BEND: MAC-Layer Proactive Mixing Protocol for Network Coding in Multi-Hop Wireless Networks

Jian Zhang
ECE Department
Rutgers University
New Brunswick, NJ, U.S.A
+1 732 445 6399
jianz@caip.rutgers.edu

Yuanzhu Peter Chen
Department of Computer Science
Memorial University of Newfoundland
St. John's, Canada
+1 709 737 6944
yzchen@cs.mun.ca

Ivan Marsic
ECE Department
Rutgers University
New Brunswick, NJ, U.S.A
+1 732 445 6399
marsic@caip.rutgers.edu

ABSTRACT

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. In BEND, any node can code and forward a packet even when the node is not the intended MAC receiver of the packet, if the node believes that in doing so it can lead the packet to its ultimate destination. Essentially, BEND considers the union of all interface queue contents at the nodes within a neighborhood, i.e. a "neighborhood coding repository", whereas traditional mixing methods only process "individual coding repositories" at separate nodes.

Categories and Subject Descriptors

C.2.2 **[Computer-Communication Networks]**: Network Protocols – *protocol architecture (OSI Model)*; C.2.1 [Computer-Communication Networks]: Network Architecture and Design – *wireless communication*.

General Terms

Design, Performance

Keywords

Wireless network, Multi-hop, Network Coding, MAC

1. INTRODUCTION

Network coding enables data flows to approach the Shannon Capacity Limit individually by splitting and combining information at intermediate nodes. In a wireless coding approach called COPE [2], packet mixing can only be performed at the joint nodes of the paths determined by the routing module, e.g. the focal nodes, which significantly limits the coding opportunities. In this work, we solve this problem with BEND, which proactively captures more coding opportunities via opportunistic mixing and forwarding on MAC layer.

2. DESIGN OF BEND

The basic operation of BEND is illustrated by a simple example in Figure 1, although BEND works under much more general conditions. In Figure 1(a), node *X* has packet p_1 for node *Y* that is two hops away, and *U* has p_2 for *V*, also two hops away. The forwarders determined by the routing protocol are nodes *A* and *C*, respectively. We assume that three other nodes, B_1, B_2, and B_3, are also in the range of *X*, *Y*, *U*, and *V*. When a packet, say p_1 or p_2, is handed from the network layer down to the MAC layer, its header is enhanced to include not only the address of the next-hop node but also that of the following-hop node. Such information can be obtained from the routing module. After node *X*'s packet p_1 and node *U*'s p_2 are transmitted, p_1 is received by nodes *A* (intended forwarder), B_1, B_2, B_3 and *V*, and p_2 is received by B_1, B_2, B_3, *C* (intended forwarder), and *Y*. Packet p_1 is placed in the queues of nodes *A*, B_1, B_2, and B_3 for they are all neighbors of p_1's second-next-hop (node *Y*) as indicated by the packet header. It is, otherwise, buffered by *V* for future decoding. Similarly, p_2 is queued at nodes B_1, B_2, B_3 and *C* and buffered at *Y*. Nodes B_1, B_2 and B_3 can choose to transmit $p_1 \oplus p_2$ if they determine that the coded packets can be correctly decoded by their second-next-hop neighbors. All of the intermediate nodes *A*, B_1, B_2 and B_3 and *C* could forward the packet(s) in their queues, coded or not. To expedite the packet forwarding, coded packets are transmitted with a higher priority without starving uncoded packets. Assume that node B_2 wins the channel and transmits $p_1 \oplus p_2$ (Figure 1(b)). The second-next-hop nodes *V* and *Y* receive the XORed packets and are able to decode them using the packets stored in their buffer. Then they instantly reply with an ACK in a "distributed bursty" way in the order specified by the enhanced MAC header. Such a reliable link-layer broadcasting mechanism also helps to remove the packets queued at the intermediate nodes to avoid packet duplication (Figure 1(c)).

3. PRELIMINARY EXPERIMENTS

We test BEND's performance and compare it with IEEE 802.11 and COPE-Sim (an ns2 implementation of COPE) in a 3-tier network, where tiers 1 and 3 each consist of 4 nodes, and tier 2 may contain 1, 2, 3, or 4 nodes, referred to as 4-1-4, 4-2-4, 4-3-4, and 4-4-4, respectively.

We measure the aggregate throughput at the four UDP receiving agents to compare BEND, COPE-Sim and 802.11 in the four topology variants. As seen in Figure 2(a), 802.11 achieves a higher throughput for increasing number of tier-2 nodes thanks to the higher diffusion gain due to more forwarders. For COPE-Sim, when it enjoys higher diffusion gain introduced by additional tier-2 nodes, it loses its coding power due to load scattering. BEND,

MobiHoc'08, May 26–30, 2008, Hong Kong SAR, China.
ACM 978-1-60558-073-9/08/05.

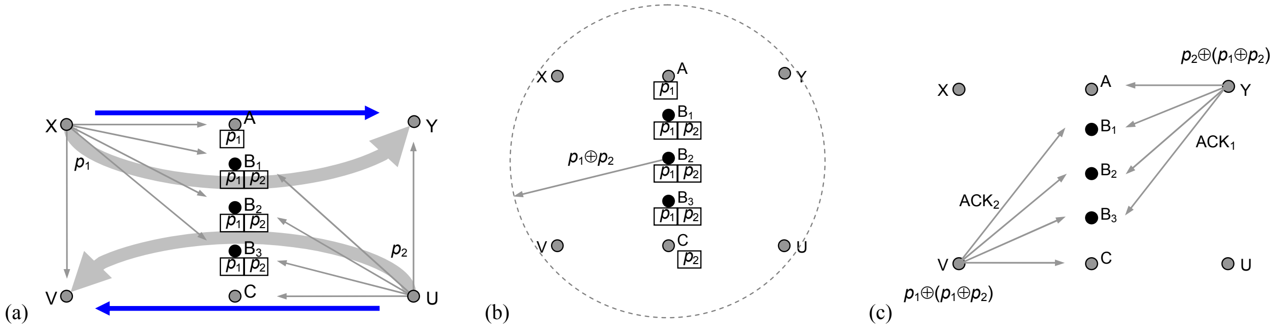

Figure 1. BEND – Design overview

however, immediately uses the maximum benefit since adding the second forwarder. For the 4-1-4 topology, where all flows go through a single tier-2 node, both COPE-Sim and BEND can almost double the throughput of 802.11 by applying network coding at this forwarder. In contrast, when there are at least 2 tier-2 nodes to provide alternative paths, BEND nearly doubles throughput gain over 802.11 compared to COPE-Sim. This consistently higher gain of BEND is realized by allowing tier-2 nodes to transmit more coded packets even when the flows do not cross at a single node as in the 4-1-4 configuration. To verify this, we record the coding ratio, the number of packets forwarded as coded to the total number forwarded by the tier-2 nodes, for the four topology variants (Figure 2(b)).

BEND solves COPE's dilemma of simultaneously achieving coding gain and diffusion gain. For COPE-Sim running in the presence of multiple tier-2 nodes, either concentrating flows at a particular node provides the coding gain or scattering flows among the forwarders provides the diffusion gain, but not both. For example, we take a set of 200 pairs of simulation of 802.11 and COPE-Sim over the 4-3-4 network, each pair records the performance of 802.11 and COPE-Sim using the same routes determined by DSDV (Figure 2(c)). Clearly, there is a negative correlation of 802.11's throughput and the number of coded transmissions of COPE-Sim. For BEND, the three tier-2 nodes work as an entity by processing the neighborhood coding repository among themselves, showing a persistently higher throughput gain than COPE-Sim.

4. DISCUSSION AND EXTENSION

BEND aims at achieving a high coding ratio for each stage of forwarding; it only requires local information and a low implementation overhead. Since it uses a per-packet decision for coding, it is more responsive to the dynamics of traffic. BEND also takes advantage of packet redundancy in the network by opportunistic forwarding. The coding chances are greatly improved with multiple potential forwarders instead of one. Moreover, coding-aware routing needs to consider not only the coding gain by combining traffic flows but also their consequential interference. These two forces have been difficult to balance with traditional methods of fixed-path routing. The idea of BEND resembles that of ExOR [1]. In ExOR, any neighbor en route can forward an overheard data packet as long as it finds that such an opportunistic forwarding leads the packet closer to its destination. Unlike ExOR, which prioritizes forwarders by their distances to the destination, BEND favors those forwarders with a chance to transmit coded packets.

5. REFERENCES

[1] S. Biswas and R. Morris. 2005. ExOR: Opportunistic routing in multi-hop wireless networks. In Proceedings of the conference on Applications, technologies, architectures, and protocols for computer communications (Philadelphia, Pennsylvania, USA, 2005). SIGCOMM'05. ACM Press, New York, NY, 133 – 144. DOI=http://doi.acm.org/10.1145/1080091.1080108

[2] S. Katti, H. Rahul, W. Hu, D. Katabi, M. Medard, and J. Crowcroft. 2006. XORs in The Air: Practical Wireless Network Coding. In Proceedings of the conference on Applications, technologies, architectures, and protocols for computer communications (Pisa, Italy, 2006). SIGCOMM'06. ACM Press, New York, NY, 243 - 254. DOI=http://doi.acm.org/10.1145/1159913.1159942

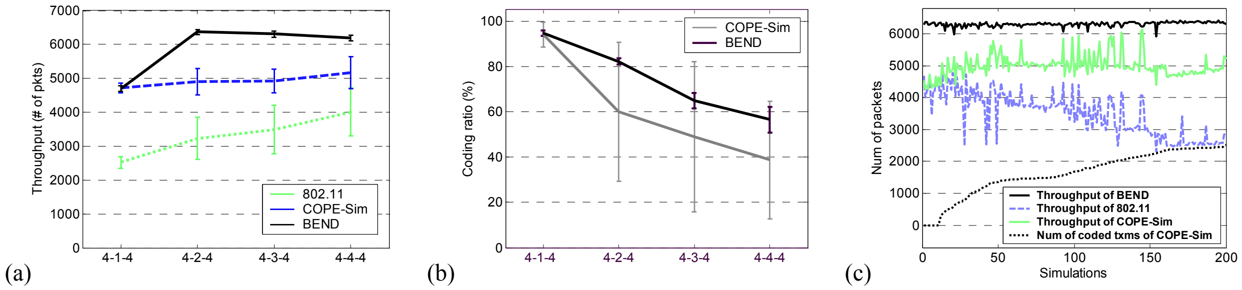

Figure 2. (a) Throughput (b) Coding ratio (c) Negative correlations between coding gain and diffusion gain