

Selection Strategies for Relay-Assisted Communication

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Abstract

The deployment of fixed relays will improve communication in wireless networks. Suitably located wireless relays facilitate communication between a source-destination node pair by receiving the source transmission and forwarding it to the destination. In a reasonably dense network, several relays may be available to assist a particular source-destination pair. Deciding which wireless relays should forward the source transmission is not straightforward, though. In particular, relay selection involves resolving tradeoffs between different layers of the OSI protocol stack, including the MAC and physical layers. This article provides an overview of the relay selection problem. We describe two types of strategies for addressing this problem, namely centralized and decentralized approaches, and present both prior work and our contributions for both types of strategies. Our contributions are both highly intuitive and illustrate the importance of system-specific design.

1 Introduction

Relay-assisted communication promises to yield both coverage extension and increased per-user throughput in ad-hoc and cellular networks [1]. The objective of relay-assisted signaling in systems such as cellular and ad-hoc networks is to both increase system capacity and extend user coverage. Recent work [2] has

demonstrated that deploying wireless relays can be a cost-effective solution by avoiding the large capital expenditure associated with base station deployment.

The term “relay-assisted signaling” encompasses several distinct, yet related communication models. One type of relay-assisted communication occurs when a source can communicate directly with an intended destination [3]. This model involves designated relay nodes that assist the destination if it cannot decode the direct transmission from the source. Multihop relaying is another type of relay-assisted communication, where a source cannot directly transmit to an intended destination [4]. In this model, the source can transmit its message through intermediate designated wireless relays until it reaches the destination. Cooperative diversity is a third type of relay-assisted communication, where the network of interest consists of multiple sources that each have their own data to transmit [5]. In this model, the multiple sources cooperate to transmit their messages to a set of destination nodes.

In the three relaying models, the set of relays that will assist a source transmission is typically defined a priori. This neglects the *relay selection problem*. Given a network that consists of several candidate wireless relays, how should the set of source-assisting relays be determined? Should the source enlist the assistance of all of the candidate relays, or is it possible to satisfy a quality-of-service (QoS) constraint at the destination by selecting a subset of the candidate nodes? How would the selection process actually work?

The relay selection problem is both difficult and multi-faceted. One physical layer-based solution is to include the decoding relay with the highest channel gain to the destination in the set of assisting relays, as this relay will forward the source message to the destination more reliably than the other decoding relays. This approach is somewhat myopic, though, and does not consider issues inherent to other layers of the OSI stack. For example, the relay with the best channel to the destination may already be serving data from other sources and will not be able to meet a delay constraint at the intended destination. Another solution is to select the relay that optimizes the balance between the metrics of channel gain and packet transmission delay. This approach, while more informed than the pure channel state solution, may break down in a network of battery-powered nodes if the selected relay needs to enter a sleep cycle to conserve power. The critical difficulty in determining the “optimal” set of assisting relay nodes is the inherent cross-layer nature of this decision.

Given the potential performance and cost-related benefits of relay-assisted signaling, though, it is clear that the relay selection problem needs to be addressed. While it is difficult to determine a set of source-assisting relays that optimize the balance between all system parameters, valuable insights can be gained from simple selection strategies that focus on a subset of the system parameters. Prior work on relay selection [6–8]

adopts this line of reasoning and designs proposed solutions around parameters such as physical-layer inter-node channel gains.

This article summarizes recent work on the relay selection problem. We first present the relaying model that we will employ throughout the rest of the article, which is the direct transmission strategy in [3]. We then describe two classes of proposed solutions to the relay selection problem, namely centralized and decentralized strategies. Finally we discuss prior work on relay selection and present our contributions in both classes of strategies. In the course of our discussion, we will show that our contributions yield valuable insights for relay-assisted network design and deployment.

2 Relay Selection Problem

The relaying model that we consider in the rest of the article is shown in Fig. 1. There are K_r relays distributed throughout the region between the source and the destination. As seen in Fig. 1, the source can communicate directly with the destination. We do not consider the effects of interference and assume that when multiple nodes simultaneously transmit, they perform distributed beamforming so that their signals coherently combine at the destination.

The source initially has a message w that it needs to convey to the destination. In this article, we assume that all K_r relays are synchronized with the impending transmission between the source and the destination. For example, we assume that request-to-send/clear-to-send (RTS/CTS) handshaking accomplishes network-wide synchronization for all decentralized strategies. Given this assumption, each relay is prepared to receive the data transmission from the source.

After the destination receives the data transmission from the source, it attempts to recover w . The destination broadcasts either an ACK or a NACK to the entire network, depending on whether or not it could recover w from the source. If a NACK is transmitted, the source attempts to select a subset of the K_r candidate relays to assist the destination in recovering w . The relay selection problem entails determining this subset of candidate relays.

Another key issue inherent to this problem is that of centralized versus decentralized selection. On the one hand, centralized selection occurs when global network information is collected at the source, which is then used to select the set of assisting relays. On the other hand, decentralized selection reduces the amount of network information at the source and shifts some of the burden of relay selection onto the relays themselves. We now discuss prior work for both types of selection algorithms.

3 Prior Work on Relay Selection

Significant progress has been made in terms of addressing the relay selection problem. While it is impossible to summarize all of the work in this area in this article, we will describe two key papers that highlight the centralized and decentralized nature of relay selection.

In terms of centralized relay selection, Zhao and Valenti propose a hybrid-ARQ based strategy for line networks [7]. They consider a time-slotted model where the source initially broadcasts its transmission to the entire network. If the destination cannot decode the initial source transmission, the network enters a contention phase where all decoding relays compete to assist the source in the next time slot. The contention phase is designed to allow only the decoding relay that is closest to the destination to forward the source transmission in the next time slot. The transmission and contention phases repeat until a timeout limit is exceeded. The proposed strategy supports various types of hybrid-ARQ, including punctured coding and Chase combining.

This algorithm is simple and highly intuitive. It is not clear, though, whether it optimizes any important system metrics such as achieved rate. Also, does the proposed algorithm work equally well for all line network configurations, or do some configurations yield better performance than others? This raises the issue of informed network deployment.

In terms of decentralized relay selection, Bletsas et al propose a timer-based strategy for arbitrary networks [8]. They consider a transmission model with RTS/CTS handshaking between the source and the destination, which allows each listening relay to determine the quality of its end-to-end path between the source and destination. Each relay then sets a timer that is inversely proportional to its end-to-end path quality, and the relay with the timer that expires first notifies the entire network with a flag packet. The transmission of the flag packet causes all of the other relays to drop out of the selection process, which allows the relay with the best end-to-end path to be selected to assist the source. The proposed strategy can be readily integrated into any network that supports RTS/CTS handshaking.

This algorithm is also simple and highly intuitive. Practical physical layer coding and modulation strategies are not discussed in [8], though. What would be the throughput yielded by the proposed algorithm when combined with adaptive modulation and coding? This raises the issue of joint design of selection algorithms and practical coding approaches.

The above questions and issues for both centralized and decentralized relay selection motivate our contributions that will be detailed in the following sections.

4 Centralized Relay Selection

Centralized relay selection occurs when the source collects global network information to select a set of assisting relays. This entails a significant amount of signaling overhead, which restricts its application to certain classes of networks. For example, in a relay-assisted cellular system, the underlying transmission protocol allows the central base station to communicate with all candidate relays.

As described in detail in [9], we have designed a simple and intuitive centralized strategy, which arises from an underlying coding approach illustrated in Fig. 2. The source splits its codeword into two component codewords. All of the candidate relays and the destination attempt to decode the original source codeword. Two signal-to-noise ratio (SNR) thresholds are defined, and a receiving node cannot decode anything if its received SNR lies below the lower threshold. A receiving node decodes one of the component codewords if its received SNR lies between the thresholds, and otherwise it decodes both of the component codewords.

Assuming that the destination cannot decode both of the component codewords from the source in its direct transmission, the source must select relays to assist it. In particular, the relays must assist the destination in decoding as much of the overall source codeword as possible.

We simplify the relay selection problem by focusing on the ergodic achieved rate. In particular, the maximum instantaneous rate is achieved if the destination can decode both component codewords. A smaller rate is achieved if the destination can only decode one of the component codewords, and a zero rate is achieved otherwise. The destination does not request any retransmissions after the relays have assisted it. Our objective in this case is to select a set \mathcal{A} of source-assisting relays to maximize the ergodic achieved rate subject to individual and sum power constraints over the selected relays.

Note that we are focusing on maximizing the ergodic achieved rate, which both minimizes the impact of fading in our relay selection strategy and maximizes the impact of relay positioning. More specifically, the ergodic achieved rate is not a function of the instantaneous channels between any of the nodes in the network. The ergodic achieved rate is a function of the source-to-relay and relay-to-destination distances for each selected relay. Thus, we have simplified the relay selection problem by focusing on path loss.

This motivates the following solution of the simplified relay selection problem: solve for the K_r network locations and the power allocation that maximize the ergodic achieved rate. Then, place the K_r candidate relays in these rate-maximizing locations and select the candidate relays with a non-zero power allocation.

One might then ask: how can this optimal strategy be applied to a fixed network? The ergodic achieved rate is a smooth function of the position for each selected relay, which implies that the achieved rate should

smoothly decrease away from any of the rate-maximizing network locations. This motivates the following strategy: find the number of relays m^* selected by the optimal strategy. Then, choose the closest relays to any of the rate-maximizing locations until m^* relays have been selected. This proximity-based selection algorithm, while not necessarily optimal, further simplifies the relay selection problem.

While the relay selection problem has been simplified to a large extent thus far, it is generally impossible to efficiently solve for the K_r rate-maximizing network locations. This motivates yet another strategy that is based on a three-node line network configuration. The idea is to solve for the rate-maximizing relay location on this line and then select the m^* relays that are closest to this location. The algorithm is presented below.

Algorithm 1. *Single Fan Out*

Step 1: Maximize the polynomial ergodic rate to find the optimal single-relay location.

Step 2: Sort the set of relays in ascending order of their proximity to the single-relay location.

Step 3: Select the closest relay to the single-relay location that has not been selected.

Step 4: If m^* relays have been selected, allocate equal power to them. Otherwise, go to Step 3.

The various simplifications of the original relay selection problem motivate intelligent network deployment based on knowledge of the underlying topography.

5 Decentralized Relay Selection

In contrast to centralized relay selection, decentralized selection occurs when the source collects partial network information. This is well-suited for applications that require minimal signaling overhead. For example, in a sensor network, battery-powered relays need to conserve transmit and receive energy.

As described in detail in [10], we have designed a decentralized selection strategy that is readily amenable to practical system deployment. Our strategy relies on opportunistic relay feedback. We can see the medium access control (MAC) layer framing structure for our protocol in Fig. 3.

We simplify the selection process by choosing a single relay to assist the source. Only a subset of the candidate relays can contend in a random-access fashion for selection. Each contending relay has both recovered the source message w and has a channel gain to the destination above a threshold η_{opp} .

After the destination broadcasts a NACK message, the network enters a contention phase, which is composed of a set of minislots. During each minislot, a contending relay sends an ACK message to the

source with a certain probability. In each minislot, if either no contending relays or at least two contending relays send ACK messages, unsuccessful contention occurs during that minislot. Successful contention occurs during a minislot if exactly one contending relay sends an ACK message.

After the contention phase, the source randomly selects one of the successfully contending relays to forward parity information to the destination. If no relays have successfully contended, the source transmits parity information to the destination. The entire process repeats until the destination recovers w or a timeout limit is exceeded.

We now present an underlying transmission strategy and an improvement for the proposed algorithm.

5.1 RCPC Signaling

We consider rate-compatible punctured convolutional (RCPC) coding, where the source chooses rates $\{R_1, R_2, \dots, R_m\}$ from a RCPC family and $R_1 > R_2 > \dots > R_m$. The rate- R_m code is used to encode w as a codeword $\mathbf{x}(w)$. During the initial direct transmission, the source sends a subset $\mathbf{x}_1(w)$ of the bits in $\mathbf{x}(w)$ to the destination, where $\mathbf{x}_1(w)$ forms a codeword from the rate- R_1 code.

If the destination cannot recover w based on the rate- R_1 code, relay selection occurs. Then, the selected relay transmits a subset $\mathbf{x}_2(w)$ of the bits in $\mathbf{x}(w)$ such that $\mathbf{x}_1(w) \cup \mathbf{x}_2(w)$ forms a codeword from the rate- R_2 code. The destination then combines the transmissions from the source and the selected relay to recover w based on the rate- R_2 code. The entire process repeats either until the destination recovers w or cannot recover w after $\mathbf{x}(w)$ is transmitted. This RCPC strategy highlights the underlying hybrid automatic-repeat-request (ARQ) framework for our proposed selection algorithms.

5.2 Channel Feedback for Refining Decentralized Selection

To improve our proposed algorithm, we can append a flag bit to the ACK message from each contending relay. The flag bit is set to '1' only if the contending relay has a channel gain to the destination that exceeds β_{opp} for $\beta_{opp} > \eta_{opp}$. As in our original algorithm, successful contention occurs during each minislot if exactly one contending relay sends an ACK message to the source.

After the contention phase concludes, the source randomly selects one of the successfully contending relays that sent a flag bit of '1' with probability $q > 0.5$ or any other successfully contending relay with probability $1 - q$. This improvement biases the relay selection process towards the contending relays with the strongest channel gains to the destination.

6 Simulation Results

In this section we present simulation results that lend additional insight for our proposed centralized and decentralized strategies. Note that if the source uses a transmit energy that yields an average SNR γ at the destination, then all selected relays use a transmit energy that yields an average SNR γ at the destination.

Fig. 4 shows how the ergodic achieved rate varies with the number of selected relays for our proposed centralized selection algorithm, which is labeled as *Single Fan Out*. For the purposes of comparison we also plot the ergodic achieved rate of a strategy labeled as *Random Relays*, which randomly selects m^* of the candidate relays. As mentioned in the previous paragraph, we impose a sum power constraint on the selected relays which is the same as the source power, accounting for the slight decrease in the achieved rate for the *Single Fan Out* with $m^* = 4$ relays. Along with outperforming the *Random Relays* strategy, the *Single Fan Out* strategy yields its largest increase in achieved rate when going from $m^* = 1$ to $m^* = 2$ selected relays. This arises from the increased relay-induced spatial diversity.

Fig. 5 shows the throughput yielded by our proposed decentralized selection algorithm, which is labeled as *ID*. Note that the proposed flag bit modification to the *ID* strategy in Section 5.2 is labeled as *ID-CSI-1*. For the purposes of comparison we also plot the throughput of a strategy labeled as *Best Gain*, which always selects the decoding relay with the best end-to-end path between the source and the destination. A decentralized version of the *Best Gain* strategy was proposed in [8]. We see that the flag bit modification in Section 5.2 closes the performance gap between our contention-based algorithm and the *Best Gain* algorithm. Also, note that our contention-based algorithm is readily amenable to practical implementation via the use of punctured coding techniques, while practical coding is not discussed in [8].

7 Conclusion

In this article we have introduced the relay selection problem. We have discussed the inherent cross-layer nature of this problem and the difficulties that arise from inter-layer interactions. Through the presentation of centralized and decentralized selection algorithms, we have demonstrated the utility of problem simplification with the aim of obtaining valuable insights and intuition. In particular, our centralized algorithm highlights the importance of topography-informed network deployment, while our decentralized algorithm highlights the importance of amenability to practical implementation.

It should be noted that due to a plethora of potential network applications, it may be more efficient

to consider network-specific selection algorithms as opposed to finding an algorithm that is optimal for all possible networks. For example, sensor network designers may want to focus on minimizing power consumption and signaling overhead, while relay-assisted cellular network designers can focus more on throughput maximization. Regardless of the specific algorithm employed, though, intelligent relay selection will prove invaluable to next-generation wireless systems.

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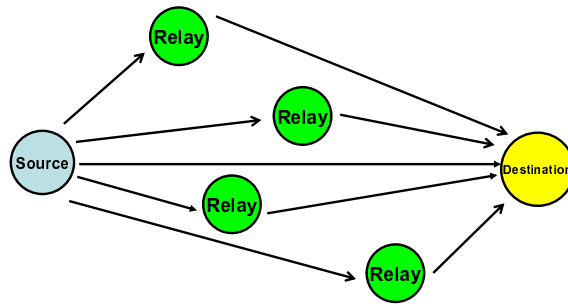


Figure 1: Relay network with direct transmission.

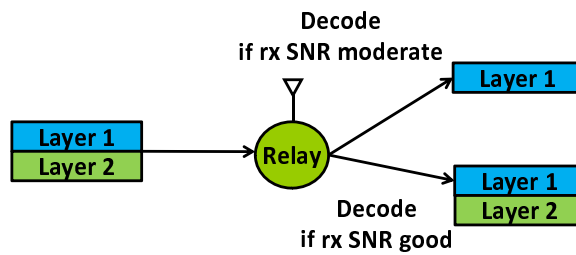


Figure 2: Two-level superposition coding.

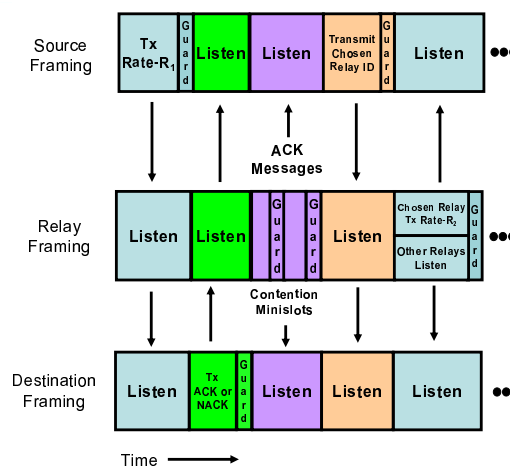


Figure 3: Framing structure for proposed decentralized selection algorithm.

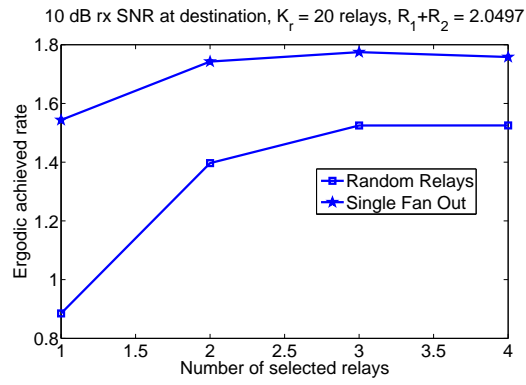


Figure 4: Ergodic achieved rate of proposed centralized selection algorithm.

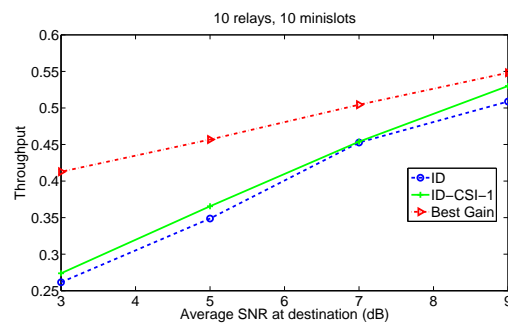


Figure 5: Throughput of decentralized selection algorithms.