Impact of Relay Selection Overhead in Cooperative Diversity Protocols

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***Abstract*—Cooperative diversity uses relays to assist source-destination transmissions to reduce link outage rates in multipath fading environments. In this paper, we model relay selection as a semi-Markov process to analyze the impact of relay selection overhead on throughput, delay, and jitter in a simple scenario. Results show that the selection overhead can significantly reduce benefits of reactive relay selection if data frames are small or only few nodes overhear the transmissions. Relaying with a preassigned relay can be more beneficial in such cases.**

***Index Terms*—Wireless communications, cooperative diversity, relay selection, signaling overhead.**

I. INTRODUCTION

Cooperative diversity is a promising technique for improving link reliability in fading-rich environments where nodes can overhear signal transmissions between a communicating pair and retransmit data to the destination [1]. It can be applied for small and low-cost radios, for instance, where multiple antennas and sophisticated receivers cannot be used.

The relay selection procedure is essential for efficient operation of cooperative diversity (see, e.g., [2], [3]). Numerous relay selection protocols have been proposed and analyzed so far. The impact of selection overhead on overall protocol performance, however, has been studied only to some extent. On one side, in theoretical papers, relay selection overhead is either not considered at all [4] or reduced to few bits [5]. On the other side, some protocol studies include selection overhead (e.g., [6], [7] based on IEEE 802.11), but the performance results are obtained through simulations and are limited to a specific implementation and overhead ratio. Shah *et al.* [8] propose an analytical model for throughput analysis of cooperative relaying with consideration of signaling overhead. Using a protocol in which a relay is selected upon source-destination transmission and always retransmits the received message, results illustrate the tradeoff between throughput and time allocated for selection.

The goal of this paper is to investigate the impact of relay selection overhead on throughput, delay, and jitter in an analytical manner for feedback-based relaying protocols, where a relay will only transmit if requested by the destination. We propose a framework that utilizes a semi-Markov process to model such a cooperative diversity protocol including its overhead duration. Results show that, due to its overhead, reactive relay selection with full diversity can, in some cases, perform worse than cooperative relaying with a single preassigned relay. The proposed framework can be extended with other types of cooperative relaying protocols. This paper extends our previous work [9] which analyzes throughput and energy efficiency of proactive and reactive relay selection schemes using similar modeling assumptions.

The paper is organized as follows. Section II describes channel model, cooperative relaying protocols, and analytical framework for reactive relay selection. Section III presents results on performance in terms of throughput, delay, and jitter in a simple line network. Section IV draws conclusions.

II. MODELING COOPERATIVE RELAYING AS A SEMI-MARKOV PROCESS

A. Radio Channel

A wireless channel between two nodes can be described as a binary random process. The channel is in state "bad" whenever the signal-to-noise ratio (SNR) at the receiver is lower than a certain threshold $\mathrm{SNR}_{\min}$. Otherwise, the channel is in state "good." This implies that only data messages sent over a channel in the good state can be decoded correctly. In a Rayleigh block fading channel, the message error probability between a source node s and a destination node d is

$$\epsilon_{sd} = 1 - \exp\left(-\frac{1}{\psi_{sd}}\right), \tag{1}$$

where $\psi_{sd} = \mathbb{E}\left(\mathrm{SNR_{sd}}\right)/\mathrm{SNR}_{\min}$ is called fading margin. The expected value of the receiver SNR is characterized by a simple pathloss model between the nodes. We have

$$\mathbb{E}\left(\mathrm{SNR_{sd}}\right) = \begin{cases} \mathrm{SNR_s}\left(d_{sd}/d_0\right)^{-\alpha}, & d_{sd} > d_0 \\ \mathrm{SNR_s}, & d_{sd} \le d_0 \end{cases} \tag{2}$$

with the SNR at s, the distance d_{sd} between s and d, a reference distance $d_0 = 1\,\mathrm{m}$, and the pathloss exponent α.

We consider independent and identically distributed (i.i.d.) slow fading, i.e., a channel state is defined by the corresponding message error probability independently.

B. Relaying Protocols

There are K nodes located around the communicating pair (s, d). One of these is selected as relay to support the transmissions. Two approaches for relay selection are considered:

- *Fixed relay.* A relay is selected once and remains relay for a long period of time (much longer than the message duration). The selection is based on long-term characteristics, such as expected SNRs. If the source-destination transmission fails and the selected relay receives the message, the relay will retransmit the message until it is delivered successfully to d. If a relay does not receive the message, s retransmits.

- *Reactive relay.* A relay is selected anew after each failed transmission. A node is selected to become relay for the current message if it has a correct copy of the message and a good channel to d (channel state information is obtained through negative ACK from d). If there are several candidates, one node will be selected at random. The chosen node then delivers the message to d. If no relay candidates are available, s retransmits the message.

In both approaches, relaying is only performed if required by the destination.

The selection of a fixed relay happens very rarely; thus the selection overhead can be neglected, and results of [9] and [10] can be applied. Using relay communication with reactively selected relays, however, requires a significant signaling overhead. Hence, we extend the Markov chain model given in [9] by taking into account the relay selection overhead. The selection delay is normalized to the message duration and is denoted by μ. As in [9], the implementation details of the protocol remain unspecified.

Further protocol assumptions are:

- Transmissions are strictly orthogonal in time.
- Relays operate in the decode-and-forward mode.
- At the receiving node, selection combining on the frame level is performed. No energy accumulation is possible.
- All nodes use the same transmission rate and power.
- Signaling messages are error-free.
- Relay selection provides the best available relay.

C. Reactive Relay Selection as a Semi-Markov Process

The states and state transitions of relaying with reactive relay selection can be modeled as a Markov chain (see Figure 1). The chain has $S = 3$ states:

- State `Tx` is a new message transmission by s;
- State `R` corresponds to a retransmission by a relay;
- State `RT` is a retransmission by s if no relay could be selected.

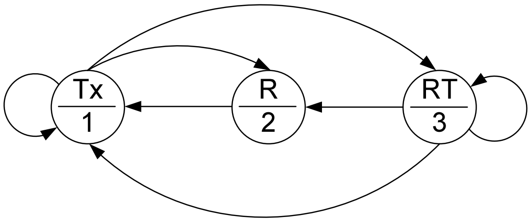

Fig. 1. Markov chain for reactive relay selection

The probability to change from state i to state j is called state transition probability P_{ij}, where $i, j \in \{1, \ldots, S\}$. For i.i.d. channels, the $(S \times S)$ state transition matrix is

$$\mathbf{P} = \begin{bmatrix} 1-\epsilon_{sd} & \epsilon_{sd}(1-q) & \epsilon_{sd}q \\ 1 & 0 & 0 \\ 1-\epsilon_{sd} & \epsilon_{sd}(1-q) & \epsilon_{sd}q \end{bmatrix}, \tag{3}$$

where

$$q = \prod_{k=1}^{K} \big(1 - (1-\epsilon_{sk})(1-\epsilon_{kd})\big). \tag{4}$$

is the probability that a relay can not be selected. For a given node k, the terms ϵ_{sk} and ϵ_{kd} represent error probabilities from the source and to the destination, respectively.

To incorporate the overhead of relay selection into this Markov chain, we introduce holding times between transitions. A holding time D_{ij} is the period during which the process stays in state i before shifting to state j. If the holding times of all transitions were equal, the process could be characterized as a discrete-time Markov process. In the given relay protocol, however, if a source-destination transmissions fails, the holding time consists of periods for relay selection and periods for message transmission. If a transmission succeeds, the holding time is only the message duration. The holding time matrix is thus

$$\mathbf{D} = \begin{bmatrix} 1 & 1+\mu & 1+\mu \\ 1 & 1 & 1 \\ 1 & 1+\mu & 1+\mu \end{bmatrix}. \tag{5}$$

A process described by a state transition matrix $\mathbf{P}$ and holding time matrix $\mathbf{D}$ is a special case of a semi-Markov process [11]. The limiting-state probabilities $\boldsymbol{\pi} = [\pi_1 \ \ldots \ \pi_S]$ for such processes are obtained in the same way as for a Markov chain with the same $\mathbf{P}$, i.e., by solving the following set of linear equations:

$$\boldsymbol{\pi}\mathbf{P} = \boldsymbol{\pi} \quad \text{with} \quad \sum_{i=1}^{S} \pi_i = 1. \tag{6}$$

1) Throughput: A message is delivered successfully to d when the process returns to state `Tx`. Rewards are assigned to transitions to indicate data delivery:

$$R_{ij} = \begin{cases} 1, & \forall i; j = 1, \\ 0, & \text{otherwise.} \end{cases} \tag{7}$$

The cumulative reward of the process after a period τ is called reward function $R(\tau)$. In the long term, $R(\tau)/\tau$ corresponds to the throughput [12] and is calculated according to the fundamental renewal-reward theorem [12] by

$$\eta = \lim_{\tau \to \infty} \frac{R(\tau)}{\tau} = \frac{\sum_{i=1}^{3} \pi_i \overline{R}_i}{\sum_{i=1}^{3} \pi_i \overline{D}_i}, \tag{8}$$

where $\overline{R}_i = \sum_{j=1}^{3} P_{ij} R_{ij}$ is the expected reward the process receives from a transition from state i, and $\overline{D}_i = \sum_{j=1}^{3} P_{ij} D_{ij}$ is the expected time the process remains in state i before making a transition. This yields

$$\eta = \frac{\pi_1}{\sum_{i=1}^{3} \pi_i \sum_{j=1}^{3} P_{ij} D_{ij}}. \tag{9}$$

2) Delay and Jitter: To obtain delay and jitter, we make use of first passage times and their second moments (also see [13]). The first passage time θ_{ij} is the time period the semi-Markov process takes to reach state j for the first time after starting from state i. Generally, the mean first passage time can be calculated by [11]

$$\overline{\theta}_{ij} = \overline{D}_i + \sum_{\substack{r=1\\ r\neq j}}^{3} P_{ir}\overline{\theta}_{rj} \, . \tag{10}$$

If $i = j$ the process returns to its starting state. The mean recurrence time for state `Tx` is the mean packet delay. It is obtained by [11]

$$\overline{\theta}_{11} = \frac{\sum_{i=1}^{3} \pi_i \overline{D}_i}{\pi_1} = \frac{1}{\eta}, \tag{11}$$

which is the inverse of the throughput as expected.

Jitter is the standard deviation of the delay, given by

$$\gamma = \sqrt{\overline{\theta_{11}^2} - \left(\overline{\theta}_{11}\right)^2}, \tag{12}$$

where $\overline{\theta_{11}^2}$ is the second moment of the recurrence time θ_{11}, which can be calculated by [11]

$$\overline{\theta_{11}^2} = \frac{1}{\pi_1}\left[\sum_{i=1}^{3} \pi_i \overline{D_i^2} + \sum_{r=\{2,3\}} \sum_{i=1}^{3} 2\pi_i P_{ir} D_{ir} \overline{\theta}_{rj}\right], \tag{13}$$

with $\overline{D_i^2} = \sum_{k=1}^{3} P_{ik} D_{ik}^2$. Using (10) we can obtain mean first passage times $\overline{\theta}_{31}$ and $\overline{\theta}_{21}$ for the introduced semi-Markov process,

$$\overline{\theta}_{21} = \overline{D}_2, \tag{14}$$

$$\overline{\theta}_{31} = \frac{\overline{D}_3 + P_{32}\overline{D}_2}{1 - P_{33}}, \tag{15}$$

and resolve (13) and (12).

III. Performance of Relaying Protocols in Line Networks

Let us now apply the semi-Markov process to analyze the performance of cooperative relaying in the one-dimensional network topology shown in Figure 2 [9]. Node s communicates with node d, where K nodes are located in between them. The distance between any two consecutive nodes is $\Delta d_K = d_{sd}/\left(K+1\right)$. For the fixed relay scheme, the node closest to the midpoint between s and d serves as relay.

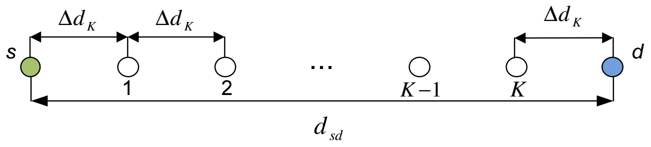

Fig. 2. Network scenario [9].

Figure 3 shows the throughput of cooperative relaying with fixed or reactive relay with various overhead ratios μ and $K = 5$ potential relays. As reference, the performance of direct source-destination communication is given (no relay), which uses a basic automatic repeat request (ARQ) upon failures. We can see that μ has significant impact on the resulting throughput. Communication with a fixed relay outperforms reactive selection for $\psi_{sd} > 0\,\mathrm{dB}$ and $\mu > 0.25$. For high fading margins, using no relaying can also be more beneficial than relaying with reactive selection.

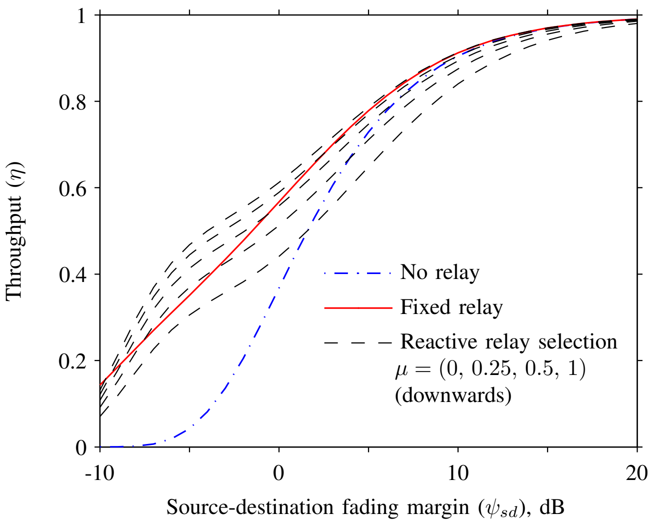

Fig. 3. Throughput as a result of communication with no relay, fixed relay, or reactively selected relay with overhead μ and $K = 5$ potential relays.

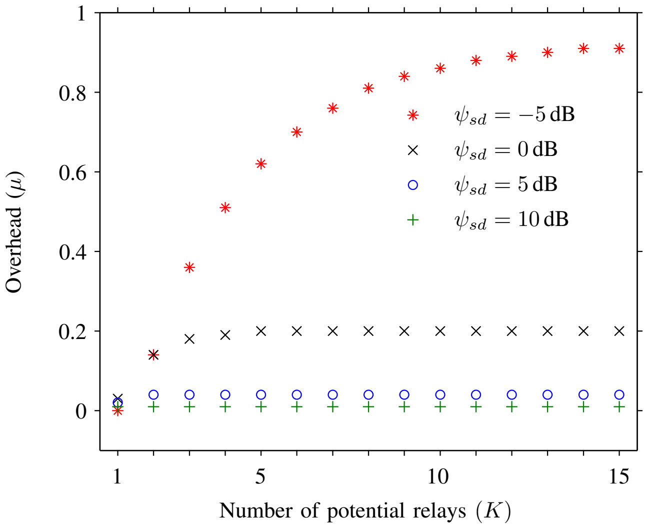

Fig. 4. Each point (K, μ) shows the number of potential relays and amount of overhead at which reactive relay selection and fixed relay schemes provide the same throughput for given source-destination fading margin ψ_{sd}.

Figure 4 shows (K, μ)-pairs at which both fixed relay and reactive relay schemes provide the same throughput for given ψ. For a given (K, μ)-pair, the throughput of reactive selection can be better than of a fixed relay, if more than K nodes are available and/or the overhead is lower than μ. At fading margins $\psi_{sd} > 5\,\mathrm{dB}$, reactive selection requires a very low selection overhead to have better throughput than relaying

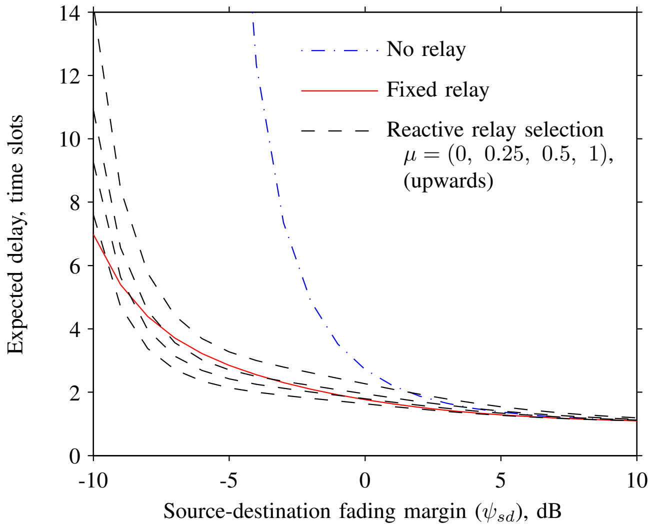

Fig. 5. Delay performance as a result of communication with no relay, fixed relay, or reactively selected relay with overhead μ and $K = 5$ potential relays.

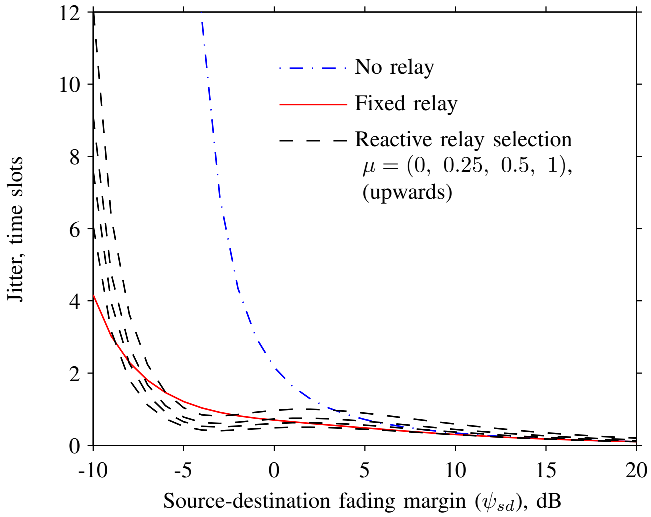

Fig. 6. Jitter as a result of communication with no relay, fixed relay, or reactively selected relay with overhead μ and $K = 5$ potential relays.

with a fixed relay; additional relay candidates do not increase the performance.

Figure 5 shows the delay performance, which is the inverse of the corresponding throughput performance. Finally, Figure 6 shows the jitter of message delivery. The jitter is very high when no relay is used at low fading margins. Significant differences between fixed relay and reactive selection and the negative effect of selection overhead can be seen for $\psi_{sd} < -5\,\mathrm{dB}$ when the delay also grows considerably.

IV. CONCLUSIONS

We analyzed the impact of selection overhead on throughput, delay, and jitter in cooperative diversity protocols with relay selection. For this purpose, we proposed a generic model based on a semi-Markov process that incorporates the relay selection duration. Results show that the overhead introduced by relay selection can reduce its performance significantly despite its higher level of diversity compared to relaying with a fixed relay and compared to non-relayed communications. This is in particular true for high fading margins ($\psi > 0\,\mathrm{dB}$) and few candidate relays, where relaying with a fixed relay can provide higher throughput.

The obtained results may be useful for the task of protocol design in wireless sensor networks, where low-cost radios are used for transmission of small data packets.

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