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MAC-layer proactive mixing for network coding in multi-hop wireless networks

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ABSTRACT

Network coding is a recent research topic in wireless networking. By combining multiple packets in a single broadcast transmission, network coding can greatly improve the capacity of multi-hop wireless networks. Packet mixing, when applied with traditional routing, can only be performed at the junctions of the paths determined by the routing module. This limits significantly the coding opportunities in the network. This paper presents a novel MAC-layer mixing method, named BEND, which proactively seizes opportunities for coding. Without relying on fixed forwarders, BEND allows each node in the neighborhood to be a potential coder and forwarder and coordinates their packet transmissions for higher coding gain. By taking advantage of redundant copies of a packet in the neighborhood coding repository, the number of mixing points, and thus the coding opportunities, can be significantly increased. This high coding gain is verified by our simulation studies.

1. Introduction

Network coding is a relatively new research area in communication networks. It enables data flows to approach the Shannon Capacity Limit individually by splitting and combining information at intermediate nodes in the network [6]. Such operations on information flows can be implemented as simple linear combinations over some finite field. Two fundamental benefits of network coding are greater throughput and higher robustness. These in turn translate to energy efficiency and fault tolerance in multi-hop wireless networks. Current research on network coding is transitioning from theoretical frameworks to increasingly practical systems.

The way that network coding increases the throughput of a multi-hop wireless network can be explained using a simple example of a 5-node network (Fig. 1) [10]. Here, nodes X, B, and O are within each other's transmission range; so are nodes Y, A, and O. Suppose that node X has a packet p_1 for Y via O and node A has a packet p_2 for B via O. In a traditional non-coding approach (Fig. 1a), after O's reception of packets p_1 and p_2, it relays these packets separately. Thus, a total of 4 transmissions are required. In contrast, if network coding is used (Fig. 1b), after O's reception of p_1 and p_2, it transmits XOR combination $p_1 \oplus p_2$ in the wireless channel. Since node B (Y, respectively) is within the transmission range of X (A, respectively), it has also overheard p_1 (p_2, respectively). With node B's knowledge of p_1 (Y's knowledge of p_2, respectively), it can reconstruct p_2 (p_1, respectively) by applying XOR $\oplus$ to the two receptions from X (A, respectively) and O. Consequently, only 3 transmissions are needed for the packet exchange. More generally, network coding can be used in such scenarios as a path transporting two flows in reverse directions (Fig. 2a) and combining multiple packets (Fig. 2b).

In a previous wireless coding approach, COPE [10], packet mixing can only be performed at the joint nodes of the paths determined by the routing module, such as the focal nodes in Figs. 1 and 2. This significantly limits the coding opportunities in the network. Clearly, in order for network

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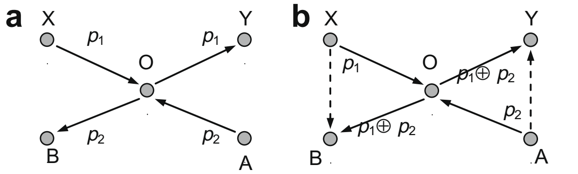

Fig. 1. Wireless network coding illustrated: (a) regular exchange; and (b) coded exchange.

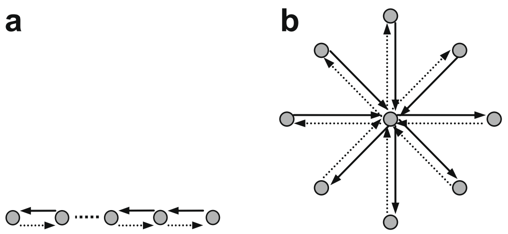

Fig. 2. More general coding scenarios: (a) chain; and (b) wheel.

coding to be useful in multi-hop wireless networks, there should exist sufficient opportunities to mix traffic flows in the network. Currently, this is achieved by concentrating flows at certain nodes in the network. This could be implemented via centralized coding-aware routing [12] or using coding-aware metrics [14]. As a result, some nodes in the network are favored by the routing module so that much traffic is routed through them for more coding opportunities. However, these approaches can be problematic. First, a network layer implementation of such a "traffic-sensitive" routing protocol is unrealistic in multi-hop wireless networks since traffic flows change over time. Routing that depends on the correlation of dynamic flows has been shown impractical, even in the Internet where the traffic is much more statistically stable over time [1,11]. Further, concentrated traffic inevitably overloads intermediate nodes in the network. These overloaded forwarders can be a vulnerable point because of higher risk of battery-energy depletion and information leaks. Other problems of traffic concentration include increased queuing delay and thus end-to-end delay, danger of buffer overflow, and further adversary effects to TCP flows. At the link layer, on one hand, traffic concentrated within a neighborhood worsens channel contention in the area. On the other hand, if flows are forced to go through a specific node, this overloaded node is bound to drop packets which it is unable to handle. This is especially problematic in multi-hop wireless networks because dropping packets along a path means invalidating the work performed by earlier forwarders and wasting the network bandwidth already consumed. The benefit of being able to scatter flows through multiple forwarders dynamically at the link layer in a multi-hop wireless network is called "*diffusion gain*" in the rest of the paper.

Indeed, traffic separation rather than concentration has been a key approach to higher throughput in mesh networks. When flows are more evenly distributed in the network, the interference among them is minimized and the network capacity limit can be approached [7]. Hence, traffic concentration in network coding conflicts the need of traffic separation. Does traffic mixing for network coding inevitably imply traffic concentration? Not really.

In this article, we present BEND, a MAC layer solution to practical network coding in multi-hop wireless networks. It is the first exploration of the broadcasting nature of wireless channels to proactively capture more coding opportunities. As a matter of fact, the result of a node's transmitting a packet is that all of its neighbors can potentially receive it, and such redundancy of packets should and can be utilized. In BEND, any node in the network can code and forward a packet even when this node is not the intended MAC receiver of the packet, if the node believes that doing so it can lead the packet to its ultimate destination. Essentially, BEND considers the union of the contents of the interface queues of the nodes within a neighborhood collectively, i.e. a "neighborhood coding repository", whereas traditional mixing methods, e.g. COPE, only process "individual coding repositories" at separate nodes. Our experimental evaluation shows that BEND creates significantly more coding opportunities in a dynamic and adaptive fashion with minimum assumptions on the routing protocol compared to prior work. The contributions of BEND are:

(1) It makes network coding practical by proactively seizing such opportunities and by using them intelligently.
(2) This is achieved without concentrating traffic flows or overloading specific nodes. It exploits the broadcasting nature of wireless channels by utilizing redundant packet copies within the proximity of a node. In this way, it achieves both diffusion gain and coding gain, which are conflicting in the existing solutions.
(3) It exploits another dimension of multi-user diversity in wireless networks. Multi-user diversity has proved to be effective in achieving higher aggregate system performance in wireless communications. Here in BEND, multi-user diversity is in the sense of diversity of queue contents at different forwarders.

The rest of the paper is organized as follows. In Section 2, we review the basic idea of BEND to help readers with the subsequent relatively involved details. We then highlight the design objectives of BEND and the challenges in Section 3. The design details are presented in Section 4. The effectiveness of BEND is tested by the experiments in Section 5. After digesting the details, the readers are walked through a discussion in the context of some recent related work on practical network coding and on exploration of the broadcasting nature in multi-hop wireless networks in Section 6. We conclude this paper in Section 7 and speculate on future research to further explore BEND.

2. Basic idea

The gist of BEND is to utilize overheard packets that are otherwise discarded in conventional networking protocols.