A Delay-Aware Hybrid Relay Selection Policy

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***Abstract*—In this paper, we propose a novel relay selection policy based on the Hybrid Relay Selection (HRS) relay selection protocol that takes into account the state of the buffers and aims at reducing the average packet delays in the network. The proposed protocol, called the Delay-Aware HRS ($\mathrm{DA-HRS}$) protocol is analyzed by means of Markov Chains and expressions for the outage probability, throughput and delay are derived. The distributed implementation of the protocol is also discussed. The performance of our proposed protocol is demonstrated via extensive simulations and comparisons with the classical HRS.**

I. Introduction

Cooperative communications in wireless networks indicated the potential for improved coverage and link reliability. For example, cooperative relaying is an efficient technique to combat fading and path-loss effects in wireless systems by providing spatial diversity (see, for example, [1]–[3]). Standards development organizations are considering how to incorporate such techniques into new standards; one such initiative is the IEEE 802.16j standardization activity, which adds relaying capabilities to IEEE 802.16 systems. For the 5G mobile communication systems, beam-division multiple access and relays with group cooperation are being developed [4].

In earlier works, in which relays were assumed to lack data buffers, relay selection was mainly based on the $\max-\min$ criterion and its variations (see, for example, [3], [5], [6] and references therein). As a result, the relay that received the source signal in the first slot is the same that is subsequently forwarding the signal towards the destination in the second slot. As a result, the performance of the $\max-\min$ relay selection policy is limited by the constraint that the links for each data transmission are determined concurrently and they are associated with the same relay.

Buffer-aided relaying breaks this coupling between the two slots, since relay nodes are now equipped with buffers that store packets. Therefore, different relays can be selected for transmission and reception, thus allowing increased degrees of freedom (see [7]–[10] and references therein). In [11], for example, the $\max-\max$ relay selection policy is proposed where the links with the strongest source-relay and relay-destination channels are selected for reception and transmission, respectively, without necessarily using the same relay. $\max-\max$ offers significant coding gain over $\max-\min$.

Most of the works in buffer-aided relay selection focus on outage probability reduction or throughput improvement. However, an issue that arises from the use of buffer-aided relays in cooperative systems apart from increasing diversity and robustness, is that buffers have increased average transmission delays (i.e., the time required on average for packets to reach the receiver). It is clear that by reducing the average delay and establishing some guarantees, buffer-aided schemes could be of use in delay intolerant applications as well. While we have witnessed the benefits of buffer-aided relaying schemes in terms of diversity and robustness, the question is whether we can improve their performance in terms of delays without compromising any of the aforementioned benefits; i.e., is there a way to reduce the average delays while maintaining the properties that make buffer-aided relaying attractive?

In our work, we investigate this question. Towards this end, we relax the requirement of link selection based on the link quality, since we consider transmissions with fixed rates, and instead, the selected link is chosen based on its buffer size only, provided that transmission on the chosen link is feasible (i.e., the link is not in outage). More specifically, a delay- and diversity-aware algorithm is proposed, based on the Hybrid Relay Selection (HRS) protocol presented in [11], where the two-slot convention is assumed (as it is the case for the $\max-\max$ relay selection protocol), but the criterion now is to keep the queues nonempty and balanced. This is achieved by choosing among the feasible source-relay (relay-destination) links the ones with the smallest (largest) data queue. We show via simulations that the proposed algorithm reduces both the average delay and the outage probability, due to establishing more balance between the data queues in the buffers. It is also shown that the average delay in the high Signal-to-Noise Ratio (SNR) regime depends only on the number of buffers and not on the buffer size, as one would expect. The implementation of the proposed protocol in a distributed fashion is also described. The performance as well as theoretical results of our proposed algorithm are demonstrated via simulations and comparisons.

The remainder of this paper is organized as follows. In Section II, we introduce the system model and preliminary discussion. In Section III, we present in detail the relay selection scheme proposed herein. A distributed approach to our scheme is proposed in Section IV. The algorithm is analyzed by means of Markov Chains in Section V and numerical evaluations appear in Section VI. Finally, conclusions are drawn in Section VII.

II. System Model

We assume a relay-assisted network consisting one source S communicates with one destination D through a cluster $\mathcal{C}$ of K Half-Duplex (HD) Decode-and-Forward (DF) relays $R_k \in \mathcal{C}$ $(1 \leq k \leq K)$. Assuming that the direct source-destination link suffers from severe fading, communication can be established only via relays. Each relay R_k holds a buffer (data queue) Q_k of capacity L (maximum number of data elements), where it can store the packets that are successfully received from the source and can be forwarded to the destination. We denote by $Q \triangleq (Q_1, Q_2, \ldots, Q_K)$ the vector containing the buffer sizes of all relays. The system model is depicted in Fig. 1.

The wireless channels are characterized by Additive White Gaussian Noise (AWGN) and frequency non-selective Rayleigh block fading according to a complex Gaussian distribution with zero mean and variance σ_{ij}^2 for the $\{i \to j\}$ link. In addition, the variance η of the AWGN is assumed to be normalized with zero mean and unit variance. The channel gains are $g_{ij} \triangleq |h_{ij}|^2$ and exponentially distributed. It is assumed that global Channel State Information (CSI) is available, unless otherwise stated. The power level chosen by the transmitter i is fixed and it is denoted by P_i, where $P_{i,\max}$ is the maximum power of a transmitter i. Time is considered to be slotted and at each time-slot the source S or one of the relays R_k attempts to transmit a packet. The source node is assumed to be saturated (it has always data to transmit) and transmits with a fixed rate equal to r_0. Equivalently, a transmission from a transmitter to its corresponding receiver is successful if the SNR of the receiver is greater or equal to a threshold γ_0, called the *capture ratio*. The value of γ_0 depends on the modulation and coding techniques of the radio that provide the required data rate of the application which is supported by the network. Hence, independently of nodal distribution and traffic pattern, a transmission from a transmitter i to its corresponding receiver j is successful (error-free) if the SNR of the receiver j, denoted by γ_j, is greater or equal to the *capture ratio* γ_0. Therefore, we require that

$$\gamma_j(P_i) \triangleq \frac{g_{ij} P_i}{\eta} \geq \gamma_0. \tag{1}$$

Link $\{i \to j\}$ is in outage if $\gamma_j(P_{i,\max}) < \gamma_0$, i.e.,

$$\frac{g_{ij} P_{i,\max}}{\eta} < \gamma_0,$$

and the probability of outage is given by

$$p_{\text{out}} = \mathbb{P}\left[g_{ij} < \frac{\gamma_0 \eta}{P_{i,\max}}\right].$$

This framework is equivalent to the *capture model* introduced in [13]. Hence, the instantaneous SNR from S to R_i and the instantaneous SNR from R_j to D, when relay R_i is selected for reception and relay R_j is selected for transmission, are expressed as $\gamma_{R_i}(P_S) = \frac{g_{SR_i} P_S}{\eta} \geq \gamma_0$, and $\gamma_D(P_{R_j}) = \frac{g_{R_j D} P_{R_j}}{\eta} \geq \gamma_0$, respectively.

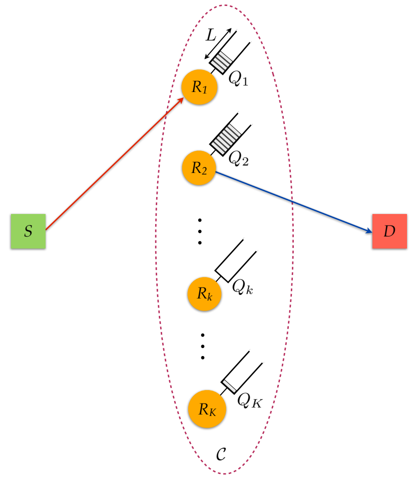


Fig. 1. The system model: Source S communicates with Destination D via a cluster of relays $R_k \in \mathcal{C}$, $k \in \{1, 2, \ldots, K\}$.

The retransmission process is based on an Acknowledgement/Negative-Acknowledgement (ACK/NACK) mechanism, in which short-length error-free packets are broadcasted by the receivers over a separate narrow-band channel.

The framework introduced herein assumes global CSI and this knowledge is used for power minimization while satisfying the fixed transmission rate r_0. However, if the CSI of the links is not known and instead only the channel connectivity state is known (i.e., whether or not the links are in outage, provided they transmit with a fixed power) at the source and relays, the procedure, results and algorithms proposed herein remain the same. The channel connectivity state is obtained through a one-bit feedback message from the receiver utilizing the ACK/NACK mechanism.

III. Delay-aware HRS

In this section, we propose an algorithm that builds on the seminal HRS algorithm proposed in [11]. The main difference is that the decision process considers, apart from the channel condition, the number of packets in the buffers of the relays. Since we consider fixed rates, and as a result we know in advance if a link is in outage or not, the decision over which of the available links is going to be selected is dominated by the packets in the buffers of the relays that have at least one of the $\{S \to R\}$ or $\{R \to D\}$ links available. Limitations due to buffering include the cases when a buffer is either full or empty. When a buffer is full, the relay cannot receive any more packets and consequently, it cannot be selected during the first slot. Similarly, an empty buffer entails that this relay cannot be selected in the second slot.

The Delay-Aware HRS $(\mathrm{DA}-\mathrm{HRS})$ algorithm, as the original HRS algorithm, uses the *two-slot convention per time-frame* (i.e., in each time-frame there exist two time-slots: one for the $\{S \to R\}$ link and one for the $\{R \to D\}$ link) and proceeds as follows: first, the infeasible links are excluded from the selection process; among the links in $\mathcal{F}_{SR}$ (i.e., feasible $\{S \rightarrow R\}$ links) the relay with the minimum buffer size is selected to receive a packet during the first slot; during the second slot, among the links in $\mathcal{F}_{RD}$ (i.e., feasible $\{R \rightarrow D\}$ links), the relay with the maximum buffer size is selected to transmit towards the destination. When more than one relays have the same buffer size (in any of the two slots) a relay is randomly selected. If either $\mathcal{F}_{SR} = \emptyset$ or $\mathcal{F}_{RD} = \emptyset$, no transmission takes place.

The $\mathrm{DA-HRS}$ algorithm during a single time-frame (consisting of two time-slots) is as follows:

Algorithm 1 Delay-Aware HRS Relay Selection

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

IV. Distributed implementation

The distributed approach for the relay selection process at both slots is based on the use of synchronized timers as proposed in [3]. At the *first slot*, the source broadcasts a pilot sequence and each relay R_i, for which $q_{SR_i} = 1$, estimates the $\{S \rightarrow R_i\}$ CSI. From that it can asses whether $b_{SR_i} = 1$. If $b_{SR_i} q_{SR_i} = 1$, then R_i participates in the competition for the slot as follows. Relay R_i starts a timer from a parameter based on the buffer size $\max\{0, Q_i + \nu_i\}$, where ν_i is uniformly distributed in $(-0.5, 0.5)$. The timer of the relay with the *minimum* buffer size will expire first. In case there exist more than one relays with the same size, ν_i will guarantee almost surely that the timers will expire on different times. The relay with the fastest timer and hence the smallest queue size transmits a short duration flag packet, signaling its presence. All relays, while waiting for their timer to expire are in listening mode. As soon as they hear another relay to flag its presence or forwarding information (the best relay), they back off. At the *second slot*, the destination broadcasts a pilot sequence and each relay R_i, for which $q_{R_iD} = 1$, estimates the $\{D \rightarrow R_i\}$ CSI. By assuming that the reciprocity property [14] of antennas holds[1] relays can estimate the $\{R_i \rightarrow D\}$ CSI. From that it can asses whether $b_{R_iD} = 1$. If $b_{R_iD} q_{R_iD} = 1$, then R_i participates in the competition for the slot, but in this case R_i starts a timer from a parameter based on the reciprocal of the buffer size $(Q_i + 1 + \nu_i)^{-1}$. The timer of the relay with the *maximum* buffer size will expire first. In case there exist more than one relays with the same buffer size, ν_i will again guarantee almost surely that the timers will expire on different time instances.

[1] Reciprocity technically only applies for antennas operating in a linear medium made of linear materials (e.g., magnetic materials that exhibit hysteresis are not linear). In general, any antenna can be assumed to be a reciprocal device.

V. Analysis

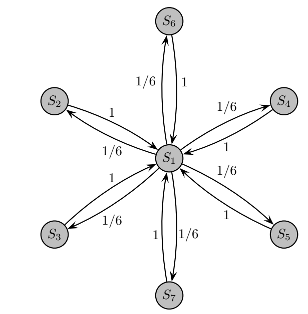
We adopt the framework based on Discrete Time Markov Chains (DTMC) proposed in [15] to analyze the $\max - \mathrm{link}$ algorithm. The states of the DTMC represent all the possible states of the buffers. The transitions between the states are given by the probabilities of successful transmissions of packets either to or from a relay. The state of the DTMC can be represented by

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

The states are predefined in a random way as all the possible $(L+1)^K$ combinations of the buffer sizes combined with the destination state, and are considered as a data input for the proposed selection policy. Let $\mathbf{A} \in \mathbb{R}^{(L+1)^K \times (L+1)^K}$ denote the state transition matrix of the DTMC, in which the entry

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

is the transition probability to move from state S_j at time t to state S_i at time $(t+1)$. In order to construct the state transition matrix $\mathbf{A}$, we need to identify the connectivity between the different states of the buffers. For each time slot, the buffer status can be modified as follows: (a) the number of elements of one relay buffer can be decreased by one, if a relay node is selected for transmission and the transmission is successful, (b) the number of elements of one buffer can be increased by one, if the source node is selected for transmission and the transmission to the relay is successful and the transmission to the destination is unsuccessful, (c) the buffer state (not the DTMC state) remains unchanged when there is an outage event (i.e., all the $\{S \rightarrow R\}$ and $\{R \rightarrow D\}$ links are in outage).



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

Fig. 2. DTMC of a network consisting of 3 relays at the high SNR regime, where the outage probability is negligible.

Analytical expressions for the average delay, outage probability and average throughput of the algorithm can be easily obtained by first constructing the DTMC with the admissible states that these algorithms reach. As an example, we will demonstrate the use of the theoretical framework to obtain the average delay for $\mathrm{DA-HRS}$ at the high SNR regime (asymptotic behavior). First, we construct the DTMC with the admissible states that these algorithms reach. More specifically, it ends up to the fact that at this regime, outages due to the lack of data in the queues are avoided by having one packet in each data queue and deviate one packet from there at each time-frame.

Due to the fact that the buffer of each relay is finite, the DTMC can be easily shown to be Stationary, Irreducible and Aperiodic (SIA) [15], i.e., a steady state π exists such that $\mathbf{A}\pi = \pi$. In Fig. 2, we provide an example of the DTMC for a network with 3 relays at the high SNR regime.
The state transition matrix is given by

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

and the steady state distribution is

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

The DTMC is constructed in a way that an outage event occurs *only when there is no change in the buffer state*. Hence, the outage probability of the system is given by the sum of the product of the probabilities of being at a stage r and having an outage event, i.e., [15]

$$p_{\text{out}} = \sum_{r=1}^{(L+1)^K} \pi_r \overline{p}_r = \text{diag}(\mathbf{A})\pi. \quad (2)$$

Hence, in our example, in the high SNR regime there is no outage and hence $p_{\text{out}} = 0$.

The existence of a steady state distribution by Little's law [16] implies finite average packet delay. The average packet delay under this framework was recently presented in [17]. We summarize the results herein for completeness. For i.i.d. channels, the average delay is the same for all relays. Hence, it is enough to analyze the average delay for a single relay. By Little's law, the average packet delay for relay R_j, denoted by $\mathbb{E}[d_j]$ is given by

$$\mathbb{E}[d_j] = \frac{\mathbb{E}[L_j]}{\mathbb{E}[T_j]}, \quad (3)$$

where $\mathbb{E}[L_j]$ and $\mathbb{E}[T_j]$ are the average queue length and average throughput, respectively. The average queue length of relay R_j is given by

$$\mathbb{E}[L_j] = \sum_{r=1}^{(L+1)^K} \pi_r Q_j^{(r)}, \quad (4)$$

Hence, the average queue length of relay R_j is

$$\mathbf{E}[L_j] = \sum_{r=1}^{7} \pi_r Q_j^{(r)} = 1 \times \frac{1}{2} + (0+1+2)\left(2 \times \frac{1}{12}\right) = 1.$$

If there is only one transmission per time-slot (e.g., [11], [15]), the average data rate of the network ρ is $1/2$ since two hops are required to reach the destination. As a result, the average throughput of relay R_j at the high SNR regime is $\mathbb{E}[T_j] = 0.5/3 = 1/6$. Here, since one extra time-slot is required for the packet to reach the destination, the average delay (invoking Little's law via (3)) is $\mathbf{E}[d_j] = 1 + 1/(1/6) = 7$.

For a network of K relays it can be easily deduced by the construction of the DTMC that the steady state distribution is given by $\pi = \begin{bmatrix} 1/2 & 1/2K & 1/2K & \dots & 1/2K \end{bmatrix}$, and it can be easily deduced that the average queue length at relay R_j is $\mathbf{E}[L_j] = 1$. Hence, by invoking the Little's law again, the average delay is given by $\mathbf{E}[d_j] = 2K + 1$, a quantity which is independent of the buffer size L. The theoretical results are justified in Fig. 3, where the average delay for $K = 5$ and different buffer sizes reached $2 \times 5 + 1 = 11$.

Note that when the outage probability is not negligible, then the full state transition matrix will be used as in [15] for the transition probabilities, complying with the rules of the proposed scheme. Thus, the steady state of the system will be computed and thereafter, the procedure is the same as above.

VI. Numerical Evaluation

The proposed algorithm was simulated under various scenarios, for different number of relays and buffer capacities. For this scheme, the system is in outage if in a time-frame no packet transmission takes place (see Algorithm 1).

$\mathrm{DA-HRS}$ and HRS are compared for different buffer sizes with respect to the average delay and outage probability. As it is shown in Fig. 3, $\mathrm{DA-HRS}$ has better performance than HRS in both the average delay and outage probability in the low and medium SNR regimes.

The effect of the different number of relays is shown in Fig. 4. More relays result in a larger average delay, but smaller outage probability. These results stem from the fact that more relays allow for more options and hence the packets remain in the buffers for longer, but at the same time, we establish increased diversity. By comparing the performance of HRS and $\mathrm{DA-HRS}$, we observe that an improvement in the average delay (top) is achieved, which is always better, while the two schemes perform identically when the channels are very good and there are no outages. Surprisingly, a big improvement is observed in the outage probability (bottom) as well. This is due to the fact that a more balanced relay selection is enforced keeping the relays with more or less uniform buffer size retaining *full diversity* at the same time.

VII. Conclusions

We propose a relay selection policy for buffer-aided relaying that aims at reducing packet delays, so that delay-sensitive applications can be supported. We analyze our proposed algorithm at the high SNR regime for ease of exposition and we show numerically that our algorithm outperforms the classical HRS both in terms of average delay and outage probability. The distributed implementation of our algorithm is also discussed and it is based on the use of synchronized timers.

Buffer-aided successive opportunistic relaying has shown a considerable improvement in terms of outage probability, throughput as well as delay reduction (e.g., [10], [18], [19]).

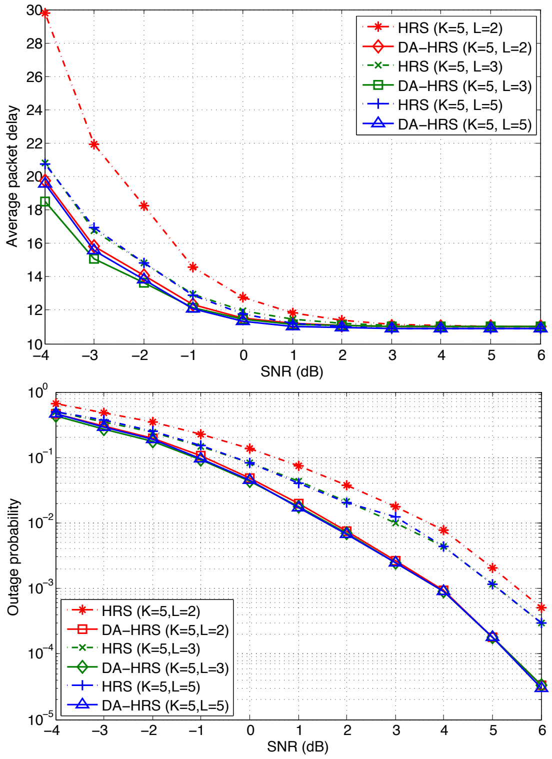


Fig. 3. Average delay (top) and outage probability (bottom) of $\mathrm{DA-HRS}$ for $K = 5$ and $L = 2, 3, 5$.

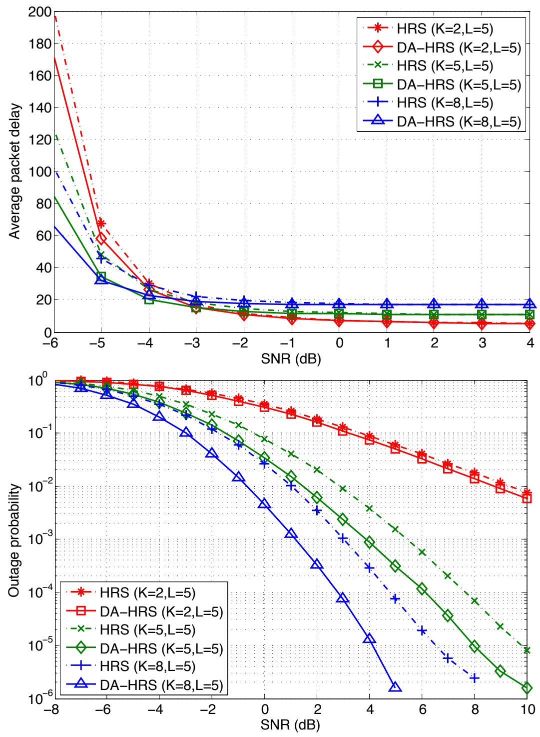


Fig. 4. Average delay (top) and outage probability (bottom) of $\mathrm{DA-HRS}$ for $K = 2, 3, 4$ and $L = 5$.

However, no delay-aware mechanisms exist for such schemes. It is anticipated that the gain from such mechanisms would further improve the performance of buffer-aided relaying in terms of delay reduction.

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