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Optimal opportunistic routing and network coding for bidirectional wireless flows ☆

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ABSTRACT

There is growing interest in recent years in routing methods for wireless networks that leverage the broadcast nature of the wireless medium and the ability of nodes to overhear their neighbors' transmissions. Such methods include *opportunistic routing (OR)*, which generally choose the next hop on a routing path only after the outcome of the previous transmission is known; and wireless *network coding (NC)*, which linearly combines packets from different flows coexisting in the network. In this paper, we study the potential benefits of forwarding schemes that combine elements from *both* the OR and NC approaches, when traffic on a bidirectional unicast connection between two nodes is relayed by multiple common neighbors. We present a theoretically optimal scheme that provides a lower bound on the expected number of transmissions required to communicate a packet in both directions as a function of link error probabilities, and demonstrate that this bound can be up to 20% lower than with either OR or NC employed alone even in a small network. Using simulation, we further explore the control overhead in a direct implementation of the scheme with a simple coordination mechanism and show that the optimal bound can be closely approached for a wide range of link error rates.

1. Introduction

The majority of routing protocols employed in multihop wireless networks are based on the traditional layered approach, using shortest-path and similar graph theory-based algorithms which view every wireless channel between two nodes as a "link" in the same sense as in wired networks. However, in general, unless fine-tuned directional antennas are employed, wireless transmissions can be overheard by additional unintended nodes in the vicinity of the sender and receiver, causing interference to their own communications and resulting in additional constraints on links that may not be used simultaneously. This fact has led to considerable research into methods to overcome the interference and maximize network capacity, ranging from channel assignment methods based on coloring of the link conflict graph ([2] and references therein), to space–time scheduling methods such as STDMA [3].

In recent years, there has been growing recognition of the broadcast nature of the wireless medium as a virtue rather than a vice, with an increasing number of studies proposing ways to exploit the ability to overhear neighboring nodes' transmissions. Most of the related research has been in the physical layer, with considerable progress achieved on *cooperative relaying* methods to improve channel capacity in a single-hop setting (cf. [4] for a detailed overview). At higher layers, which are the focus of this paper, the proposed methods for leveraging the wireless overhearing capability can be broadly classified into two major categories: opportunistic routing and wireless network coding. In *opportunistic routing (OR)*, the next-hop forwarding node is chosen on-the-fly, rather than deter-

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mined in advance by a routing protocol. This is exemplified by the ExOR protocol [5], where batches of packets are simply broadcast without acknowledgments; after every batch, each neighbor (in a predetermined priority order) forwards the packets it has successfully received, skipping those that it could overhear to be already forwarded by other neighbors. In *network coding (NC)*, data packets from different flows are mixed, thereby allowing a single transmission to hold different information content for different receivers. For example, the COPE protocol [6] illustrates how the number of transmissions is reduced in a bidirectional flow between a pair of endpoints via one or more intermediate relays, when the relays can broadcast bitwise-XOR combinations of messages from both sides (rather than forwarding each one separately), allowing each endpoint to recover the other's message by XOR-ing it again with its own.[1]

While both OR and NC approaches have a similar goal, namely to reduce transmissions by exploiting the free broadcasting feature in wireless networks, they are unrelated techniques that target different network conditions. Indeed, opportunistic routing is valuable in low-quality wireless environments, where channels have high error rates and volatility (e.g. due to fading). On the other hand, network coding achieves its best performance improvement with perfectly error-free channels, and is highly sensitive to errors. This naturally raises the question whether forwarding schemes that combine elements from both techniques may achieve a further performance gain in practical networks, with "medium"-quality channel conditions that are between the above extremes. A typical scenario is shown in Fig. 1, with two nodes (A, B) that engage in a bidirectional connection, where any of their multiple neighbors can potentially forward their packets. It is clear in this case that neither a pure OR method (e.g. ExOR), used independently in both directions without accounting for coding opportunities, nor a pure NC method (e.g. COPE) used with a single pre-selected neighbor, will achieve the best outcome if the link error rates are medium-to-high.

Our contribution in this paper is as follows. First, we demonstrate that, in general, naïve opportunistic network coding methods are sub-optimal unless the network is symmetrical (i.e. all neighbor nodes have identical link quality to both endpoints), and may even perform worse than NC over a single pre-chosen neighbor. Motivated by the above observation, we then formally define an *optimal* forwarding scheme as one that minimizes the expected total number of data transmissions required to deliver one packet in each direction of the flow. The key distinguishing features in the schemes we consider are that (1) the forwarding decision may be based on the full reception state of all nodes, not only the number of coding opportunities; and (2) we allow opportunistic forwarding to be applied *after* network coding, i.e. a node may retransmit a coded packet even if it is unable to decode its components by itself. We present a dynamic programming algorithm that finds the optimal scheme in a generic network instance with given link error rates, and demonstrate numerically that, even in a simple network with two intermediate relays, the expected number of transmissions can potentially be improved by a further 20% from existing approaches. Since the optimal scheme requires perfect knowledge of the set of packets received in every node at all times, it provides a lower bound on the average number of transmissions that can be achieved with any scheme in practice. Subsequently, we study the performance of an implementation of the optimal scheme with a simple coordination mechanism, where all nodes report the reception state in a series of acknowledgments after every data packet. We show via simulation that the performance of the scheme remains robust even under relatively high loss rates of coordination messages (acknowledgments), and that most of the benefit of the theoretical optimal scheme can still be achieved even after the coordination overhead is taken into account.

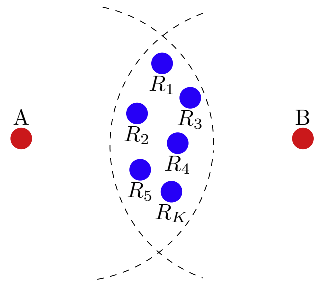

Fig. 1. Bidirectional communication with multiple neighbors.

The rest of this paper is organized as follows. After reviewing the related literature in Section 2, we present the system model and formally define optimal forwarding schemes in Section 3. We present the dynamic programming algorithm for finding the optimal scheme in Section 4, and illustrate the resulting performance numerically in Section 5. In Section 6, we consider the impact of the coordination overhead, and in particular of possible losses of coordination messages, on the resulting performance. Section 7 concludes the paper and discusses some directions for future extension of our results.

2. Related work

The concept of opportunistic routing dates back to the Selection Diversity Forwarding (SDF) proposal [7], where each packet is broadcast with a list of potential next hop forwarders; neighbors that overhear the packet and find themselves on the list reply with acknowledgments that (optionally) contain their forward link state information, which is then used by the source to choose the best next hop. Some later proposals, such as link-layer anycast [8] and Geographic Random Forwarding (GeRaF) [9], are essentially variations on the same idea that use RTS/CTS exchanges, instead of actual data packets, to determine the next hop. Opportunistic routing methods became popular after the demonstration of the performance boosts achieved by the ExOR protocol [5], in which there is no ex-

[1] The idea is not limited only to bidirectional flows between a pair of endpoints; generally, NC can be applied on packets from several flows intersecting at a common node, provided that packets from each flow can be overheard by all the next-hop nodes of all other flows.