Network Coding on Wireless Multi-hop Networks

Sheng Jin
shengj

Ayush Agrawal
ayushagr

Coding – Source, Channel and Network

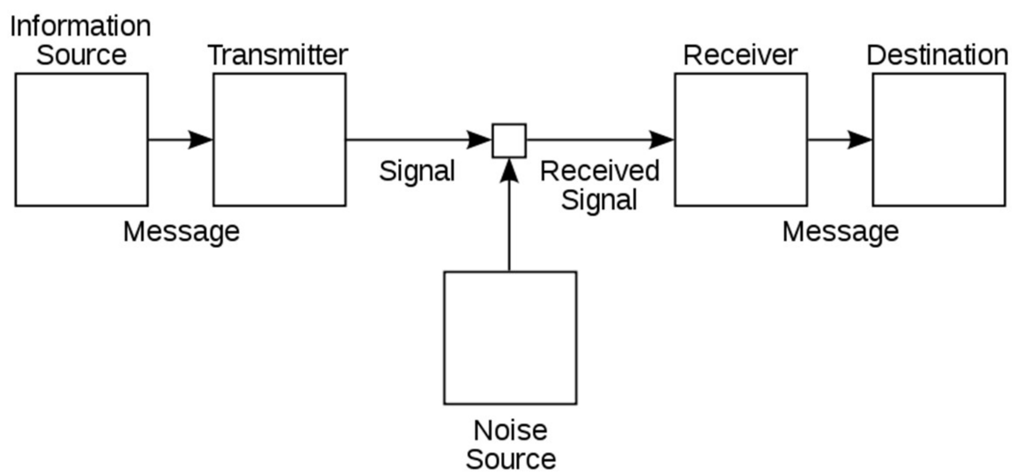
Coding – manipulation of information/data representation.

• **Source coding** - coding applied at the source which can be decoded at the destination. Ex: Huffman encoding (compression).

• **Channel coding** – coding applied at the transmitter which can be decoded at the receiver. Ex: forward error correction.

• **Network coding** – coding applied at the various nodes of a network. Ex: linear coding.

Common aim: increase the "**throughput"**



Network Coding

"Networking technique where operations are performed on data as it passed through the nodes with a network."

• Commodity flow: the network nodes simply forward data.
• Information flow : the network nodes operate in a manner as to increase the flow of information through the network.

• Most common operation: Accumulation.
Example: Linear coding.

• First proposed in the paper "Network Information Flow" [1]
Used the butterfly network as an example.
Showed network coding can outperform routing!
Min-Cut-Max-Flow theorem generalizes the idea.

• Earliest example: satellite relaying data between two nodes.
• Types of network coding: linear, randomized, opportunistic, etc.

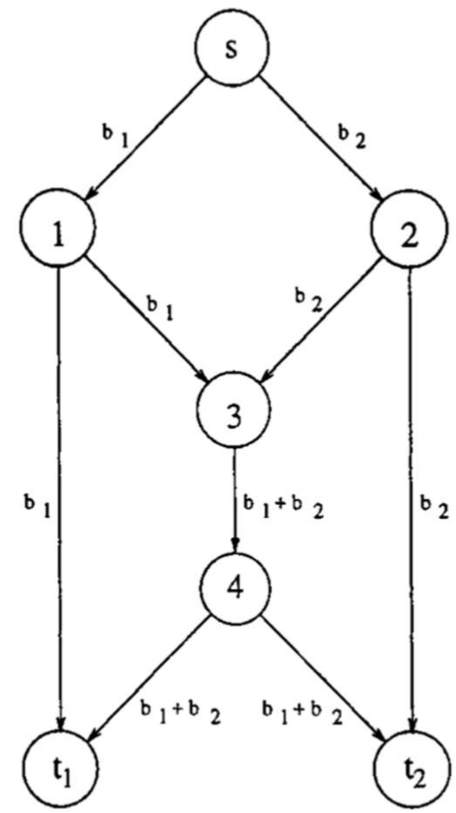


Fig. Butterfly network

Overview

- Applications of network coding to wireless networks.
  - Embracing the broadcast nature of the medium.
  - Embracing interference itself.
- Applications of network coding to wireless applications.
- Evaluation of the state of the area and future.

Network coding for wireless networks

• Ways to increase throughput in a wireless network from networking perspective:

(1) Better routing metric
(2) Tweaking higher level protocols such as TCP
(3) Opportunistic network coding
(4) Integrating MAC and IP layers for opportunistic routing

The common observation made by methods (3) and (4) is that broadcasting comes for free in wireless communication. So why not exploit it. We shall further examine these methods.

XORs in the Air: Practical Wireless Network Coding [6]

COPE - a new forwarding architecture that improves the throughput of wireless networks.

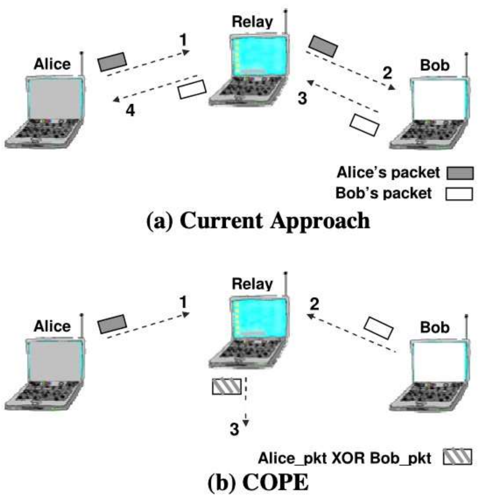


Figure 1—A simple example of how COPE increases the throughput. It allows Alice and Bob to exchange a pair of packets using 3 transmissions instead of 4 (numbers on arrows show the order of transmission).

COPE uses opportunistic network coding.

Basic principle:
In a single transmission, try XORing as many packets as possible as you believe all next hop receivers will be able to decode.

Three main techniques:

(1) Opportunistic Listening
(2) Opportunistic Coding
(3) Learning Neighbor State

COPE describes the implementation as a layer between IP and MAC layer and addresses the general case of unicast traffic.

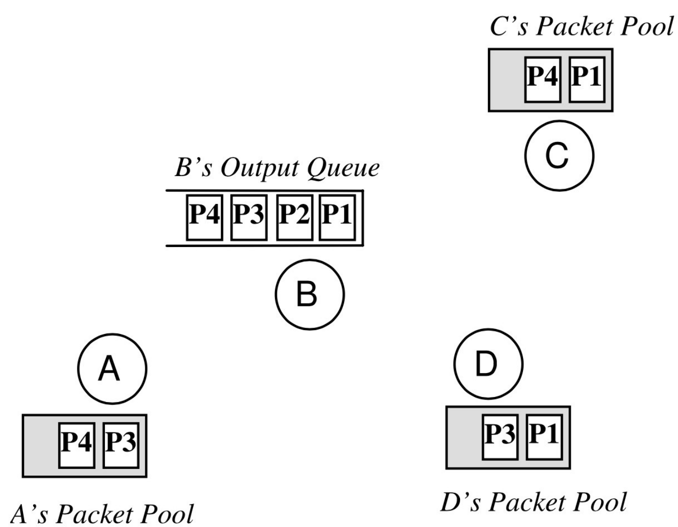
COPE: Design choices

- Packet Coding
  - never delaying packets
  - preference to XORing packets of similar size (2 virtual queues per neighbor)
  - never code together packets headed to the same next hop
  - searching for appropriate packets to code is efficient
  - avoid packet reordering

- Packet Decoding
  - maintain a packet pool

- Transmission
  - pseudo-broadcast since broadcast in MAC 802.11 lacks both reliability and back off.
  - piggyback on unicasts
  - hop by hop acks
  - asynchronous acks and retransmissions

- Reordering Agent



COPE: Testbed and results

• Testbed: a 20-node wireless testbed that spans two floors in our building connected via an open lounge. The nodes of the testbed are distributed in several offices, passages, and lounges.

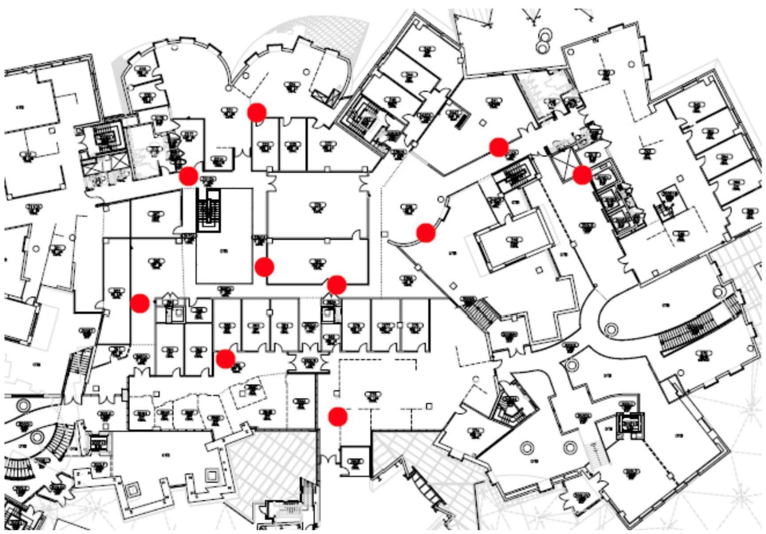


Figure 7—**Node locations for one floor of the testbed.**

• For random UDP flows: 3-4x increase.

• For a mesh network connected to the Internet via a gateway, the throughput improvement observed with COPE varies depending on the ratio of download traffic to upload traffic at the gateway, and ranges from 5% to 70%.

• Hidden terminals create a high loss rate that cannot be masked even with the maximum number of 802.11 retransmissions. In these environments, TCP does not send enough to utilize the medium and does not create coding opportunities. In environments with no hidden terminals, TCP's throughput improvement with COPE agrees with the expected coding gain.

COPE: Some insights

• COPE increases the actual information rate of the medium hence its benefits are sustained even if the medium is fully utilized which is not true for approaches increasing the network traffic using things like opportunistic routing.

• Without network coding, fairness and efficiency are conflicting goals - throughput increases if the node with the better channel captures the medium and sends at full blast.

- ° Network coding, however, aligns these two objectives
- ° Fairness increases the overall throughput of the network
- ° COPE + MAC gains observed during experiments

Example scenario for COPE + MAC gains: Let's say the MAC layer tries to be fairly (equally) allocate the bandwidth between all participating nodes. Now if one node has more to transmit (which is generally the case for the relay nodes), it will have to wait for its next slot. With network coding the node that has more to transmit can mix packets in a single transmission and can thus make do in the bandwidth that was allocated to it.

ExOR: Opportunistic Multi-Hop Routing for Wireless Networks [2]

Opportunistic Routing: a routing approach that makes use of the broadcasting nature of the wireless transmission. It dynamically choose the next hop from the overhearing nodes after the transmission itself, make use of the presumably independent probability of receiving the packets.

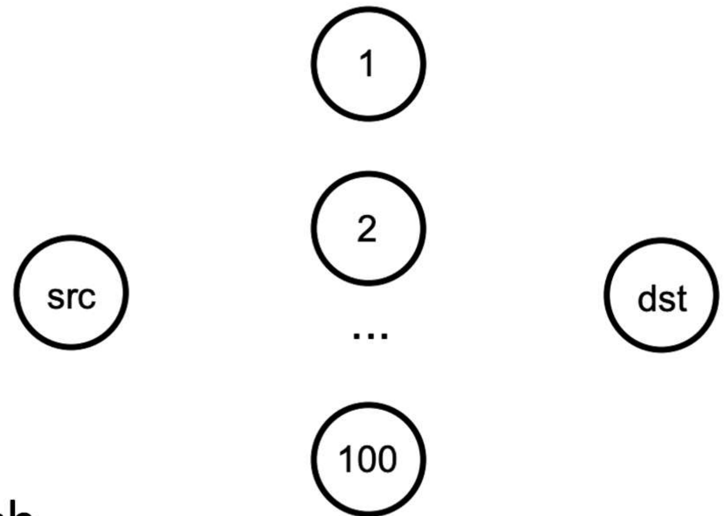
ExOR: A routing and MAC protocol which firstly introduced Opportunistic Routing.

No network coding involved yet.

ExOR: Basic Idea

- Due to the broadcasting nature of wireless transmission, the packets sent by the sender will be received by multiple nodes.
- The protocol operates on batches of packets.
- The sender has a list of nodes, prioritized by the "closeness" to the destination.
- Each packet in the batch is only forwarded by the closest node which receives the packet.
- ETX can be a metric for the closeness.

ExOR: Procedure



Source node:

1.Prepare batch.

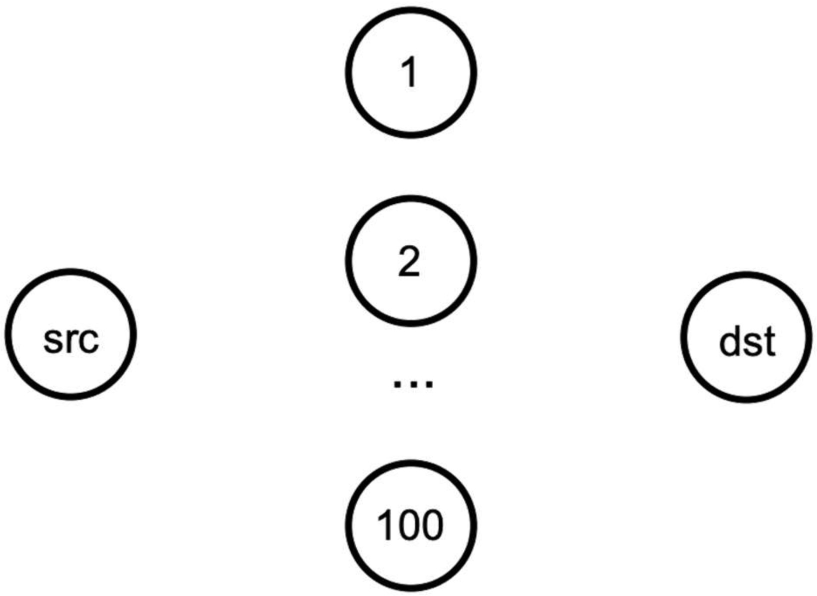
2.Specify Forwarder List: cost metric.

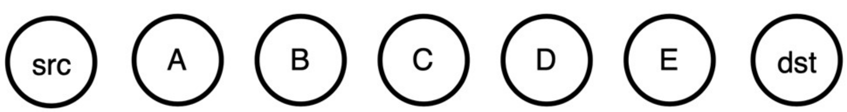
3.Broadcast.

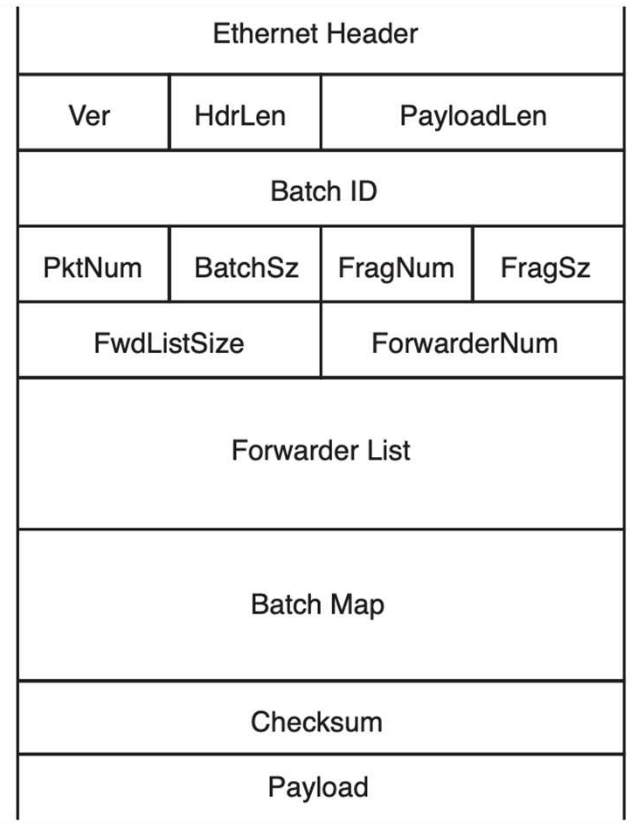
Potential relay nodes:

1. Receive packets and await the end of batch.
2. Keep updating the Batch Map.
3. Nodes broadcast packets, which are not acknowledged by nodes of higher priority. The time depends on hearing the node before it or the timer.
4. Use traditional routing for last few packets (say, 10%).

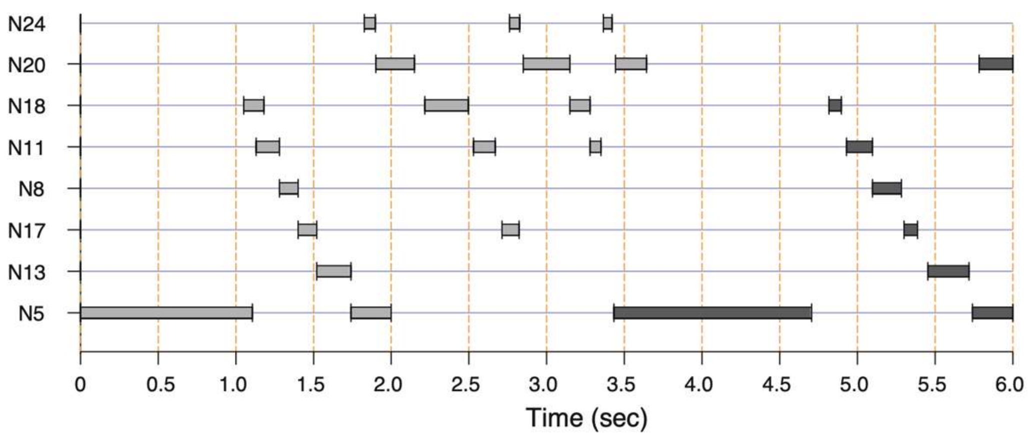
ExOR: Procedure

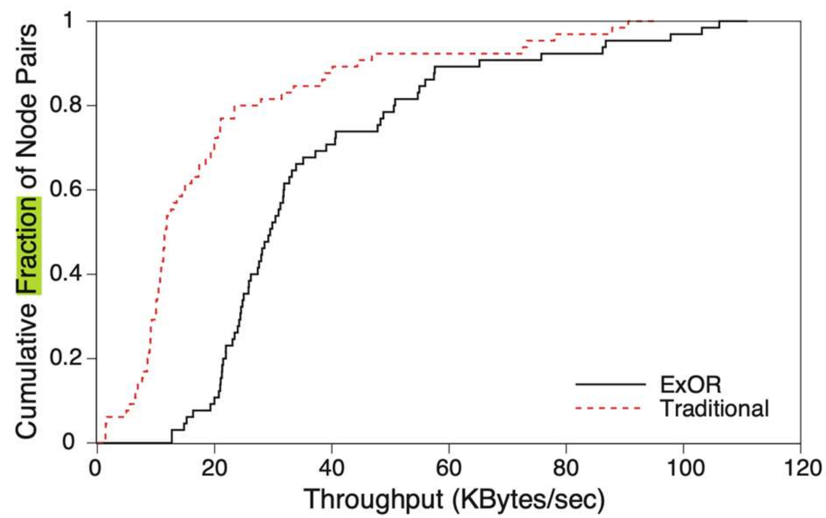




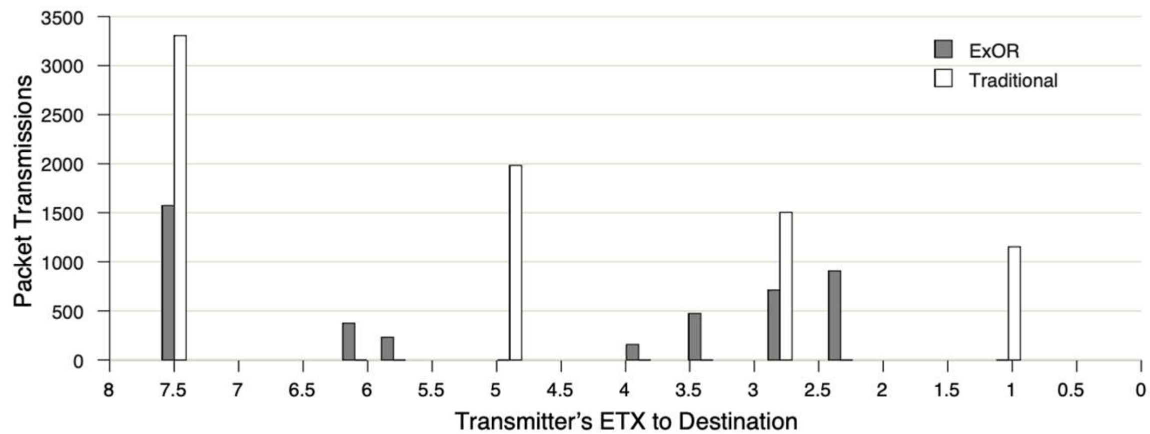


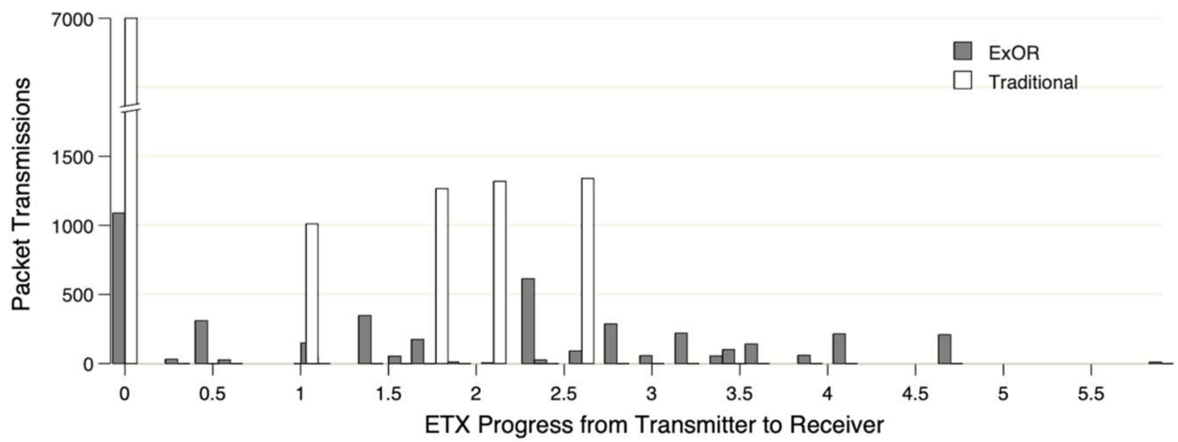
ExOR: Results



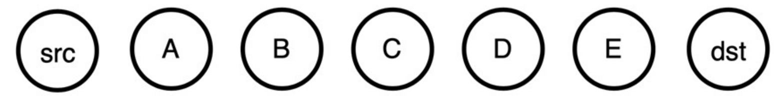


ExOR: Results





ExOR: Discussion



Summary:

- ExOR leaverages the receiver diversity.
- Transmit before choosing relay.
- Use scheduling to avoid collision.

Potential problems:

- Overhead of sharing the batch map.
- Possible collision. The timer adds complexity of the protocol.
- Relys on the lower prioritized nodes hearing higher prioritized nodes sending the packets.
- Strict scheduling and synchronization (thus less spatial reuse).
- Physical layer issues: power control, interference

MORE: MAC-independent opportunistic routing protocol [3]

An opportunistic routing protocol combined with network coding.

The idea is similar with random linear network coding.

Does not require topology information.

Independent of MAC, so the abstraction between layers is maintained.

MORE: Procedure

Source node:

1.Prepare batch

2.Specify Forwarder List: ETX metric

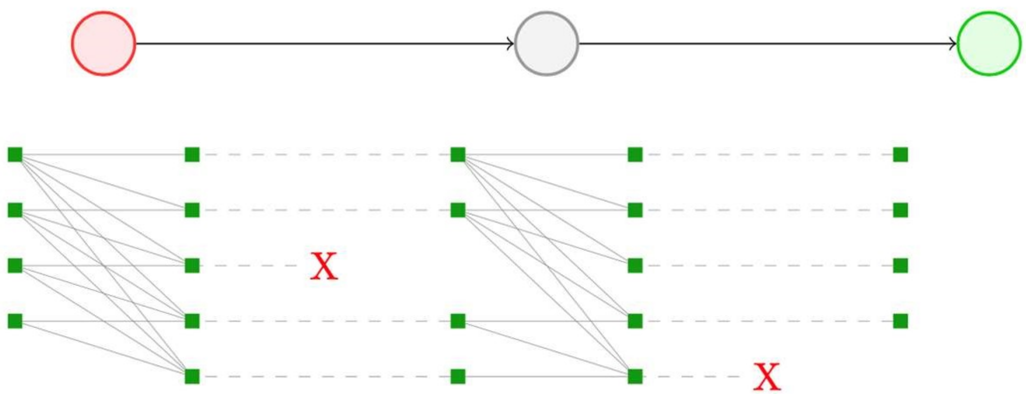
3.Coding: Do linear combination of the native packets

4.Terminate batch transmission when ACK is received

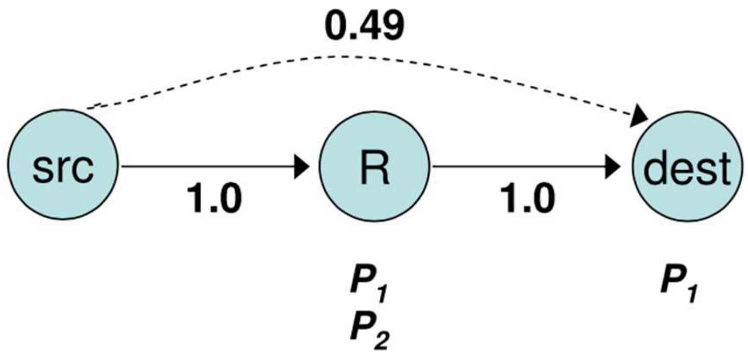
Relay nodes:

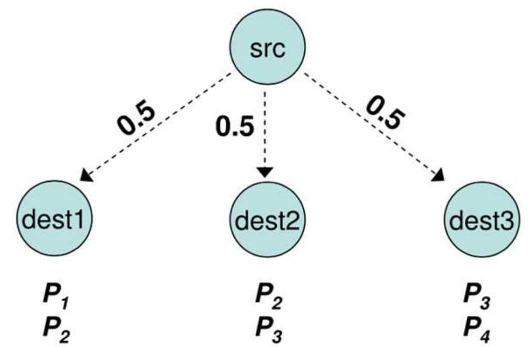
1. Listen to all transmissions. If the received packet does not have this node in the forward list, or does not contains new information (linearly dependent of other received packets), the packet is abandoned.
2. On receiving a packet, forward a random linear combination of packets.

MORE: Procedure

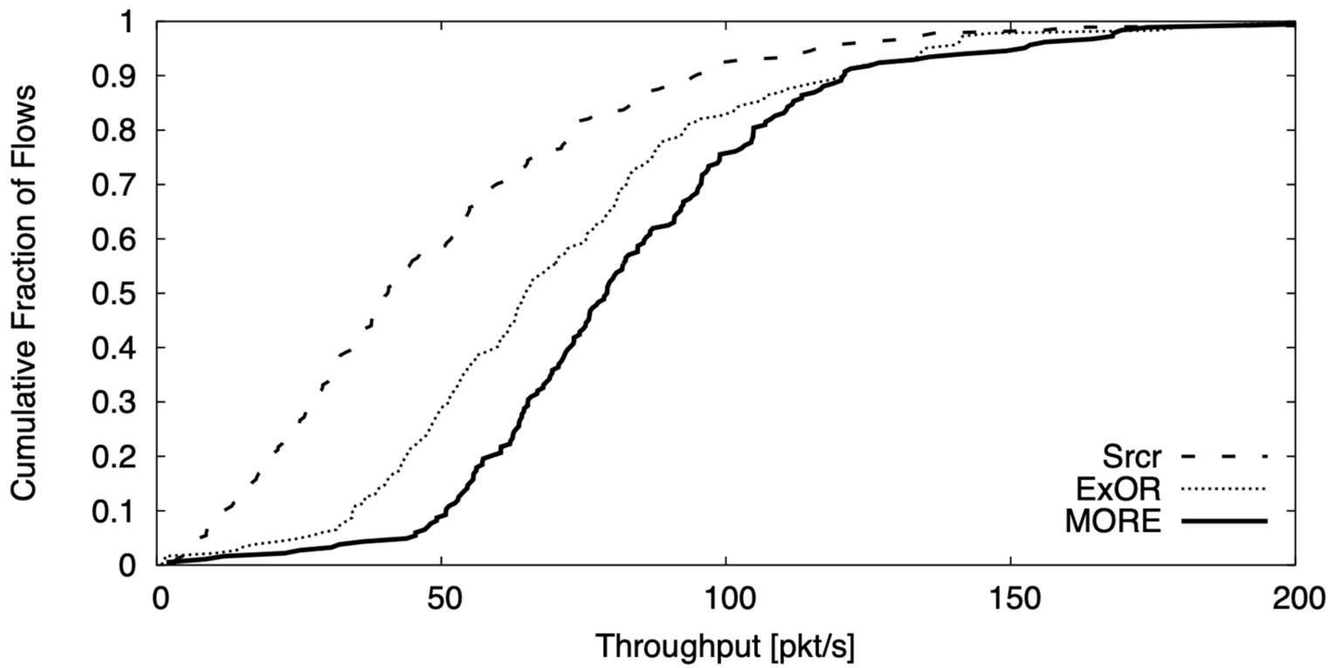


[4]





MORE: Results



MORE's median throughput is 22% higher than ExOR. In comparison to Srcr, MORE achieves a median throughput gain of 95%

MORE: Discussion

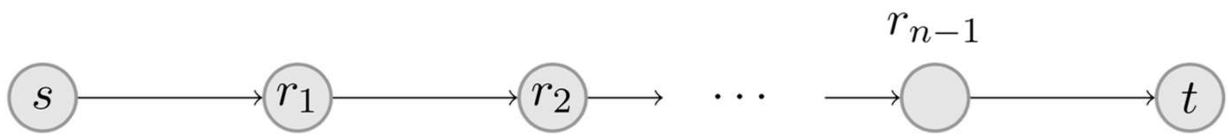
No scheduler needed. Better spatial reuse.

The issue that replicate transmissions of the same information still exists, but the redundancy will not accumulate.

However, there is overhead of determining whether a packet contains new information (by Gaussian elimination)

Does not resolve accumulated packet loss issue

Accumulated Packet Loss



All links have a packet loss rate 0.2.

Intermediate Operation	Maximum Rate
forwarding	$0.8^n \to 0$
network coding	0.8

[4]

BATched Sparse Code [5]

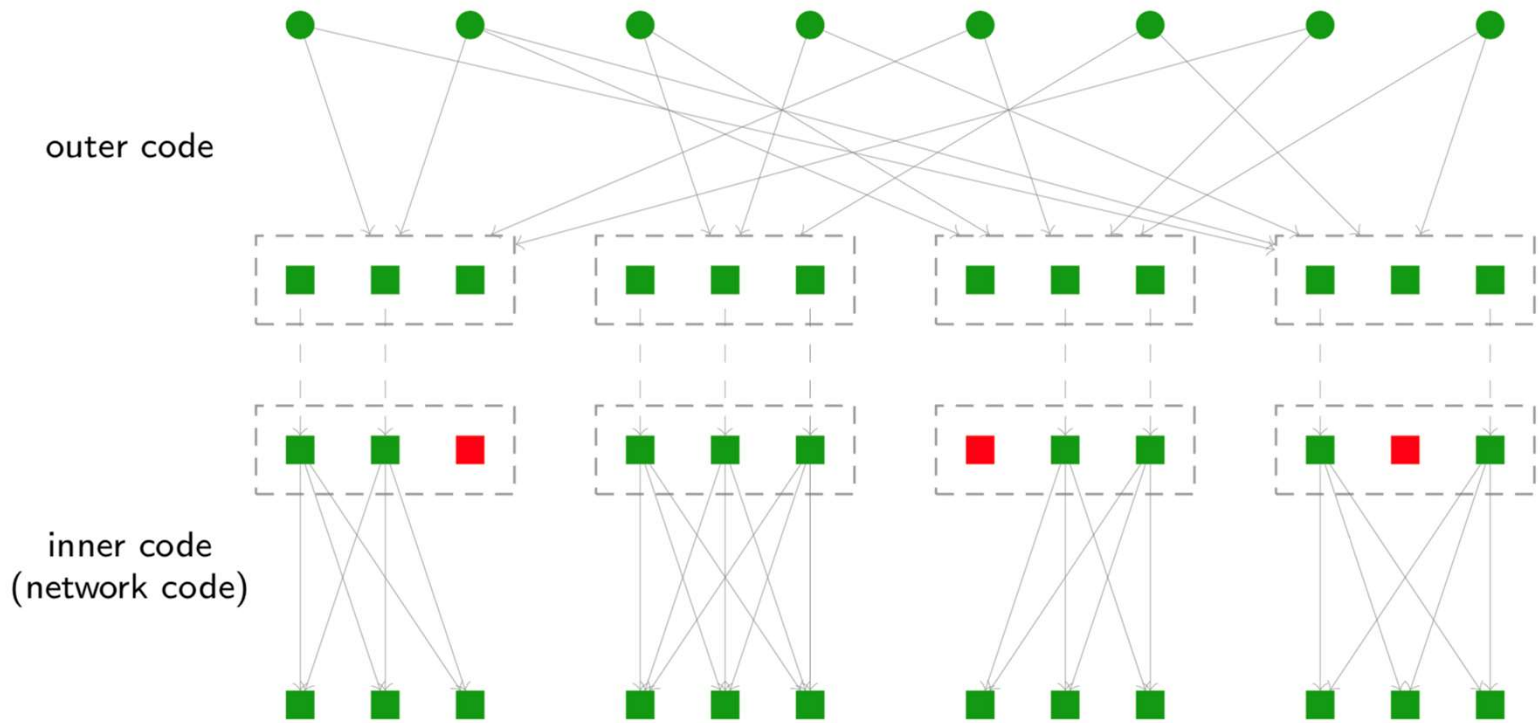
A type of network coding for multi-hop wireless networks with packet loss.

Has an Inner-Code-Outer-Code framework. The coding method is very similar toe MORE.

The outer code generates batches of coded packets. The number of batches can be unlimited. Outer encoding and decoding at source and destination.

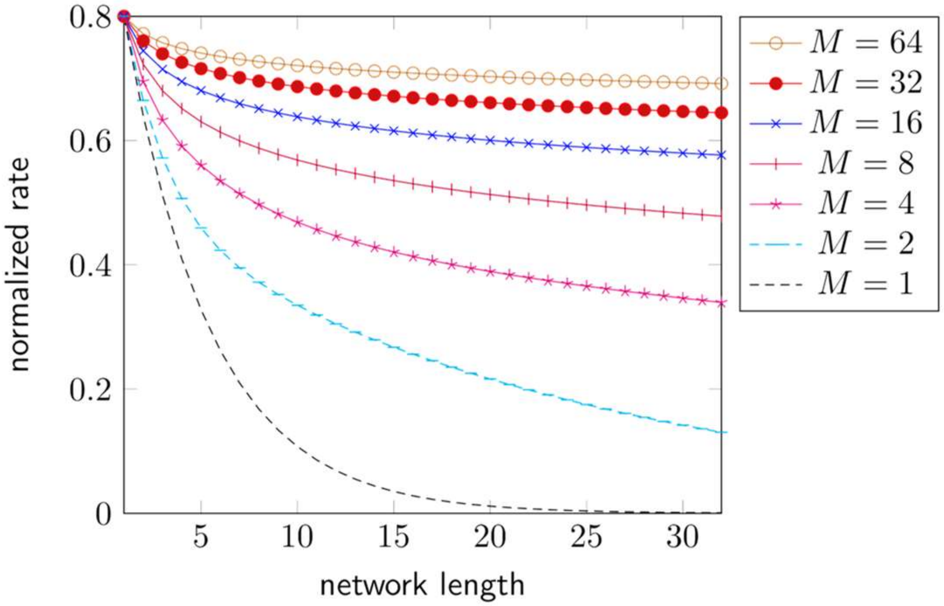
The inner code performs random linear combination of packets within a batch, called recoding. Recoding at all relay nodes.

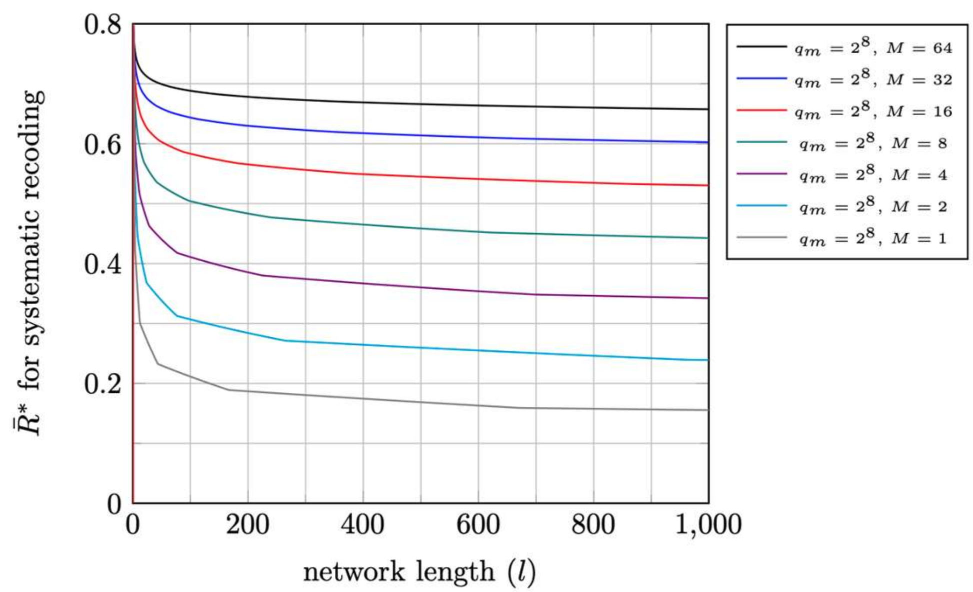
BATched Sparse Code



[4]

Multi-hop network and BATched Sparse Code





Achievable rates for line networks (up to 1000 hops)

[4]

BATched Sparse Code: Discussion

Replicate transmissions of the same information is desired: redundancy to confront packet loss.

Does not require topology information.

Achieves near min-cut-max-flow bound.

Does not leverage receiver diversity and the broadcasting nature.

Comparing ExOR with BATched Sparse Codes

- ExOR is an opportunistic routing protocol which uses wireless property to improve throughput.
- MORE is another opportunistic routing which applies network coding.
- BATched Sparse Codes has similar coding schema as MORE, which can confront packet loss.
- It is possible to combine the Inner-Code-Outer-Code framework of BATched Sparse Codes with the MORE

Physical wireless network coding

• Uses interference as a friend in radio networks.

Interface mixes the signals naturally. If each receiver has enough information, they can recover the data they want from the mixed signal.

• A network of as small as two nodes can reap the benefits of network coding.

•One of the key issues in PNC is how to deal with the asynchronies between the signals transmitted simultaneously by the two end nodes.

• Reliability of transmission is also one of the challenges that face PNC. Channel coding is typically used to solve this issue.

Applications & Future

- Applications:

  - File Download
    -> Nodes in Bit Torrent choose among the rarest block among its neighbors to download.
    -> The local rarest might not be the global rarest.
    -> With network coding there will be no need to locate and request the global rarest.
  - Live media broadcast, etc.

- Future:

Still a hot area of research.
Can make use of properties of wireless communication like interference.
Ties with SDN, overlay networks and content centric networks makes the future seem more promising.

References

[1] R. Ahlswede, Ning Cai, S. -. R. Li and R. W. Yeung, "Network information flow," in IEEE Transactions on Information Theory, vol. 46, no. 4, pp. 1204-1216, July 2000.

[2] Biswas S, Morris R. ExOR: opportunistic multi-hop routing for wireless networks[C]//Proceedings of the 2005 conference on Applications, technologies, architectures, and protocols for computer communications. 2005: 133-144.

[3] Chachulski S, Jennings M, Katti S, et al. Trading structure for randomness in wireless opportunistic routing[J]. ACM SIGCOMM Computer Communication Review, 2007, 37(4): 169-180.

[4] Figures are adopted from the tutorial slides of "BATS Codes: Theory and Practice" at 2018 IEEE International Symposium on Information Theory

[5] Yang S, Yeung R W. Batched sparse codes[J]. IEEE Transactions on Information Theory, 2014, 60(9): 5322-5346.

[6] *XORs in The Air: Practical Wireless Network Coding*. nms.csail.mit.edu/~sachin/papers/copesc.pdf.