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Multi-Hop-Aware Cooperative Relaying

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***Abstract*—We address the drawbacks of Cooperative Relaying regarding its spectral inefficiency and its channel over reservation compared to direct transmissions. We propose to exploit routing information in cooperative relaying to reduce these disadvantages. In this paper we present a complete system design of *Multi-Hop-Aware Cooperative Relaying* and investigate different relay selection policies for it. Performance tests indicate that it significantly outperforms hop-by-hop cooperative relaying in terms of throughput.**

***Index Terms*—cooperative diversity, cooperative relaying, relay selection, D-STBC, routing**

I. INTRODUCTION

In cooperative relaying a node denoted as relay overhears the direct transmission between source and destination and on demand (incremental relaying [1]) forwards this data to the destination. The destination receives the same message via two independent paths, which introduces diversity and thus mitigates small scale fading. It depends on the coherence time of the channel whether a relay retransmission is preferable to a retransmission by the source. For instance for a long coherence time, the retransmission from the source would suffer the same error probability as in the original transmission. In such cases relaying is preferable. The same data received via different paths can be combined at the destination using combination techniques like Maximum Ratio Combining (MRC).

During the past years, the research focus has been predominantly on physical layer aspects and information theoretical bounds. Recently, protocol and system aspects of cooperative relaying have started to be investigated [2], [3]. The interplay of cooperative relaying and layers above the Medium Access Control (MAC) layer and also potential synergies of combining cooperative relaying tasks with tasks of upper layers have not yet been intensively addressed.

We investigate the benefits of exploiting routing information in cooperative relaying. We call such a scheme Multi-Hop-Aware Cooperative Relaying (MHA-Coop-Relaying). The main contributions of this work are: introducing the basic idea, providing a system design, investigating different relay selection policies, and showing the achievable throughput gain.

The remainder of this paper is organized as follows: Section II describes the different phases of cooperative relaying and presents some related work. Section III introduces the basic idea of MHA-Coop-Relaying. Section IV gives a detailed protocol design by pointing out the differences to hop-by-hop cooperative relaying. Section V first explains our modeling and simulation assumptions and present simulation results of our proposed system.

II. PHASES OF COOPERATIVE RELAYING AND RELATED WORK

Cooperative relaying consists basically of three main phases: (i) *relay selection*, (ii) *direct transmission* and (iii) *cooperative transmission*.

Relay selection is often based on the Channel State Information (CSI) between the communication participants [4]. This information can also be augmented by other information like remaining battery power [5]. The channel characteristics determine the required rate of relay selection. In the absence of any long term channel information relay selection is done anew for each transmission. Since cooperative relaying needs anyway a channel reservation for source, destination, and relay, selection schemes are often combined with medium access protocols [2], [3]. This also reduces the overhead introduced by probing the channel which is required to estimate the CSI. In the *direct transmission phase* the source sends the data and both the destination and the selected relay try to receive it. If the destination succeeds, an `ACK` is sent to inform both the source and the relay that no cooperative transmission or retransmission is necessary.

Whenever the direct link fails, the *cooperative transmission phase* is entered. If the relay was able to decode the message or the Signal-to-Noise-Ratio (SNR) of it is above some threshold, the data is forwarded to the destination. Then the destination tries to combine both received transmissions. If it is successful an `ACK` is transmitted. If it fails the system is in outage and a retransmission from the source is required. Apparently, cooperative relaying needs at least twice the duration of a single transmission. If in the cooperative transmission phase multiple relays are used Distributed Space Time Block Codes (D-STBCs) [1] can be applied to keep the reduction of the spectral efficiency small. Relays transmit concurrently (instead of consecutively) after data processing using orthogonal codes. Laneman et al. analyze in [1] the outage behavior of D-STBCs and show its supremacy compared to repetition based cooperation. The differences between Space Time Block Codes (STBCs) and D-STBCs are discussed in [6]. An example of a cooperative relaying scheme based on IEEE 802.11 which uses D-STBC is CD-MAC [7]. Cooperation is used as soon as the destination does not reply to a normal `RTS` message. In such case the source and a previous selected relay transmit a `C-RTS` message concurrently using a D-STBC. The destination and its own relay reply with a `C-CTS` again using orthogonal codes. Therefore, channel reservation, data transmission and acknowledgments are done in a cooperative manner.

The authors of [8] study the problem of cooperative transmission-side diversity and routing in a static wireless network and analytically derive the achievable energy saving. Their analysis assume perfect coordination among cooperating nodes in an Additive White Gaussian Noise (AWGN) channel. Ibrahim et al. [9] introduce two different cooperative routing protocols in Rayleigh fading channels which try to minimize the overall energy consumption in delivering messages. Intermediate nodes determine whether a cooperative transmission is preferable to a direct transmission for a required end-to-end throughput. The authors of [10] introduce a scheme called Simple Packet Combining which explores weak links which are not considered from routing protocols.

III. MHA-COOP-RELAYING: BASIC IDEA

In the example depicted in Fig. 1, R_1 and R_2 support the transmission from S to D_1 and from D_1 to D_2, respectively. Cooperation is performed in a hop-by-hop manner to enhance the reliability of each individual link – cooperation between multiple hops is not exploited. We denote such schemes in the sequel as *hop-by-hop cooperative relaying*.

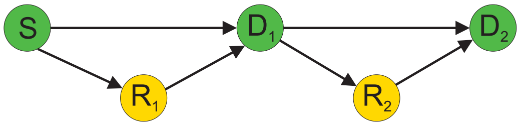

Fig. 1. Hop-by-hop cooperative relaying

Selection of cooperative relays and overhearing direct transmissions consume time and energy [11]. Furthermore, the wireless channel needs to be reserved for both the direct and the cooperative transmission phase. Nevertheless, the necessity of cooperation is a random process, that depends on the instantaneous CSI. Thus, whenever the direct transmission succeeds, energy and time invested for cooperation are spent without any benefit. The channel utilization is also decreased, since the medium was reserved for the duration of the complete cooperative process and cannot be used by other terminals – we call this situation *over-reservation*.

Given that the overall task is to deliver messages to a final destination and not to an intermediate node, hop-by-hop cooperative relaying suffers from its limited perspective.

We propose a different approach of cooperative relaying which exploits routing information. Fig. 2 depicts a sub-path of a route. Node S has to forward the message to the next hop identified by D_1. D_2 is in a two hop distance of S. R_1 is in transmission range of S, D_1 and D_2. We call R_1 a *multi-hop relay*. R_2 is just in transmission range of D_1 and D_2 and is thus denoted as *single-hop relay*. A multi-hop aware relay delivers also information to D_2 during the cooperative transmission phase. This information can be used as some kind of incremental redundancy [10], [12] in a following cooperation process initiated by D_1. Multi-hop relays should forward received messages regardless of the direct transmission success. D_2 may already receive the message correctly from the relay making a later transmission from D_1 unnecessary. Whenever the message being routed reaches D_2 during a cooperation process initiated by S a *2-hop-progress* is achieved. The fact that multi-hop relays always transmit the overheard data avoids over-reservations and improves channel utilization. MHA-Coop-Relaying utilizes time, energy and bandwidth spend for the cooperation process more efficiently than hop-by-hop cooperative relaying.

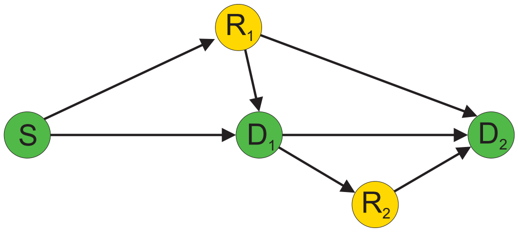

Fig. 2. Multi-hop-aware cooperative relaying

IV. MHA-COOP-RELAYING: PROTOCOL ARCHITECTURE

In this section we present a protocol architecture which provides MHA-Coop-Relaying. We describe the differences to traditional hop-by-hop cooperative relaying for each phase of the cooperation process. In the description we refer to the node names used in Fig. 2.

A. Relay Selection

Relay selection is extended to consider an additional link for all potential relays to D_2. Relay selection needs to have access to the routing information. It depends on the type of routing protocol which information needs to be provided by S. This information (e.g. the address of D_2) can be piggybacked with a channel probing message like `RTS` (Ready to send) as used in [4]. D_1 propagates this information by its `CTS` (Clear to send) message. In that way D_2 knows about the MHA-Coop-Relaying process and sends if possible (there is no other communication in its neighborhood) its own probing message `CTS2`. After exchanging these probing messages two sets of potential relaying nodes are formed:

- Set $\mathcal{H}$ – nodes that have only links to S and D_1 but are not in transmission range of D_2.
- Set $\mathcal{M}$ – nodes that have links to S, D_1 and D_2.

Obviously, $\mathcal{H}$ and/or $\mathcal{M}$ can be empty, indicating that there are no potential relays in that domain. $\mathcal{T}$ is the union set of $\mathcal{H}$ and $\mathcal{M}$, thus containing all potential relays. For the single-hop relay selection, Bletsas et al. [4] propose following selection criterion:

$$r = \underset{i \in \mathcal{T}}{\operatorname{argmax}} \left(\min \left(h_{S,i}, h_{D_1,i} \right) \right), \tag{1}$$

with r being the selected relay and $h_{S,i}$ and $h_{D1,i}$ being the CSI between S and node i and D_1 and i, respectively.

This selection criteria compares bottlenecks in the context of reliability and chooses as relay the node with the lowest unreliable link. For MHA-Coop-Relaying we compare the best single-hop relay (we just consider $\mathcal{H}$ instead of $\mathcal{T}$ in(1)) with the best multi-hop relay in terms of their minimum CSI. The node with the higher CSI is chosen as current relay:

$$\begin{aligned} r &= \operatorname*{argmax}_{i\in\mathcal{T}} \begin{cases} A(i), & i\in\mathcal{H} \\ B(i), & i\in\mathcal{M} \end{cases} \\ \forall i\in\mathcal{H}: A(i) &= \min\left(h_{S,i}, h_{D_1,i}\right) . \end{aligned} \tag{2}$$

For $B(i)$ we investigate three different policies for finding the best multi-hop relay. All of these policies choose the maximum value of local minimums of CSI from S to nodes in $\mathcal{M}$ and a value depending on the used policy:

- The *min-policy* (3) chooses the smallest CSI from the relay candidate links to D_1 and D_2:

$$\forall i\in\mathcal{M}: B_{\text{min}}(i) = \min\left(h_{S,i}, h_{D_1,i}, h_{D_2,i}\right) \tag{3}$$

- The *max-policy* (4) selects the best CSI of the links from relay candidate to D_1 and D_2:

$$\forall i\in\mathcal{M}: B_{\text{max}}(i) = \min\left(h_{S,i}, \max\left(h_{D_1,i}, h_{D_2,i}\right)\right) \tag{4}$$

- The *harmonic-policy* (5) combines both CSI of the links from relay candidate to D_1 and D_2 using the harmonic mean:

$$\forall i\in\mathcal{M}: B_{\text{harmonic}}(i) = \min\left(h_{S,i}, \frac{2\cdot h_{D_1,i}h_{D_2,i}}{h_{D_1,i}+h_{D_2,i}}\right) \tag{5}$$

B. Direct Transmission Phase

This phase starts with the data transmission from S. Whenever a single-hop relay is selected and D_1 succeeds in receiving the data from S the cooperative transmission phase is skipped. If a multi-hop relay is selected, the cooperative transmission is always conducted and D_1 does not give any feedback of its own reception.

C. Cooperative Transmission Phase

In Fig. 3 we present a flow diagram of the behavior of D_1 after the direct transmission phase. If D_1 is not able to decode the message via direct link it waits for the relay to forward the data. If the relay does not respond within a certain period of time a `NACK` is transmitted to S indicating an outage. If a transmission from the relay is received, D_1 combines it with the data received from S using MRC.

If D_1 decodes the message during direct transmission phase and a multi-hop relay is chosen, D_1 transmits this message instantly to D_2. This is done concurrently with the transmission from R_1 using D-STBCs.

A multi-hop relay which receives data from S always forwards it. Before its transmission, data is encoded using the two antenna space time code. Single-hop relays wait for a positive acknowledge from D_1. If a time-out occurs they relay the data.

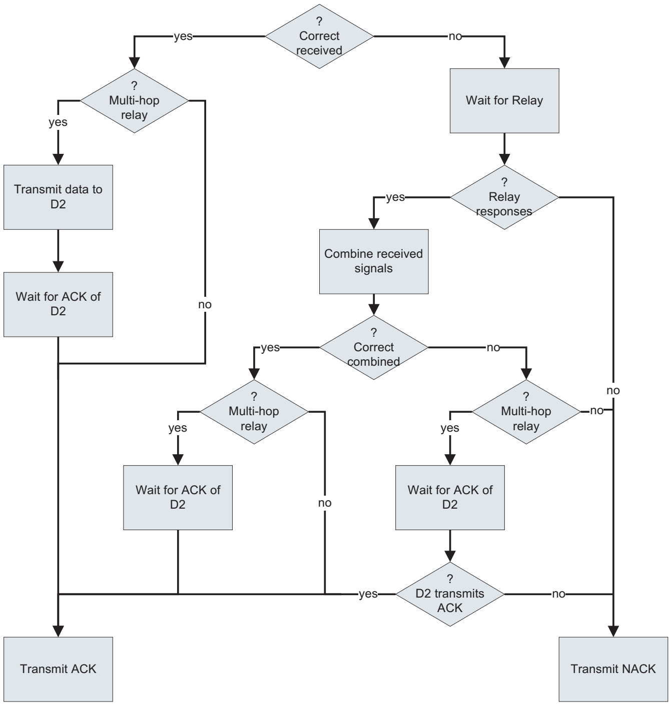

Fig. 3. Cooperative Transmission Phase

D_2 tries to collect as much information as possible for decoding the message. Thus, it tries to overhear the direct transmission of S (compare to [10]). It will receive more useful data during the cooperative transmission phase. Since data transmitted during this phase is encoded by D-STBC, D_2 needs to know the CSI of the links from R_1 and D_1 to itself. However, it can happen that just one of the nodes, D_1 or R_1, can forward the data to D_2. In this case, D_2 needs to know which of them is transmitting to be able to decode the original information. This can be done by comparing the CSI measured during the cooperative transmission with the one obtained for the links to D_1 and R_1 during the relay selection. If the new measured value differs considerably from the old ones, it can be assumed that both nodes are transmitting simultaneously.

In MHA-Coop-Relaying it is not necessary that all intermediate routing nodes receive each message correctly. For example in Fig. 2 it is sufficient that D_2 decodes the message from S. For the overall task of message transmission from S to D_2 it is unimportant that D_1 receives the message. Therefore, acknowledging needs to be adapted for MHA-Coop-Relaying. In the case D_2 is able to receive the message correctly, it transmits an `ACK` to D_1 which forwards it to S. In the case D_2 does not successfully decode the message, D_2 does not transmit an `ACK` after the cooperative transmission and D_1 reports its own success in decoding the message.

V. MHA-COOP-RELAYING: EVALUATION

A. Assumptions and Simulation Environment

We assume that the received signal y at a time instant t can be described by $y(t) = h \cdot x(t) + n(t)$, with x

being the transmitted signal, h the fading coefficient, and n the noise. Our performance studies assume quasi-static flat fading. The fading coefficient h is constant throughout one cooperation process, i.e., during relay selection, direct transmission and cooperative transmission phase. For each process, a coefficient h is chosen randomly from a Rayleigh distribution with parameter $\sigma = \sqrt{L/2}$, with L being the path loss of the observed link. The noise n is modeled by a Gaussian distribution with zero mean and variance $N_0/2$. Further modeling assumptions are:

- Radios cannot transmit and receive at the same time.
- A centralized medium access protocol is assumed.
- CSI are perfectly known at the nodes but are not exploited for transmissions.
- All links are symmetrical.
- Coherent antipodal modulation is used (e.g., BPSK).
- Relays perform decode-and-forward [13].
- MRC is used to combine messages.

The transmission power and the data rate are kept constant in all considered systems. Furthermore, we assume an existing routing protocol to discover and maintain the routes between nodes. The protocol used for relay selection has access to routing information, it knows at least addresses of the next two hops.

B. Simulation Results

We compare MHA-Coop-Relaying with different relay selection policies with hop-by-hop cooperative relaying and direct transmission. For comparison we use a fixed two-hop route with an equal distance d between nodes of the route with d being chosen to provide a Packet Error Rate (PER) of 10^{-3} in the case of AWGN. Potential relaying candidates are uniformly distributed in a square with side length $2d$. Routing nodes S, D_1 and D_2 are aligned at the coordinates $(0, d)$, (d, d) and $(2d, d)$, respectively. Simulations are run until a 99% confidence interval smaller than one percent of the measured values is reached. Simulations are repeated for other node distributions until the 99% confidence interval is smaller than one percent of the averaged values.

In Fig. 4 the outage probabilities of S are depicted for direct transmission, hop-by-hop cooperative relaying and MHA-Coop-Relaying as a function of the number of deployed nodes. An outage occurs whenever a retransmission of a packet from S is necessary – neither D_1 nor D_2 decode the message during the cooperative process. For hop-by-hop cooperative relaying policy (1) is applied. In case of MHA-Coop-Relaying the results for *max*, *min* and *harmonic-policies* are presented. Generally, the outage decreases with increasing node density. The outage probabilities for MHA-Coop-Relaying using *max-policy* and hop-by-hop cooperative relaying are identical and are smaller than in the other policies. The highest outage, besides the one of direct transmissions, is obtained by using the *min-policy*.

Fig. 5 illustrates the 2-hop-progress probability of the different selection policies of MHA-Coop-Relaying. We define a 2-hop-progress as the event D_2 receives a message during a cooperation process initiated by S. The probability of a 2-hop-progress increases with the number of deployed nodes for the *min* and the *harmonic-policy* and decreases in the depicted domain in the case of the *max-policy*.

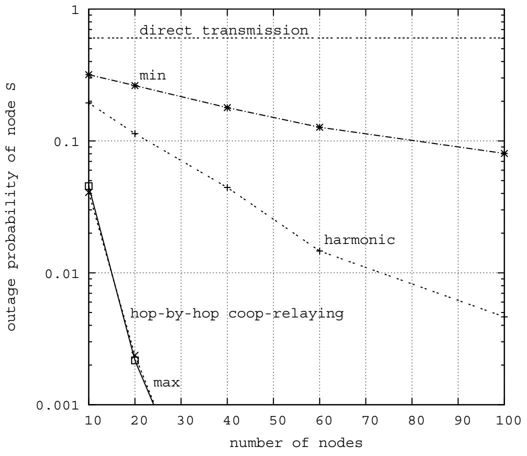

Fig. 4. Outage probabilities of S

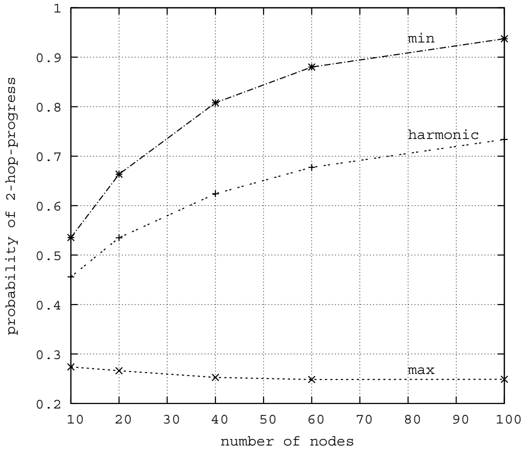

Fig. 5. Two hop progress of selection policies

Fig. 6 depicts the fraction of selected relays as function of their distance to S on the x-axis. The distances are normalized by the hop length d (e.g., D_1 and D_2 have a normalized distance of 1 and 2 from S, respectively). In the case of hop-by-hop cooperative-relaying the selected relays tend to be in a region with equal distances to S and D_1. This is also the preferred region of relays selected by the *max-policy* which explains the identical outage performance of those two schemes. At low node densities nodes are less concentrated in the preferential regions. At high node densities nodes tend to be more concentrated in these regions, augmenting the likelihood of choosing a relay from there. Thus, the probability of selecting relays which are also in transmission range of D_2 is decreasing with increasing node densities. This explains the characteristics of the 2-hop-progress performance of the *max-policy*.

Relays selected by the *min-policy* are likely to be in the

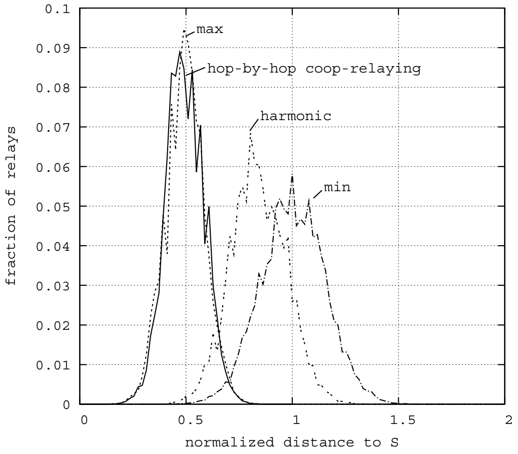

Fig. 6. Fraction of selected relays depending on the distance from S

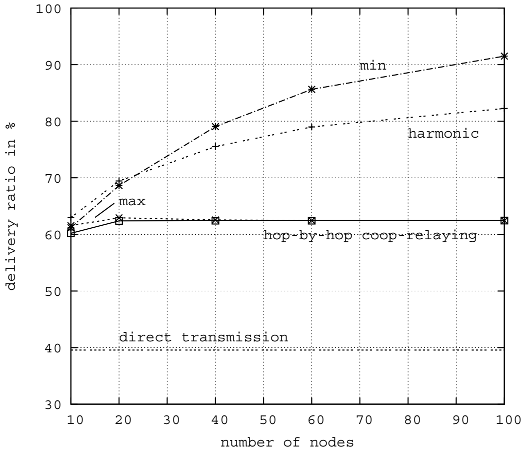

Fig. 7. Delivery Ratio

vicinity of D_1. In that region the CSI from relays to S and D_2 are in average equal. Cooperative transmissions hardly ever benefit from hop gains which explains the higher outage rate compared to the other cooperative schemes.
The *harmonic-policy* combines link qualities from relay candidates to D_1 and D_2 using the harmonic mean. Relays selected by this policy are in the region between the ones from the *max* and the *min-policy*.

For the final performance comparison illustrated in Fig. 7, we use *delivery ratio*, which is defined as the ratio of received messages at D_2 to the number of transmitted messages at S. The high 2-hop-progress probability of the *min-policy* compensates its higher outage liability and achieves above a certain number of deployed nodes the best performance of the examined schemes. As node density increases, the delivery ratio approximates the optimum. When direct transmissions fail, selected relays can immediately adopt the role of the intermediate routing nodes and no additional delays are introduced. Below 23 deployed nodes MHA-Coop-Relaying using the *harmonic-policy* performs better than the *min-policy* because of its overall smaller outage probability. The performance gains of MHA-Coop-Relaying using the *max-policy* are small compared to hop-by-hop cooperative relaying. In sparse networks a minor delivery ratio improvement can be observed.

VI. CONCLUSION

In the work at hand we introduced MHA-Coop-Relaying which exploits synergy effects between cooperative relaying and message routing in wireless ad-hoc networks. Relays are selected by taking route information into account, so that they are in transmission range of three consecutive hops of a routed message. We analyzed three different selection policies and showed that all of them outperform hop-by-hop cooperative relaying. Our simulation results indicate that the *min-policy* is preferable in dense networks but in sparse networks we recommend to use the *harmonic-policy*. Our further work is to investigate MHA-Coop-Relaying in combination with a MAC protocol and different routing algorithms.

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