made in outage performance in order to achieve gains in capacity and delay.

While our scheme offers significant improvements, it lacks adaptivity, especially in cases one of the source-relay or relay-destination links is not good. In this case the end-to-end communication is considered to be in outage. However, it should be possible with schemes that adapt to the channel characteristics (e.g., use power control or rate adaptation) to offer capacity gains without sacrificing the robustness of the network. Furthermore, a hybrid scheme could be used that could switch from successive transmission to single transmission whenever successive transmission is not possible.

The combination of buffers with successive transmissions open a new avenue in relay networks and there exist several open issues remaining to be investigated. Below, we provide a short list.

1. The capacity region of a buffer-aided successive opportunistic network should be investigated in order to better quantify the capacity gains. Previous works [17, 18] consider only two relays that take turns to support successive relaying. Also, there was no buffering considerations and there was a coupling among decoding of the previous packet and forwarding towards the destination in the next time-slot. As a result, the effect of opportunistic relay selection and buffering must be investigated in the derivation of the exact capacity regions.
2. More sophisticated scheduling techniques should be employed in order to avoid having empty or full buffers. More specifically, the relay selection algorithm should consider the buffer status in order to balance the occurrences of empty or full relay which have a direct effect on diversity since these relays are deprived from selection.
3. Considering energy aspects in such networks, we observe that having a constant transmission power is sub-optimal since the transmission rate is fixed

and there exists inter-relay interference. In order to maximize the lifetime of wireless devices, especially if we assume that the relays rely on batteries to operate (and hence the lifetime of the network), power adaptation should be considered. The problem is attractive since the development of novel algorithms in interference-limited environments is an active area of research.

4. The proposed scheme, as most of the available relay selection schemes in the literature, requires channel state information (CSI) knowledge regarding the link between the interfering relays. As a result, the improved performance by optimally selecting the relay pair is achieved at the expense of additional CSI. Moreover, in the cases where interference arises, the nodes must report the level of interference they experience. Solutions based on the dynamic changes of the network or CSI based on long-term channel conditions and interference statistics could be investigated.
5. More efficient ways of interference mitigation and exploitation can be examined based on network coding or multiple-input multiple-output (MIMO) techniques, e.g., beamforming and interference alignment.
6. 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 reduce the average delay.

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