Coding Opportunity Aware Backbone Metrics for Broadcast in Wireless Networks

Shuai Wang[1] Guang Tan[2] Yunhuai Liu[3] Hongbo Jiang[4] Tian He[1]

[1]Department of Computer Science and Engineering, University of Minnesota, U.S.
[2]SIAT, Chinese Academy of Sciences, China
[3]Third Research Institute of the Ministry of Pubic Security, China
[4]Department of EIE, Huazhong University of Science and Technology, China
{shuaiw,tianhe}@cs.umn.edu, guang.tan@siat.ac.cn, {yunhuai.liu, hongbojiang2004}@gmail.com

***Abstract*—Reducing transmission redundancy is key to the efficiency of wireless network broadcast. A standard technique to achieve this is to create a *network backbone* consisting of a subset of nodes that are responsible for data forwarding, while other nodes act as passive receivers. On top of this, network coding (NC) is often used to further reduce unnecessary transmissions. The main problem with this backbone+NC approach is that the backbone construction process is blind of what is needed by NC, thus may produce a structure with little benefit to the NC algorithms. To address this problem, we propose a Coding Opportunity Aware Backbone (COAB) construction scheme, which seeks to maximally exploit coding opportunities when selecting backbone forwarders. We show that the better informed backbone construction process leads to significantly increased coding frequency, at minimal cost of localized information exchange. The highlight of our work is COAB's broad applicability and effectiveness. We integrate COAB with ten state-of-the-art broadcast algorithms, specified in eight publications [1]–[8], and evaluate it with prototype implementations with 30 MICAz nodes. The experimental results show that our design outperforms the existing schemes substantially.**

I. Introduction

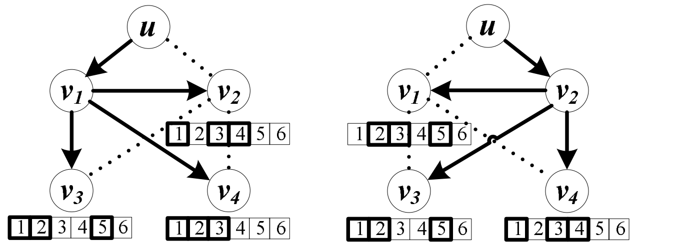
Reducing transmission redundancy is key to the energy efficiency of broadcast in wireless ad hoc networks. Existing optimization schemes (e.g., [1]–[9]) can be divided into two categories: probabilistic and deterministic. In the probabilistic approach [9], each node rebroadcasts the packet to its neighbors with a given forwarding probability. In contrast, deterministic approach predetermines particular nodes that forward the broadcast packet. In this method, a virtual network backbone is created. Nodes on the backbone are called the *forwarders*, which take the responsibility of delivering packets to their neighbors, while other nodes act as passive receivers. The backbone can be constructed with tree based method [3], cluster based method [1], [7], [8], and pruning based method [2], [4]–[6].

On top of the network backbone, network coding (NC) techniques can be used to further reduce unnecessary transmissions. Originally proposed by R. Ahlswede et al. [10], this technique has been adapted to support broadcast applications in wireless networks [11]–[16]. In these work, two coding strategies, i.e., COPE type network coding (XOR) [17] and random linear network coding (RLNC) [18], are used. XOR coding strategy is used to apply to the deterministic approach [13], [16], while RLNC is usually considered upon the probabilistic approach [11], [12].

In this paper, we consider the combination of NC with the deterministic approach. The main problem with traditional designs is that the backbone construction process is independent of NC, implying that it is unaware of what is needed by NC. This may lead to a network structure of which NC can take little advantage. It is known that the power of NC depends on how many coding opportunities exist in the network [19], which is a function of packet reception status at the nodes. If such status information can be used by the backbone construction algorithm in such a way that the coding opportunities are maximized, then we can hopefully obtain more benefit from NC.

COAB contains a novel forwarder selection method to choose which nodes should broadcast packets. At the heart of this method is a metric called the *per-link covering cost*, which considers not only link quality, but also the reception status of neighbors. Thus we can estimate the coding opportunity and measure the broadcast efficiency of each link with NC in advance. With the help of the metric, COAB does not select forwarders until it calculates the best forwarding structure under current reception status. This deferred choice gives each broadcast packet multiple opportunities to make progress. As a result, COAB finds more opportunities for NC to save transmissions.

The major contribution of our work is COAB's broad applicability and effectiveness. The forwarder selection strategy can be easily combined with existing backbone construction algorithms to make the broadcast more efficient. We augment ten backbone construction algorithms, i.e., (i) tree based method [3], (ii) cluster based method [1], [7], [8], and (iii) pruning based method [2], [4]–[6], with our design. We evaluate the energy efficiency of COAB with prototype implementations with 30 MICAz nodes. Experimental results show that compared to the traditional backbone schemes, COAB saves up to 50% of the broadcast transmissions. Our algorithm increases the coding opportunities by up to 50% compared to the backbone+NC schemes, resulting in an additional energy gain of 20-30% for typical network settings.



(a) Case 1: v_1 is the forwarder (b) Case 2: v_2 is the forwarder

Fig. 1. Impact of coding opportunity on broadcast.In the packet reception bitmap, a block with a thick borderline means received packets, and a block with a thin borderline means a lost one.

TABLE I
NOTATION USED IN THIS PAPER

Notation	Description
$e_j(u) = \{u, v_j\}$	A link from node u to v_j, we use e_j for short when u is clear from the context
$p(e)$	The link quality, measured by the transmission success rate
$\varepsilon(u)$	The expected transmission count for u to reliable broadcast one packet
$\beta_{nc}(u)$	The total number of reduced broadcast packets on node u with NC
$\xi_{nc}(V(u))$	The per-link covering cost of u to broadcast a packet to the node set $V(u)$ with NC

The rest of the paper is structured as follows. Section II presents the motivation of our design. Section III analyzes the model. In Section IV, we introduce the main design of COAB as well as how to integrate COAB with previous broadcast algorithms. Evaluation results from testbed experiments are shown in Sections V. Finally, Section VI concludes the paper.

II. Motivation

A. Network Coding Based Broadcast Rule

Network coding has great potential to improve the broadcast efficiency by saving redundant transmissions in wireless networks. When a source node broadcasts a coded packet to all its receivers, we need to make sure that all the receivers have already gathered enough packets to decode the new one. We specify the broadcast coding rule as follows:

Definition 1: (**Broadcast Coding Rule**) Consider a node u transmitting an encoded packet $p' = \oplus(p_1, p_2, \ldots, p_K)$. In order to decode p', each receiver should have already received $K-1$ packets among p_i, $i = 1, 2, \ldots, K$.

For NC based broadcast, we seek to encode as many packets as possible. To transmit, a node picks the first packet in its output queue, checks whether the remaining packets satisfy the broadcast coding rule and encodes as many packets as possible. Normally the number of packets that can be encoded into a single packet is small (bounded by the node's degree). Therefore, the computational overhead is insignificant.

B. Coding Opportunity in Broadcast

We use an example to show how the coding opportunity affects the efficiency of broadcast. Figure 1 shows two broadcast routes in a network, where source node u wants to broadcast packets to the other nodes. In Figure 1(a), after u sends the packet, node v_1 is selected as the forwarder, and node v_2, v_3 and v_4 are *covered* by the forwarder v_1. Node v_1 broadcasts the received packet (from source node u) to all the nodes it covers to accomplish the broadcast task. In Figure 1(b), similarly, node v_2 is selected as the forwarder. The broadcast task completes when node v_2 successfully delivers the packet to its covered nodes.

A node's packet reception information can be found from the packet reception bitmaps under each node in Figures 1(a) and 1(b), where a block with a thick borderline means a packet being received, and a block with a thin borderline means a packet being missed. Now let's examine the number of packet transmissions needed for the two cases separately.

• CASE 1 (Figure 1(a)): Node v_1 is selected as the forwarder and it needs to retransmit packets $\{p_2, p_3, p_4, p_5, p_6\}$. With the help of NC, v_1 needs to retransmit packet $\{p_2 \oplus p_3, p_4, p_5, p_6\}$ to make sure all the nodes it covers receive all the packets.

• CASE 2 (Figure 1(b)): Node v_2 is selected as the forwarder and it needs to retransmit all the six packets. With the help of NC, v_2 only needs to retransmit three packets $\{p_1 \oplus p_2 \oplus p_3, p_4 \oplus p_5, p_6\}$ to make up the losses on v_1, v_3 and v_4.

Comparing the two cases, we can see that the broadcast in CASE 2 has more coding opportunities than in CASE 1: CASE 2 has two coding operations where the first XORed packet involves 3 original packets and the second involves 2. CASE 1 only has one coding operation with 2 original packets XORed together. The total number of retransmissions for CASE 1 is 4 while that for CASE 2 is 3. This suggests that in broadcast, if we can manage to increase the coding opportunities when we select the forwarder, then the number of transmissions can be reduced.

III. Model Analysis

We aim to fully exploit NC opportunities to reduce transmissions. A basic question is: How much benefit can we get from NC? To answer the question, we first calculate the expected number of transmissions needed for reliable delivery of a packet from a source to all its receivers without considering NC. Then, we quantify the benefit of coding opportunities in reducing transmissions. Some notations used in this paper are listed in Table I.

A. Expected Transmission Count

Denote by $\varepsilon(u)$ the expected number of transmissions needed by forwarder u to deliver one packet to all its covered nodes without considering NC. The total number of transmissions for the broadcast is thus $\varepsilon = \sum \varepsilon(u)$. Let the set of nodes covered by forwarder u be $V(u) = \{v_1, v_2, \ldots, v_M\}$, where $M = |V(u)|$. Let the link quality between u and its covered node v_j be $p(e_j)$, $j = 1, 2, \ldots, M$. The corresponding packet loss probability is denoted $p(\overline{e_j}) = 1 - p(e_j)$. Without loss of generality, we assume $p(e_1) \geq p(e_2) \geq p(e_3) \geq \ldots \geq p(e_M)$.

Consider the M covered nodes case, where node u is the forwarder and node set $\{v_1, v_2, \ldots, v_M\}$ is covered by u.

$p(e_1 \cap e_2 \ldots \cap e_M)$ is the probability that all the M receivers successfully receive a packet. Without correlated shadowing and severe interference [20], wireless links are considered to be independent [21]. This means $p(e_1 \cap e_2 \ldots \cap e_M) = p(e_1)p(e_2)\ldots p(e_M)$.

Let $\Pr(\varepsilon(u) > k)$ be the probability that u needs more than k transmissions to deliver a packet to all the M receivers, then the expected transmission count for u to reliable broadcast one packet can be calculated as

$$
\begin{aligned}
E[\varepsilon(u)] =& \sum_{k=1}^{+\infty} k \cdot Pr(\varepsilon(u) = k) \\
=& \sum_{k=1}^{+\infty} k \cdot (Pr(\varepsilon(u) > k-1) - Pr(\varepsilon(u) > k)) \\
=& Pr(\varepsilon(u) > 0) - Pr(\varepsilon(u) > 1) + 2Pr(\varepsilon(u) > 1) \\
& - 2Pr(\varepsilon(u) > 2) + 3Pr(\varepsilon(u) > 3) - \ldots \\
=& \sum_{k=0}^{+\infty} Pr(\varepsilon(u) > k)
\end{aligned}
\tag{1}
$$

where $Pr(\varepsilon(u) > k)$ is given by

$$
\begin{aligned}
Pr(\varepsilon(u) > k) =& \sum_{i=1}^{M} p(\bar{e_i})^k - \sum_{1 \le i < j \le M} (p(\bar{e_i})p(\bar{e_j}))^k \\
& + \sum_{1 \le i < j < l \le M} (p(\bar{e_i})p(\bar{e_j})p(\bar{e_l}))^k + \ldots \\
& + (-1)^M (p(\bar{e_1})p(\bar{e_2})\ldots p(\bar{e_M}))^k.
\end{aligned}
\tag{2}
$$

Based on Eq.(1) and Eq.(2), we get the expectation for source node u to reliable broadcast one packet to its covered node set $\{v_1, v_2, \ldots, v_M\}$.

B. *Coding Opportunities Estimation*

From the example in Section II, we can find that the coding opportunity is crucially dependent on the forwarder selection: we can get more benefit from NC if node v_2 (Figure 1(b)) is selected as the forwarder. Therefore, it is imperative to estimate the benefit of NC for each forwarder candidate. First, let's give the definition of coding opportunity:

Definition 2: (**Coding Opportunity**) For packets buffered in an output queue, if there exist a group of packets that satisfy the broadcast coding rule and thus can be encoded together, we call this condition a coding opportunity.

Let the number of coding opportunities with k_i original packets involved in an encoded packet be t_i, $2 \le k_i \le M$. Node u's total reduced number of broadcast packets by using network coding $\beta_{nc}(u)$ is given by

$$\beta_{nc}(u) = \sum_{i=2}^{M} (k_i - 1)t_i \tag{3}$$

Note that each broadcast packet may need multiple retransmissions to ensure it being received by all the receivers. This makes great room for NC to reduce transmissions.

IV. COAB Metric

This section describes the main design of the COAB metric. Then we introduce how to integrate COAB metric with backbones construction.

A. *Forwarder Selection*

Consider a node u with covered node set $V(u) = \{v_1, v_2, \ldots v_M\}$. For each link e_j, the expected number of transmissions needed to successfully send a packet to node v_j is $\frac{1}{p(e_j)}$. For the lost packet, we adopt a hop-by-hop retransmission model – more specifically a simple automatic repeat request (ARQ) mechanism at the MAC layer. The ARQ mechanism uses ACKs and timeouts to achieve reliable packet transmissions. If a forwarder does not receive an ACK before the timeout, it retransmits the packet until it receives an ACK or exceeds a predefined number of transmissions.

Our goal is to design a broadcast scheme that minimizes the total number of transmissions in a network using NC. Based on the observations that packet delivery efficiency highly depends on link quality and NC opportunities, we use a metric called the *per-link covering cost* to guide forwarder selection.

1) Impact of link status: In COAB, we define the *per-link covering cost without NC* as follows.

Definition 3: (**Per-link Covering Cost without NC**) The forwarder node u's per-link covering cost is the number of transmissions needed by u to deliver a packet to all of its covered nodes *without* using NC, divided by the number of u's covered nodes, that is,

$$\xi(V(u)) = \frac{\varepsilon(u)}{M}, \tag{4}$$

where M is the number of u's covered nodes. $\xi(V(u))$ offers a good estimate for the expected transmission count for a successful packet delivery without NC. It captures a basic characteristic of lossy links. $\xi(V(u))$ suggests that selecting a proper forwarder should consider covered nodes with good link qualities.

To calculate $\xi(V(u))$, we need to know $p(e_j)$. In wireless networks, link quality is known to be dynamic. In COAB, every node periodically sends out a HELLO message at an adaptive time interval which is increased or decreased based on the link's stability. Every HELLO message is identified by the node ID and a packet sequence number. The message is used not only for one-hop neighbor discovery, but also for updating $p(e_j)$. The calculation of link quality is straightforward. Every node maintains a reception record of all HELLO messages from its neighboring nodes within a time window W (e.g., W = 6). In order to reduce the required memory space and mitigate the overhead of control messages, the record is represented in a bitmap format (e.g., [110010]) for each neighbor. Such records are exchanged within a HELLO message every W seconds among neighboring nodes.

2) Impact of network coding: We use $\xi_{nc}(V(u))$ to denote the per-link covering cost *with* NC and call it per-link covering cost for short.

TABLE II
TEN STATE-OF-ART PROTOCOLS SUPPORTED BY COAB

Protocol Name	Reference	Network Info.	Hello Msg	Broadcast Msg	Category
Spanning Tree	[3]	One-hop	ID	Msg only	Tree-based
Cluster Tree	[1]	Quazi-Global	Global	Msg only	Tree and Cluster-based
Forwarding Node Cluster	[8]	Local	ID	Covered set	Tree and Cluster-based
Clustering	[7]	Quazi-Local	Degree	Msg only	Cluster-based
Multi-Point Relay	[6]	Two-hop	One-hop	Msg + Covered set	Pruning-based
Self Pruning	[4]	One-hop	One-hop	Msg + Covered set	Pruning-based
Partial Dominating Pruning	[5]	Two-hop	One-hop	Msg + Covered set	Pruning-based
Dominating Pruning	[4]	Two-hop	One-hop	Msg + Covered set	Pruning-based
Total Dominating Pruning	[5]	Two-hop	One-hop	Msg + Covered set	Pruning-based
RNG Relay Subset	[2]	Two-hop	One-hop	Msg only	Pruning-based

Definition 4: (**Per-link Covering Cost**) $\xi_{nc}(V(u))$ equals the average number of transmissions needed by forwarder u to reliably deliver a single packet over a single link *with* NC, that is,

$$\xi_{nc}(V(u)) = \frac{(|\Phi(u)| - \beta_{nc}(u))}{|\Phi(u)|}\xi(V(u)), \quad (5)$$

where $\Phi(u)$ is the packet set in node u's output queue. In COAB, $\xi_{nc}(V(u))$ is used as the metric for forwarder selection.

B. Integrating COAB Metric with Backbones

We classify the existing reliable broadcast algorithms into tree-based [3], cluster-based [1], [7], [8], and pruning-based [2], [4]–[6]. Thus far, we have successfully implemented ten classical algorithms and embedded COAB with them. The basic information of these algorithms is shown in Table II. We briefly introduce how to embed our design into these tree backbone construction algorithms, and thus bringing them an improvement on energy efficiency. In Tree+COAB, instead to find the nodes with maximum leaves, we choose the nodes with $\min(\xi_{nc})$ as the tree nodes. To combine cluster based broadcast with COAB, the algorithm Cluster+COAB first selects nodes with $\min(\xi_{nc})$ to form a maximal independent set (MIS). Then, Cluster+COAB finds connectors to link the nodes in MIS. In Pruning+COAB, each forwarder adds its one-hop neighbors with $\min(\xi_{nc})$ to forwarder set to cover its two-hop neighbors.

Running the COAB algorithm introduces little additional communication cost. The main overhead is from two sources. One is packet reception bitmap exchange between neighboring nodes which is used to calculate the expected transmission count, coding opportunity and the broadcast link cost. The exchange of bitmap is already required by previous network coding schemes [17]. Besides, the bitmap is designed to be very short (e.g., 2 bytes) so this overhead is negligible. The other part of overhead is the exchange of one-hop neighbor information, which is required by backbone construction algorithms [5], [6], [8]. Thus, applying COAB will hardly affect the system's overall performance.

Fig. 2. Testbed

V. TESTBED IMPLEMENTATION

A. Experiment Setup

We deploy 30 MICAz nodes randomly on an in-door testbed shown in Figure 2. In the beginning of the experiment, a control node is used to remotely configure radio parameters, i.e., transmission power and channel. According to the testbed size, i.e., 24 feet by 8 feet, the power is set to be -25dBm. We use 802.15.4's channel 26, which is free of external interference (e.g.,WiFi). Based on these radio settings, each node broadcasts 100 HELLO packets in turn. Each packet was identified by a sequence number. The transmission rate is 5 packets/sec. All the received packets are recorded in the MICAz nodes' flash memory. When all the nodes finish broadcasting 100 packets, they send their packet reception information to a sink node which is connected to PC. We thus obtain the information required by COAB, i.e., link qualities and packet receiving patterns, from packet reception history, and calculate the backbone for broadcast using the forwarder selection method. Then, the corresponding nodes in the testbed are selected as forwarders (the backbone). The forwarders keep on broadcasting packets until all their covered nodes receive 100 packet.

We use two metrics for performance evaluation: (i) Number of Transmissions, which is defined as the number of transmissions needed by a broadcast scheme to reliably broadcast 100 packets to the whole network. (ii) Number of Coding Operations, defined as the number of times that network coding occurs during the experiment. It is used to measure coding opportunities.

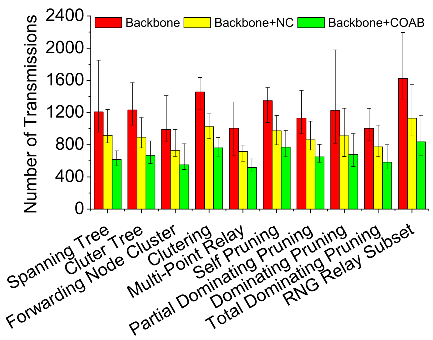


Fig. 3. Num. of Transmissions

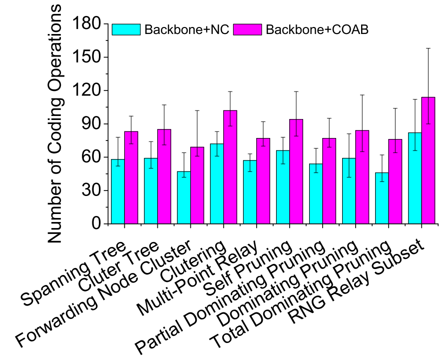


Fig. 4. Num. of Coding operations

B. Main Performance Results

The experimental results of the ten classical reliable broadcast protocols are shown in Figure 3. The first bar (in red) in each set of data represents the broadcast transmissions needed by the backbone schemes, while the second bar (in yellow) and the third bar (in green) represent the transmissions needed by backbone+NC and backbone+COAB schemes separately. For example, for the Spanning Tree algorithm, the nodes need 1208 transmissions on average to guarantee that every node in the network receives 100 packet, while the number is 616 when COAB is combined with Spanning Tree, achieving a reduction of 49%. The average transmission of backbone+NC and backbone+COAB is 892 and 662, respectively. On average, our design COAB reduces transmissions of backbone+NC by 26%. For the number of coding operations in Figure 4, we see that on average, backbone+COAB produces 43% more coding opportunities than backbone+NC. These improvements turn out to be very helpful for broadcast efficiency.

VI. Conclusion

In this paper we have studied the effect of network coding opportunity on the performance of broadcast. We developed a new forwarder selection metric to capture potential coding opportunities. Our design can be widely used in broadcast algorithms. We integrate COAB with ten state-of-the-art broadcast algorithms, and evaluate our design with testbed experiments. The results confirm the effectiveness of our design in exploiting coding opportunities and improving energy efficiency.

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