XORs in the air: Practical Wireless Network Coding

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SIGCOMM '06

Presented by
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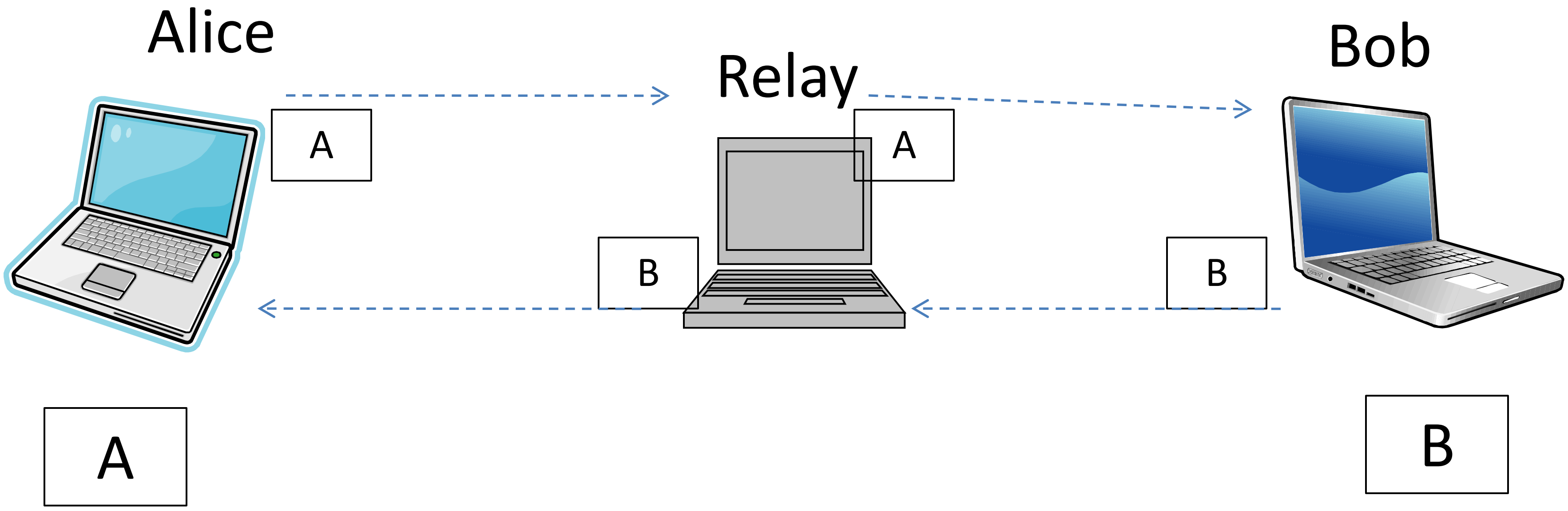
Problem

Increase the throughput of dense wireless networks

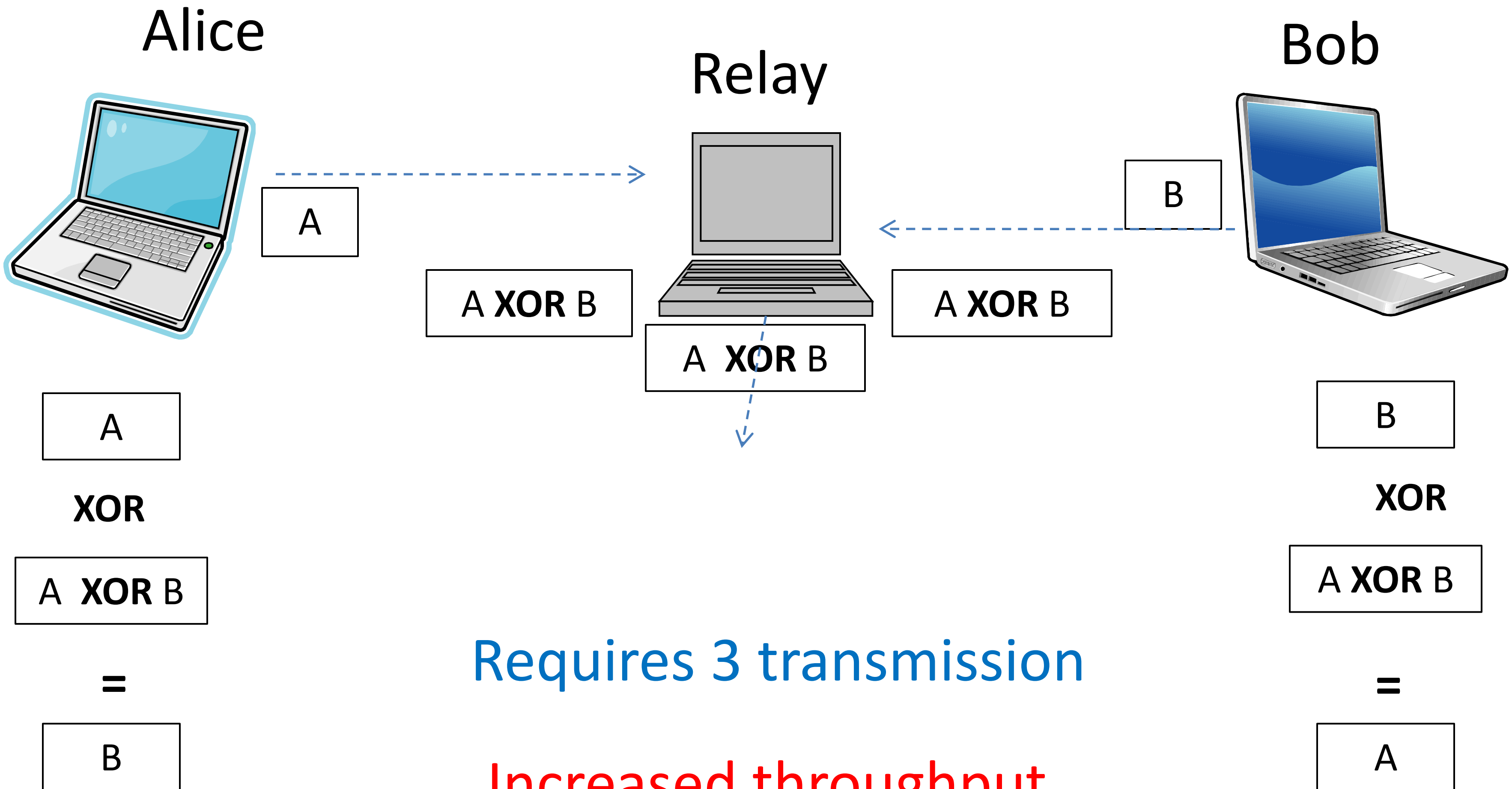
Network Coding

Current Approach



Requires 4 transmission

COPE Approach



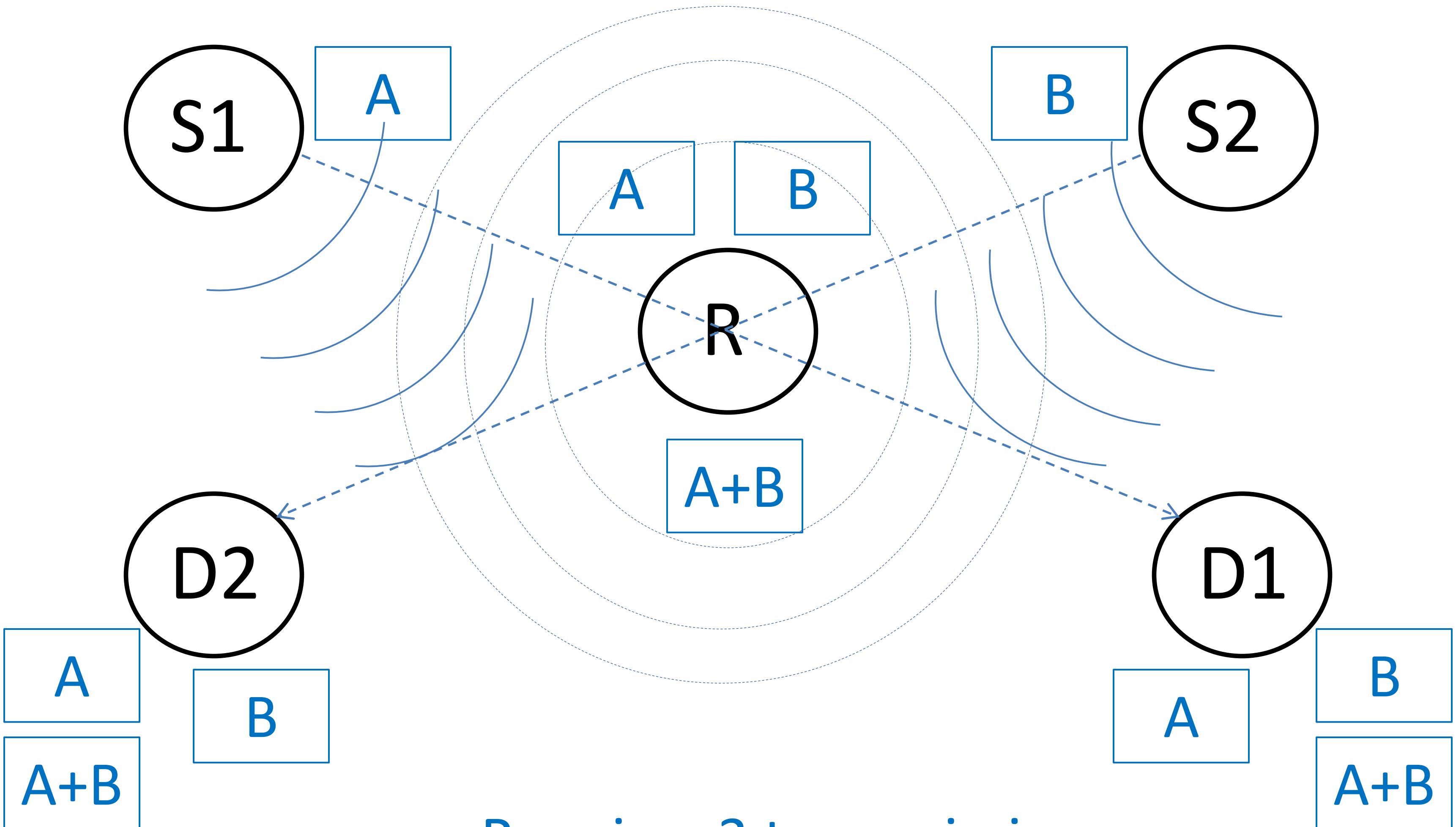
Requires 3 transmission

Increased throughput

COPE Approach

- Exploits shared nature of wireless medium
  - Every node snoops on all packets
  - A node stores all heard packets for a limited time
- Tell neighbors which packets it has heard
- Perform opportunistic coding
  - XOR multiple packets and transmit them as single packet
- Decode the encoded packet using stored packets

Scenario



Requires 3 transmission

Outline

- Design
- Cope Gains
- Making it work
- Implementation details
- Experimental results

Overview

- Opportunistic listening
- Opportunistic coding
- Learning neighbor state

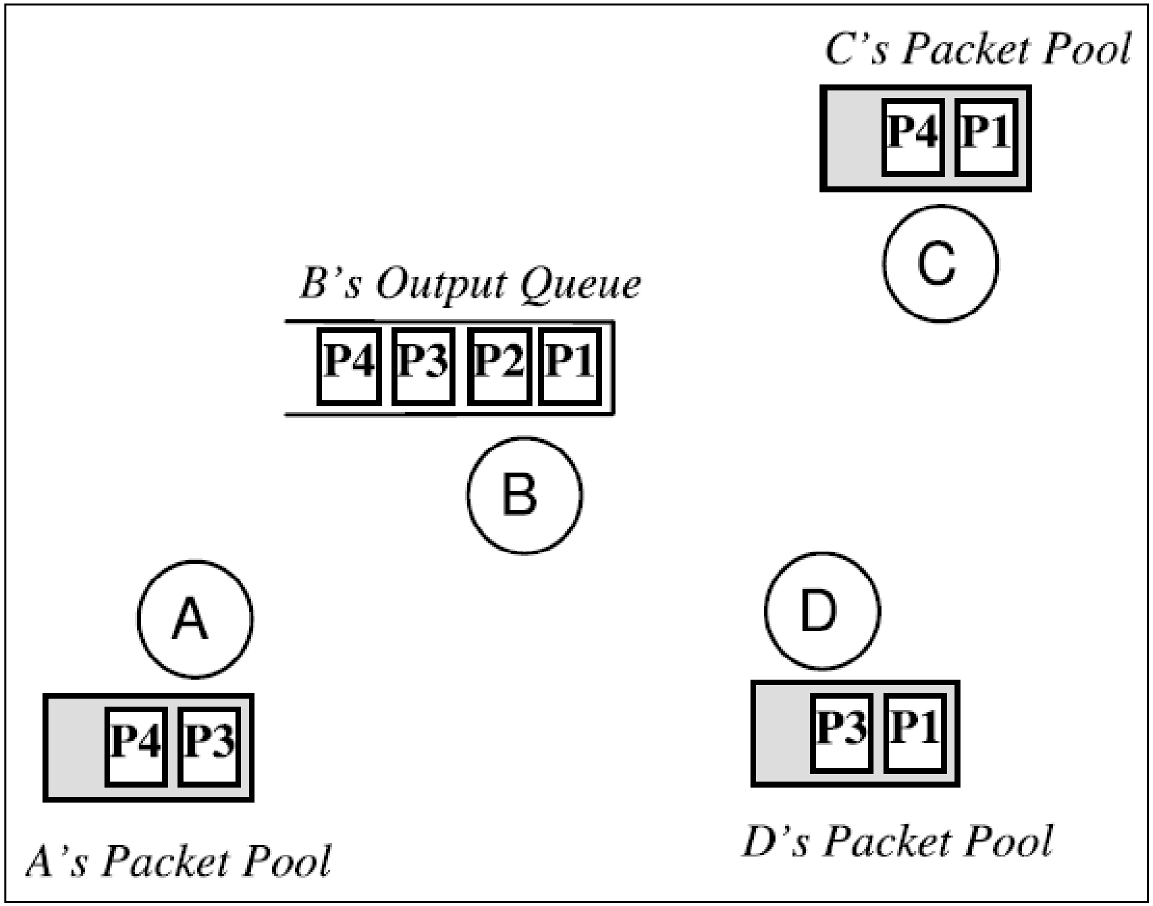
Opportunistic listening

- Exploit broadcast nature of wireless
  - Set nodes in promiscuous mode
  - Opportunities to overhear packets
- Store the overheard packets
  - Limited time period (T = 0.5s)
- Broadcast reception reports to tell neighbors which packets it has stored
  - Annotate with data packets
  - If no data packets, send reception reports periodically

Opportunistic coding

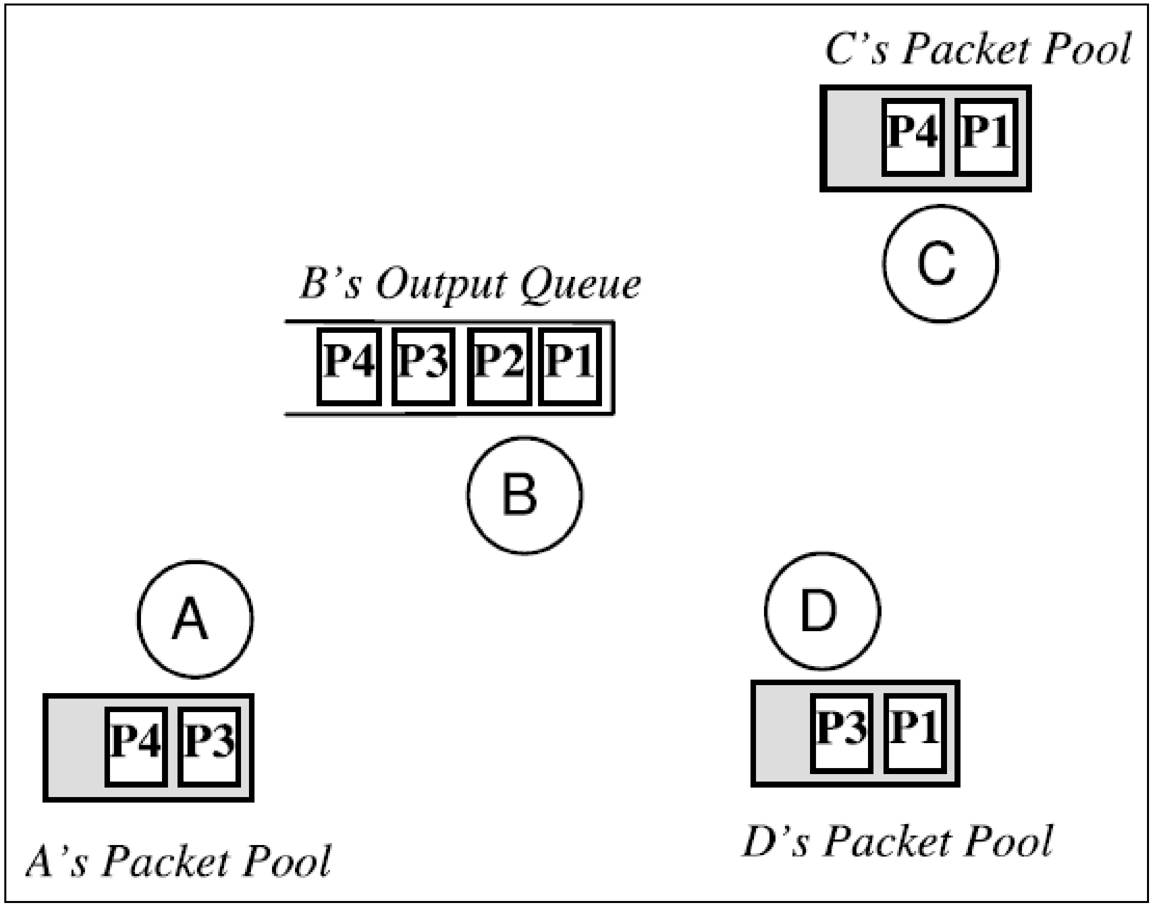
What packets to code together to maximize throughput?

Opportunistic coding



Packets in B's Queue	Next Hop
P1	A
P2	C
P3	C
P4	D

Opportunistic coding

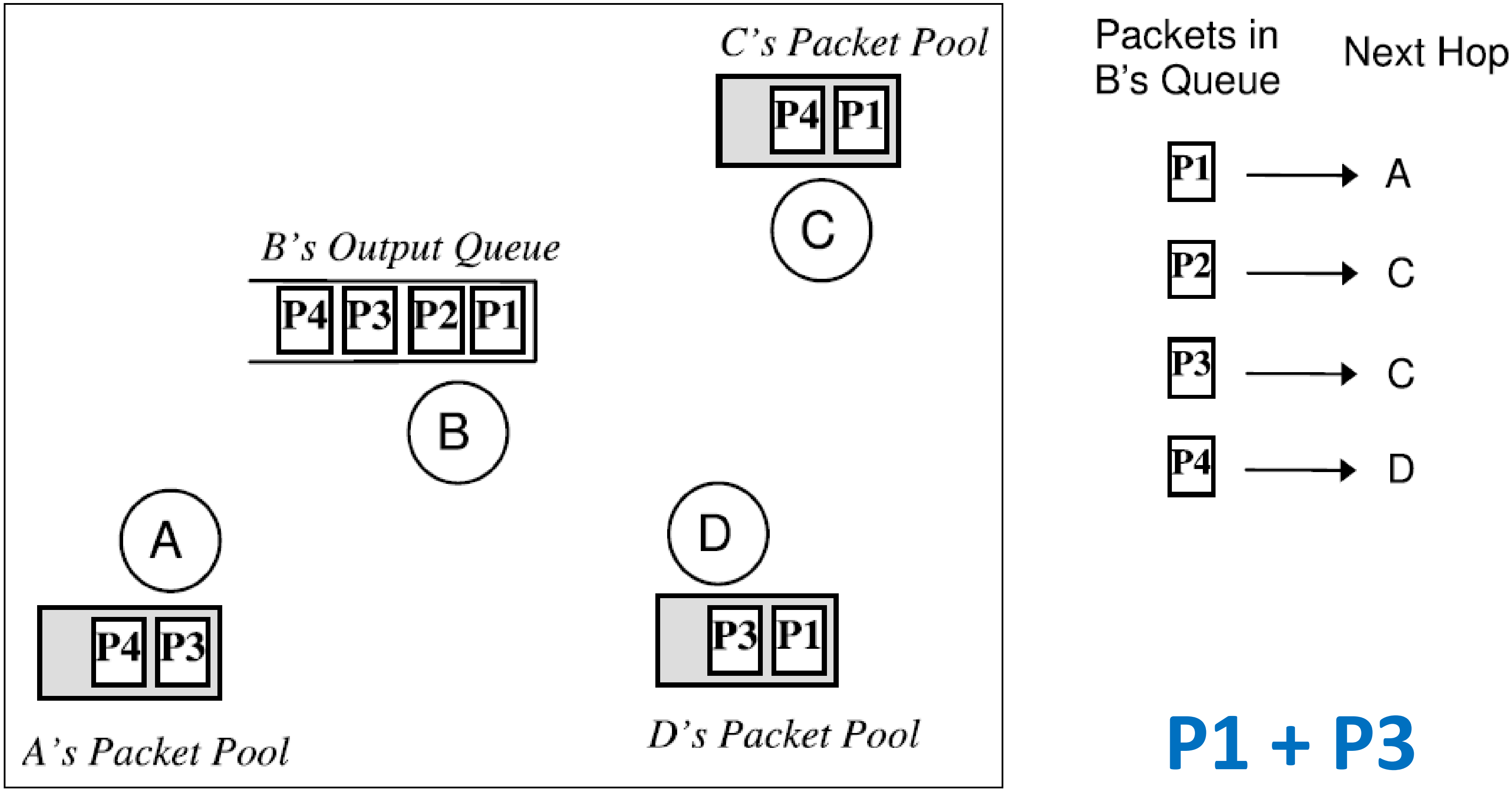


Packets in B's Queue	Next Hop
P1	A
P2	C
P3	C
P4	D

P1 + P2

Bad Coding – C can decode but A can't

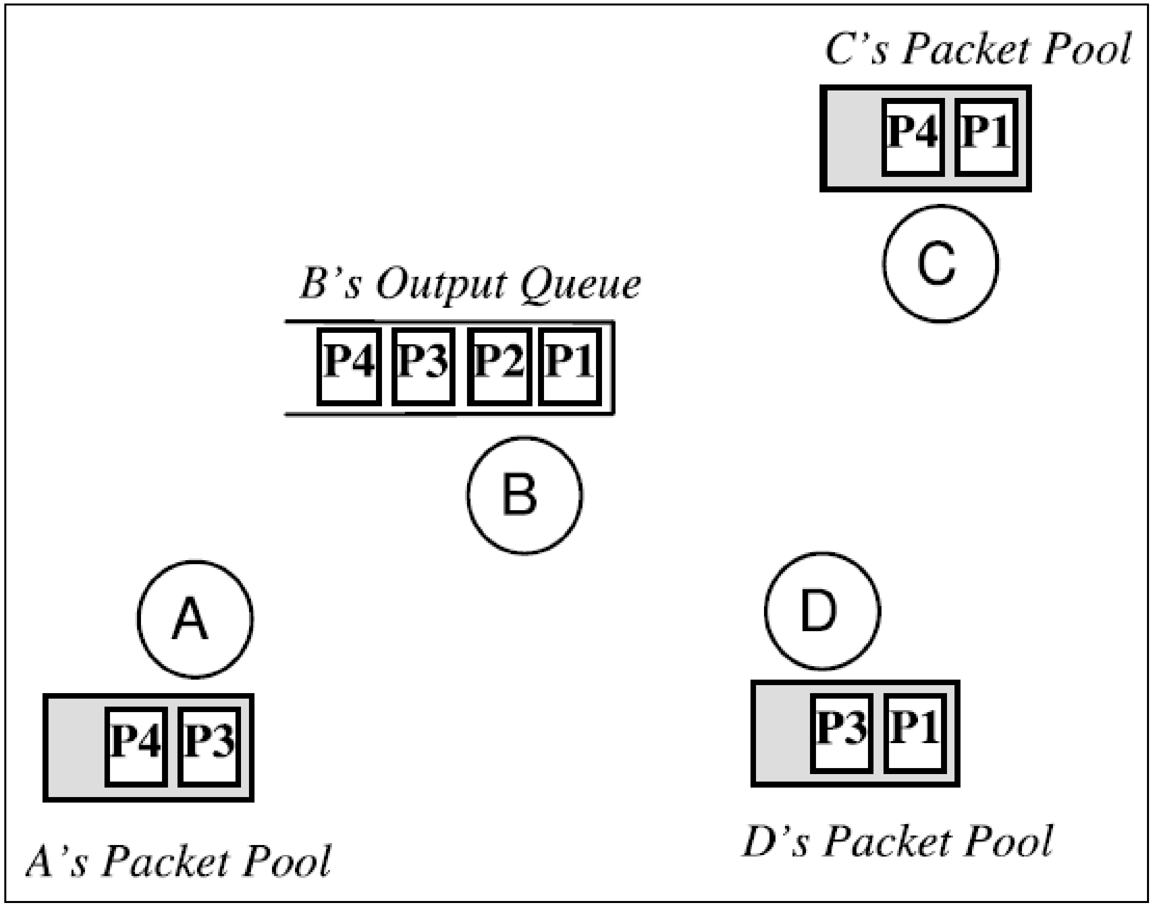
Opportunistic coding



P1 + P3

Better Coding – Both A and C can decode

Opportunistic coding



Packets in B's Queue	Next Hop
P1	A
P2	C
P3	C
P4	D

P1 + P3 + P4

Best Coding – Nodes A, C, D can decode

Opportunistic coding

- Maximize the number of native packets delivered in a single transmission
- While ensuring that each intended next hop has enough information to decode its native packet

Opportunistic coding

To transmit n packets: $p_1, ..., p_n$

To n next hops: $r_1, ..., r_n$

A node can XOR the n packets together only if each next hop r_i has all n-1 packets p_j for j!=i

Choose the largest n that satisfies the above rule

Learning Neighbor State

How does a node know what packets its neighbors have?

- Send reception reports
- During congestion, reports may get lost in collisions or may arrive late

Learning Neighbor State

- Wireless routing protocols compute delivery probability between every pair of nodes and broadcast them
  - E.g.: ETX

- Using these weights,
  - Estimate the probability that a particular neighbor has a packet

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COPE Gains

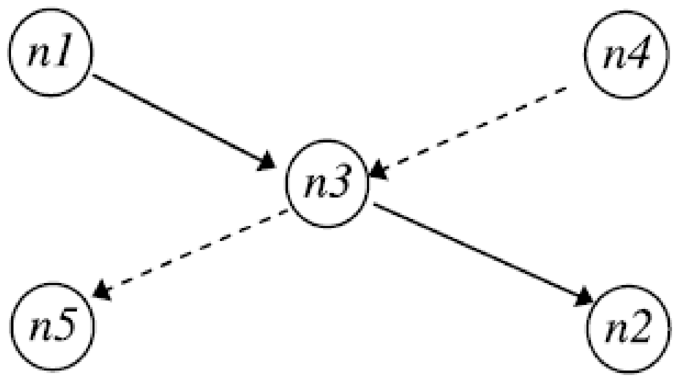
- Coding Gain
- Coding + MAC Gain

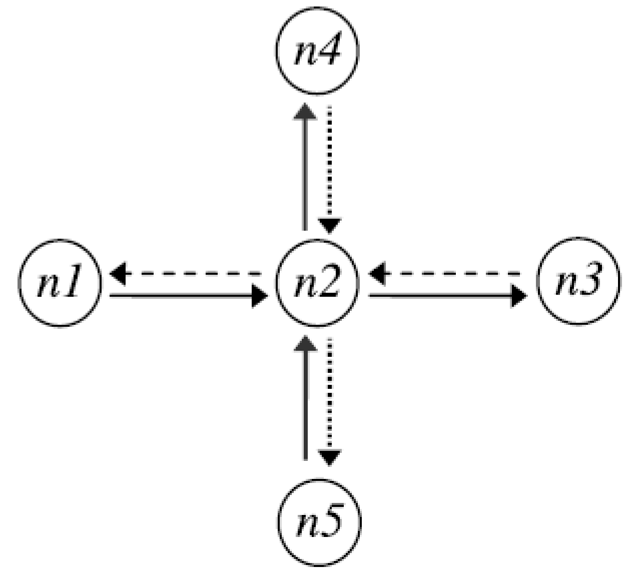
Coding Gain

$$\text{Coding Gain} = \frac{\text{Number of transmissions required by non-coding approach}}{\text{Minimum number of transmissions used by COPE}}$$

Alice & Bob experiment – Coding gain = 4/3 = 1.33

Coding Gain

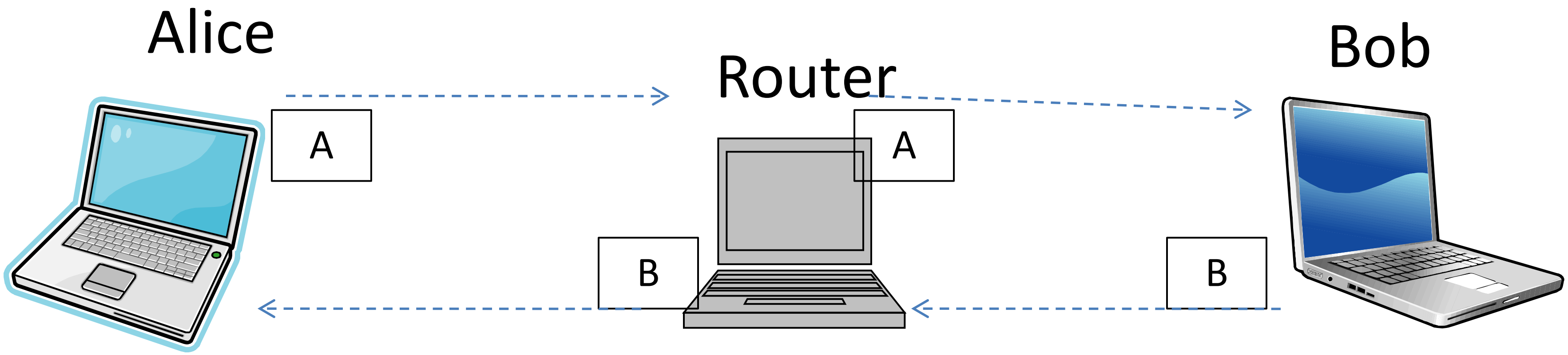




Coding gain = 4/3 = 1.33

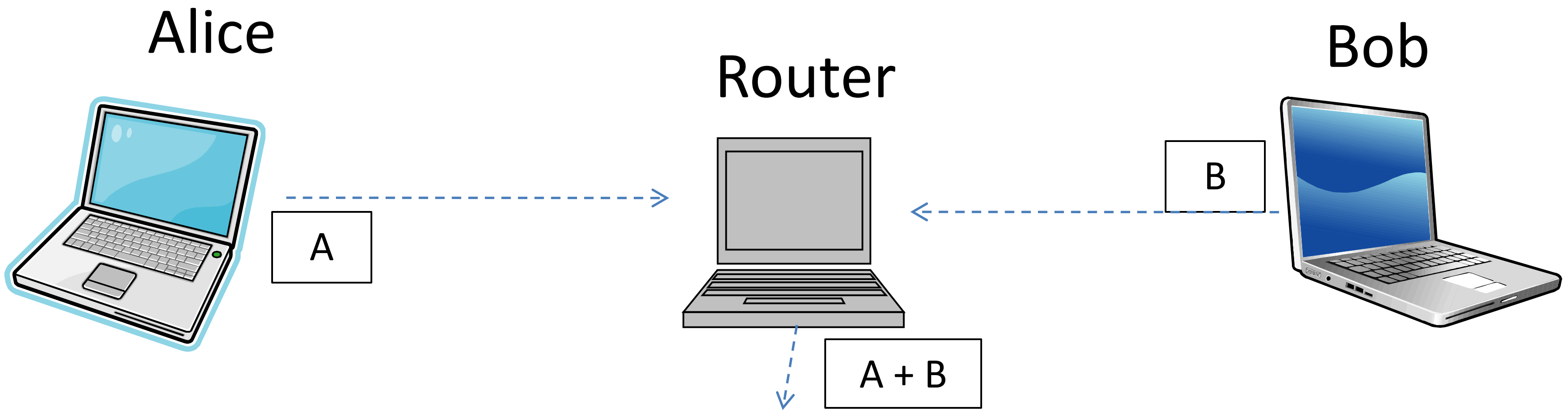
Coding gain = 8/5 = 1.6

Coding + MAC Gain



- MAC divides the bandwidth equally between the 3 contending nodes
- The router needs to transmit twice as many packets
- Hence router is a bottleneck
  - Half the packets are dropped as routers queue

Coding + MAC Gain



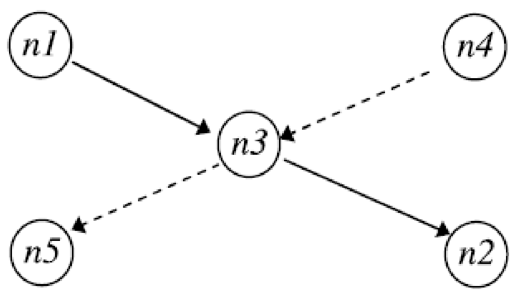
- COPE – XOR pairs of packets
  - router drains packets twice as fast

Coding + MAC gain = 2

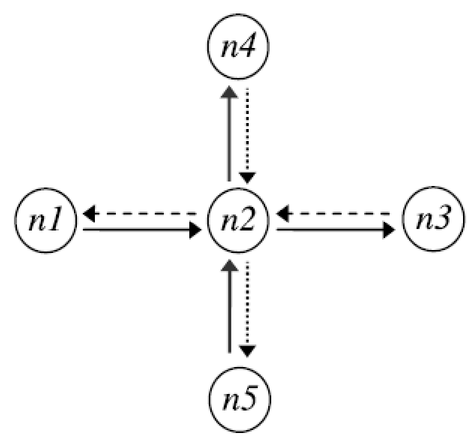
Coding + MAC Gain

- For topologies with single bottleneck

$$\text{Coding + MAC Gain} = \frac{\text{Draining rate with COPE}}{\text{Draining rate without COPE}}$$



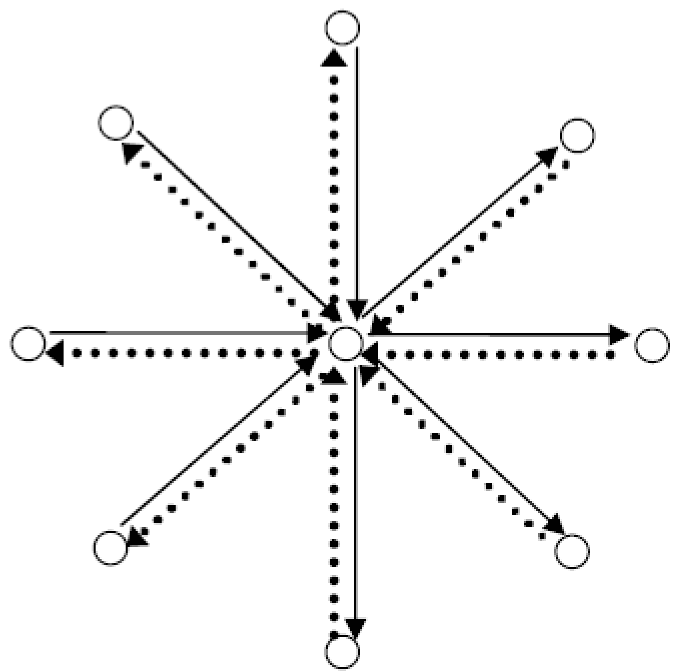
Coding + MAC gain = 2



Coding + MAC gain = 4

Coding + MAC Gain

- In the presence of opportunistic listening, COPE's maximum Coding + MAC gain is unbounded.



N -> ∞

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Making it work

- Packet Coding Algorithm
- Packet Decoding
- Pseudo-broadcast
- Hop-by-hop ACKs and Retransmissions
- Preventing TCP packet reordering

Packet Coding Algorithm

- Never delaying packets
  - Does not wait for additional codable packets to arrive
- Preference to XOR packets of similar lengths
  - Pad zeros if different lengths
- Maintain two virtual queues per neighbor
  - One for small, one for large packets
- Dequeue the packet at the head of the FIFO
  - Look only at the head of the virtual queues
- Each neighbor has a high probability of decoding the packet – Threshold probability

Packet Coding Algorithm

1 Coding Procedure

```
Pick packet p at the head of the output queue.
Natives = {p}
Nexthops = {nexthop(p)}
if size(p) > 100 bytes then
    which_queue = 1
else
    which_queue = 0
end if
for Neighbor i = 1 to M do
    Pick packet p_i, the head of virtual queue Q(i, which_queue)
    if ∀n ∈ Nexthops ∪{i}, Pr[n can decode p ⊕ p_i] ≥ G then
        p = p ⊕ p_i
        Natives = Natives ∪{p_i}
        Nexthops = Nexthops ∪{i}
    end if
end for
which_queue = !which_queue
for Neighbor i = 1 to M do
    Pick packet p_i, the head of virtual queue Q(i, which_queue)
    if ∀n ∈ Nexthops ∪{i}, Pr[n can decode p ⊕ p_i] ≥ G then
        p = p ⊕ p_i
        Natives = Natives ∪{p_i}
        Nexthops = Nexthops ∪{i}
    end if
end for
return p
```

Packet Decoding

- Each node maintains a *Packet Pool*
  - Packets it received or sent out
- Packets are stored in a hash table keyed on packet id
- Encoded packet with n packets
  - XOR with n – 1 packets from packet pool

Pseudo-broadcast

- Broadcast
  - No ACKs
  - No retransmissions
  - Poor reliability and lack of back-off
- Unicast
  - ACKed as soon as received
  - Sender back-off exponentially if no ACKs
  - Retransmissions
  - More Reliable

Pseudo-broadcast

- Pseudo-broadcast
  - Unicast packet to one of its recipients
  - That node ACKs and hence the transmission is reliable
  - Since others listen in promiscuous mode they receive the packet as well
  - An XOR header is added after the link-layer header listing all next hops
    - Each node checks the XOR header if it is a recipient and processes the packet

Hop-by-hop ACKs and Retransmissions

- Encoded packets require all next hops to ack the receipt of the associated native packet
  - Only one node ACKs (pseudo-broadcast)
  - There is still a probability of loss to other next hops
  - Hence, each node ACKs the reception of native packet
  - If not-acked, retransmitted, potentially encoded with other packets
  - Overhead - highly inefficient

Hop-by-hop ACKs and Retransmissions

- Asynchronous ACKs and Retransmissions
  - Cumulatively ACK every T_a seconds
  - If a packet is not ACKed in T_a seconds, retransmitted
  - Piggy-back ACKs in COPE header of data packets
  - If no data packets, send periodic control packets (same packets as reception reports)

Preventing TCP Packet Reordering

- Asynchronous ACKs can cause packet reordering
  - TCP can take this as a sign of congestion
- Ordering agent
  - Ensures TCP packets are delivered in order
  - Maintains packet buffer

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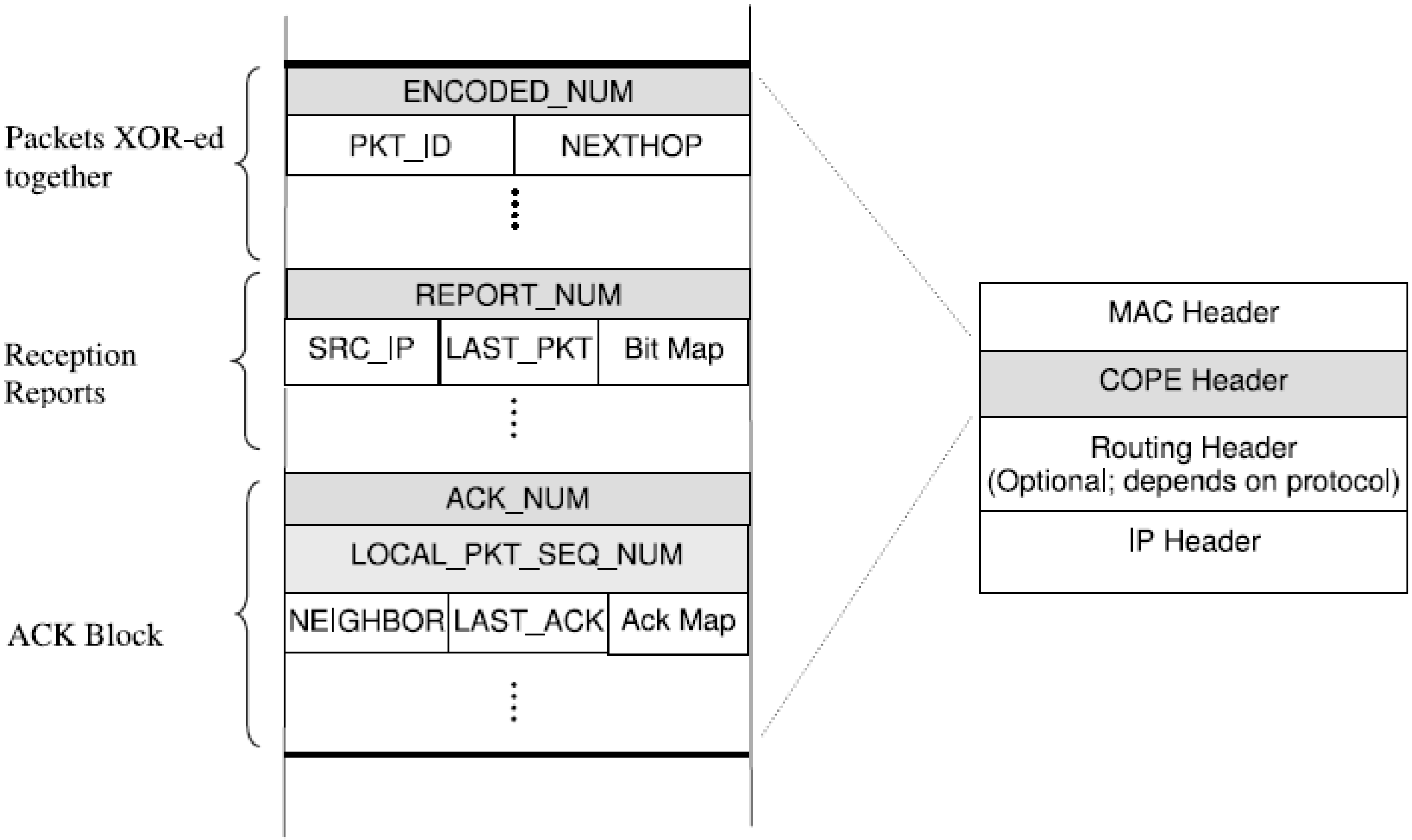
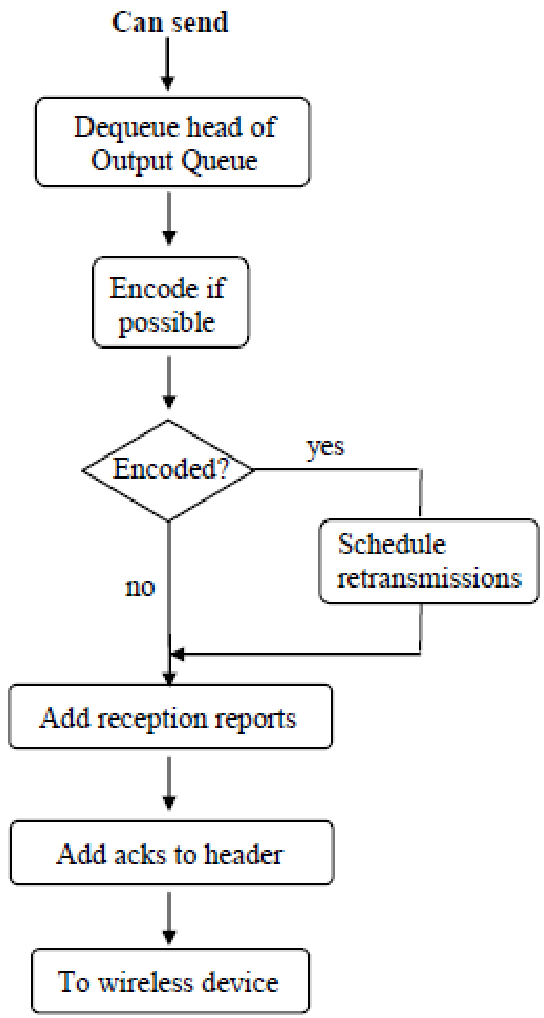
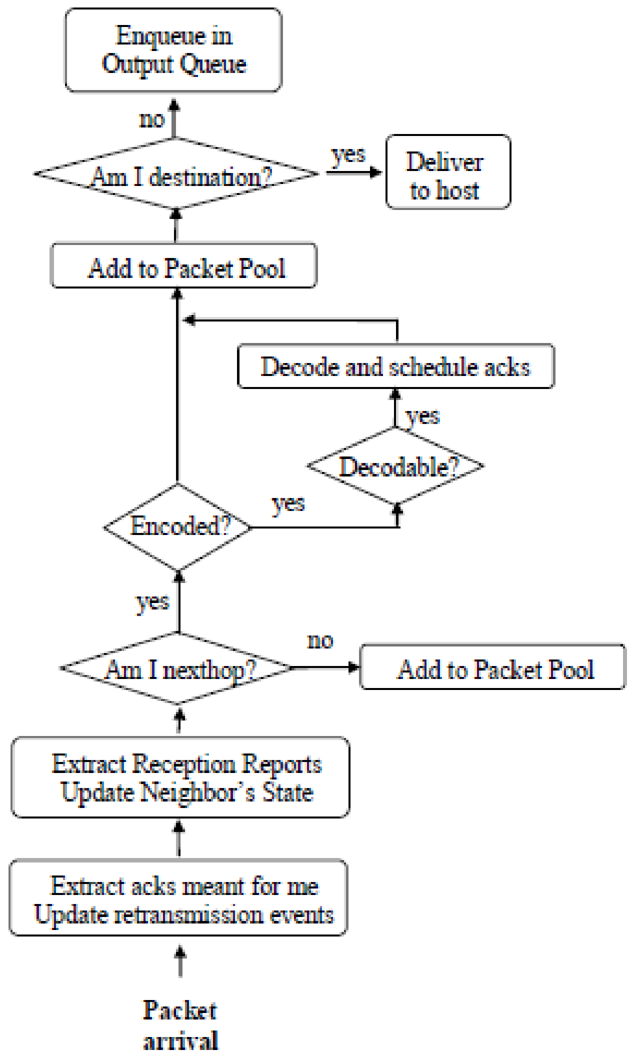
Packet Format



Control flow - Sender



Control flow - Receiver



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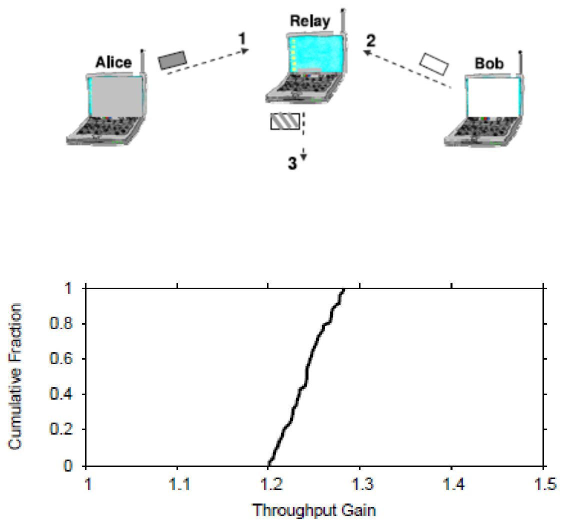
Testbed

- 20 nodes
  - Path between nodes are 1 to 6 hops in length
  - 802.11a with a bit-rate of 6Mb/s
- Software
  - Linux and click toolkit
  - User daemon and exposes a new interface
  - Applications use this interface
    - No modification to application is necessary
- Traffic model
  - *udpgen* to generate UDP traffic
  - *ttcp* to generate TCP traffic
  - Poisson arrivals, Pareto file size distribution

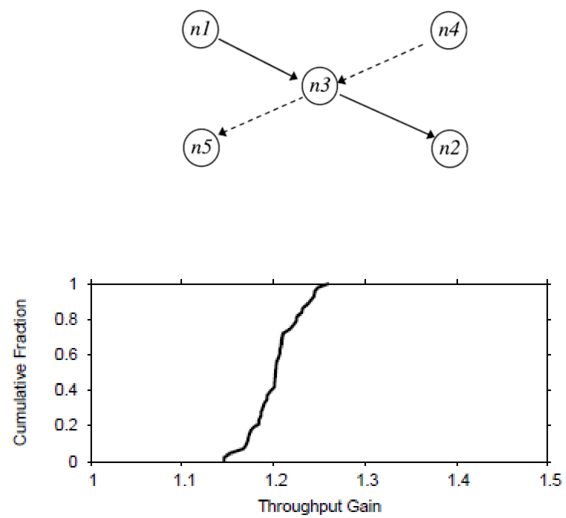
Metrics

- Network throughput
  - Total end-to-end throughput (sum of throughput of all flows in a network)
- Throughput gain
  - The ratio of measured throughput with and without COPE
  - Calculate from two consecutive experiments, with coding turned on and off

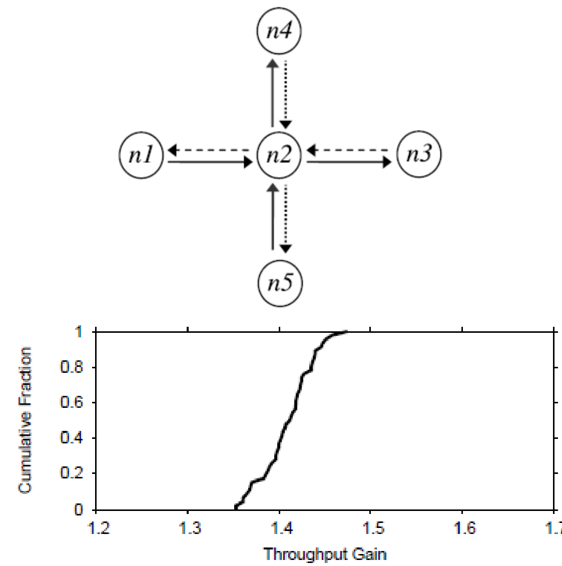
Long-lived TCP flows



(a) TCP gain in the Alice-and-Bob topology



(b) TCP gain in the X-topology

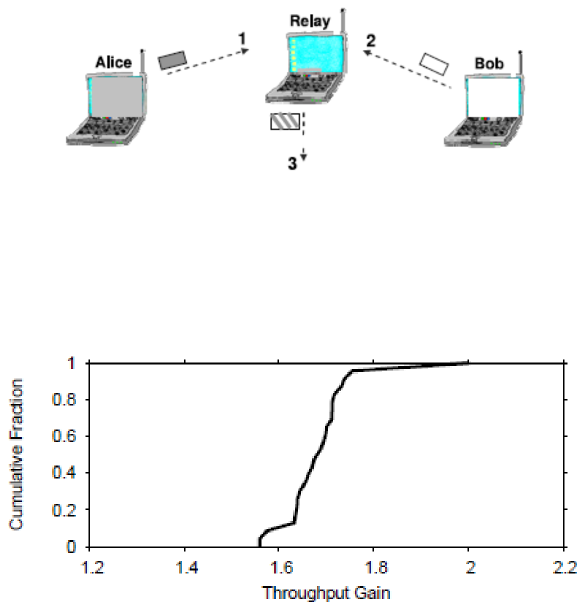


(c) TCP gain in the cross topology

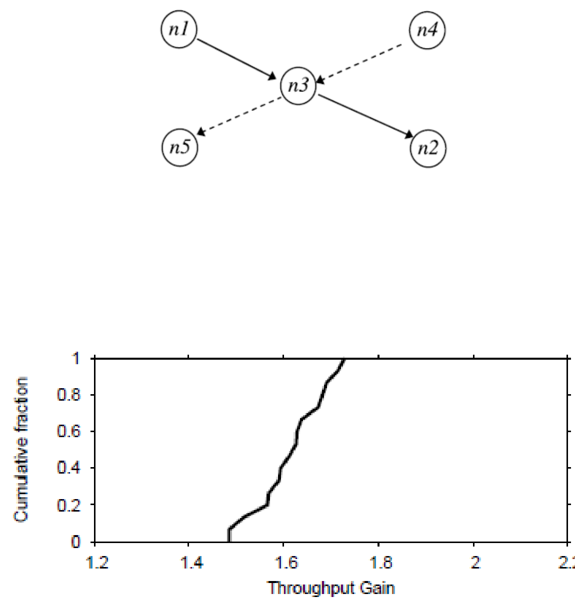
Close to 1.33 | Close to 1.33 | Close to 1.6

- Close to coding gain
  - TCP backs-off due to congestion control
  - To match the draining rate at the bottleneck

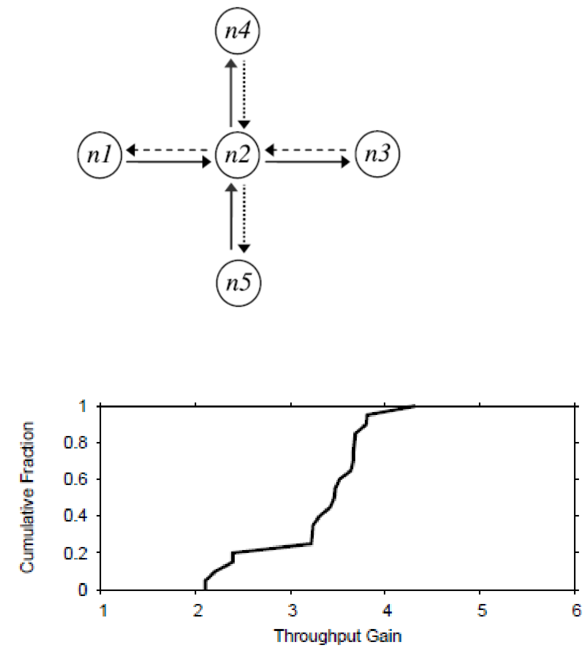
Long-lived UDP flows



(a) UDP gain in the Alice-and-Bob topology



(b) UDP gain in the X-topology



(c) UDP gain in the cross topology

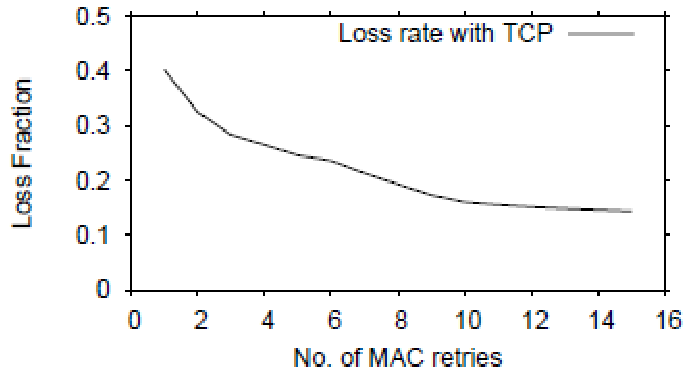
- Close to Coding + MAC gain
  - XOR headers add small overhead (5-8%)
  - The difference is also due to imperfect overhearing

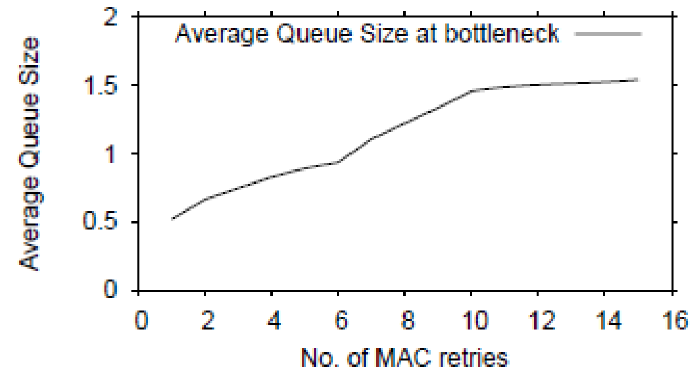
Ad-hoc network - TCP

- TCP flows
  - Arrive according to Poisson process
  - Pick sender and receiver randomly
  - Transfer files (size - Pareto distribution)

- Does not show any significant improvement
  - TCP's reaction to collision-related losses
  - Hidden terminals

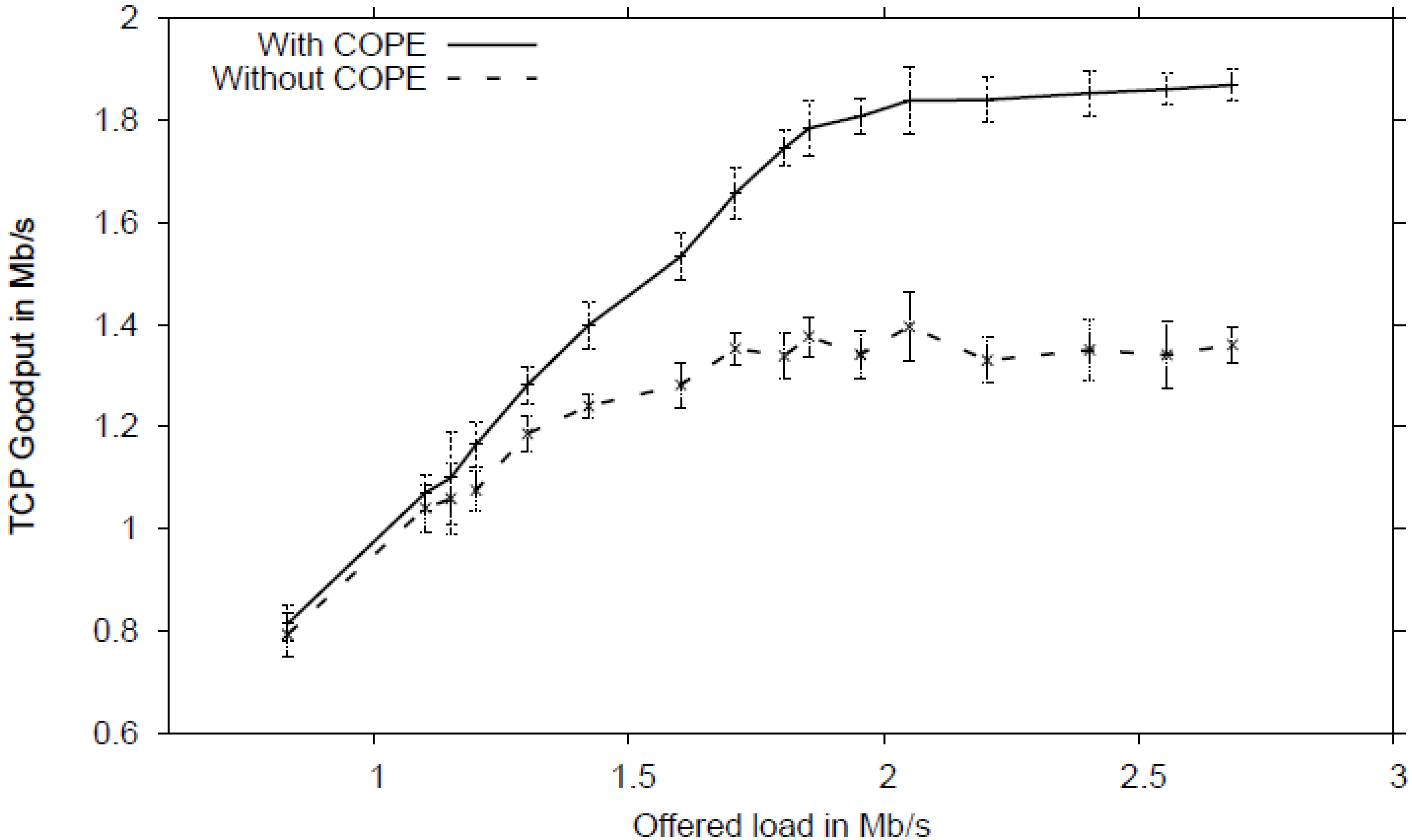
Ad-hoc network - TCP





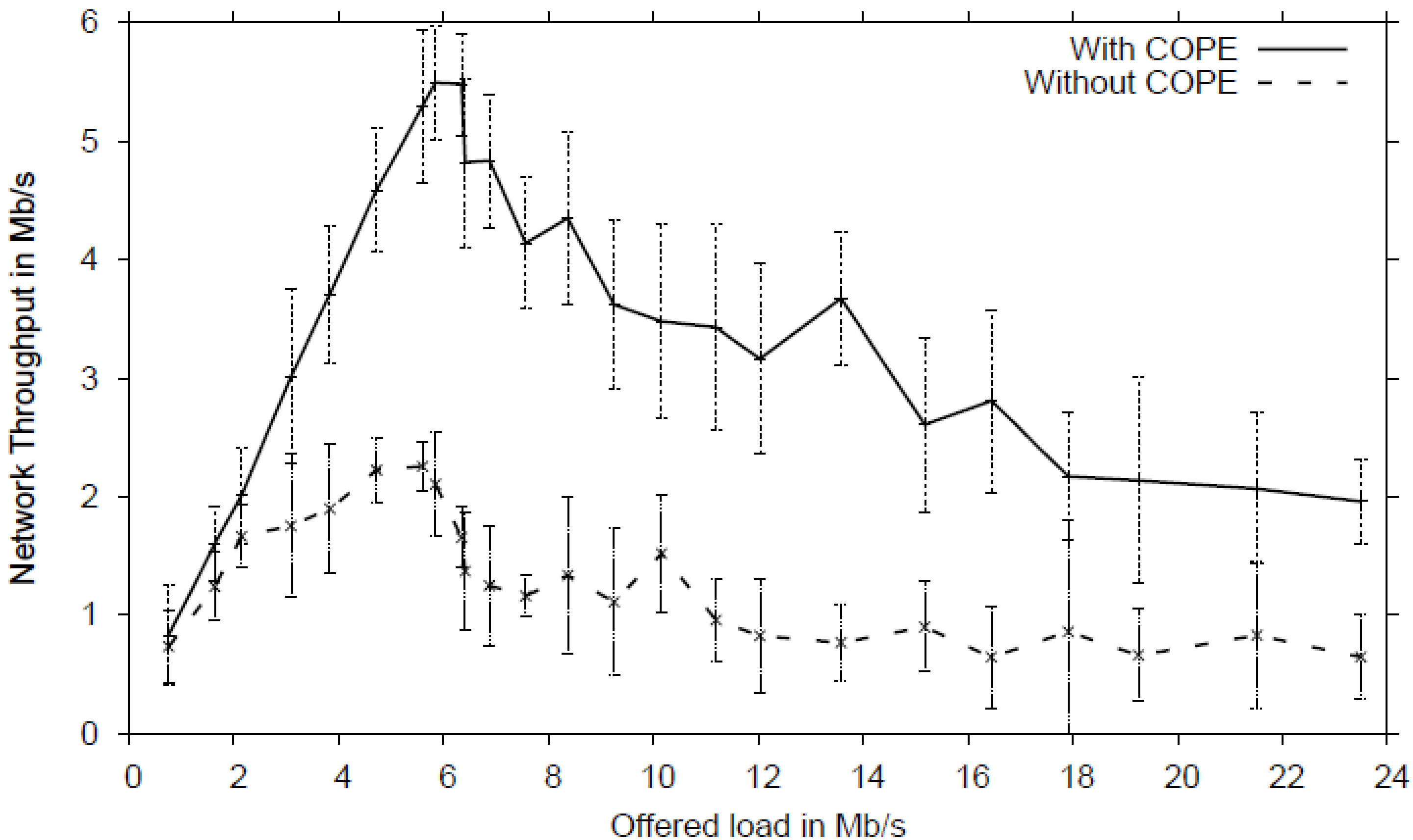
- Even with 15 MAC retries, 14% loss
  - Due to hidden terminals
- Bottleneck never see enough traffic to make use of coding
  - Few coding opportunities

TCP with no hidden terminals



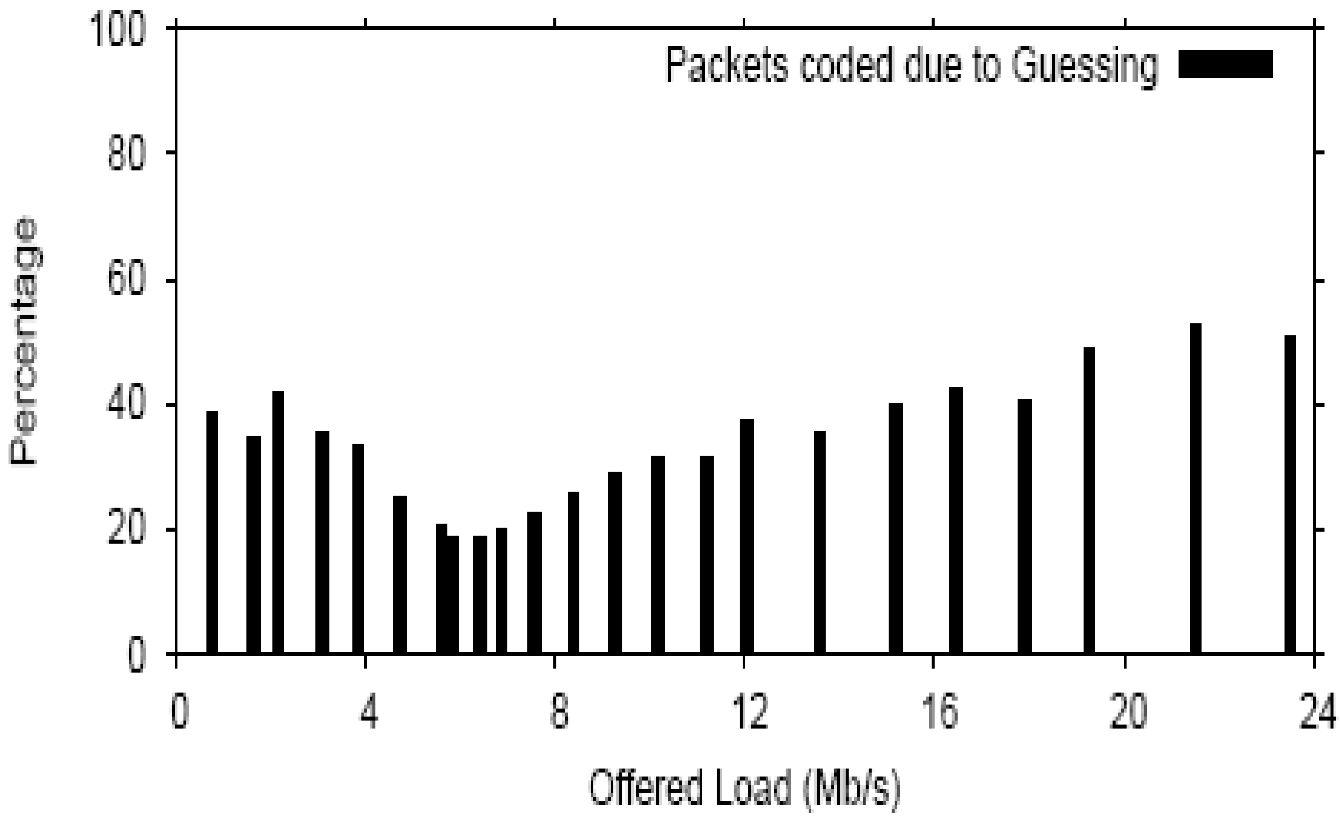
38% improvement in TCP goodput

Ad-hoc network - UDP

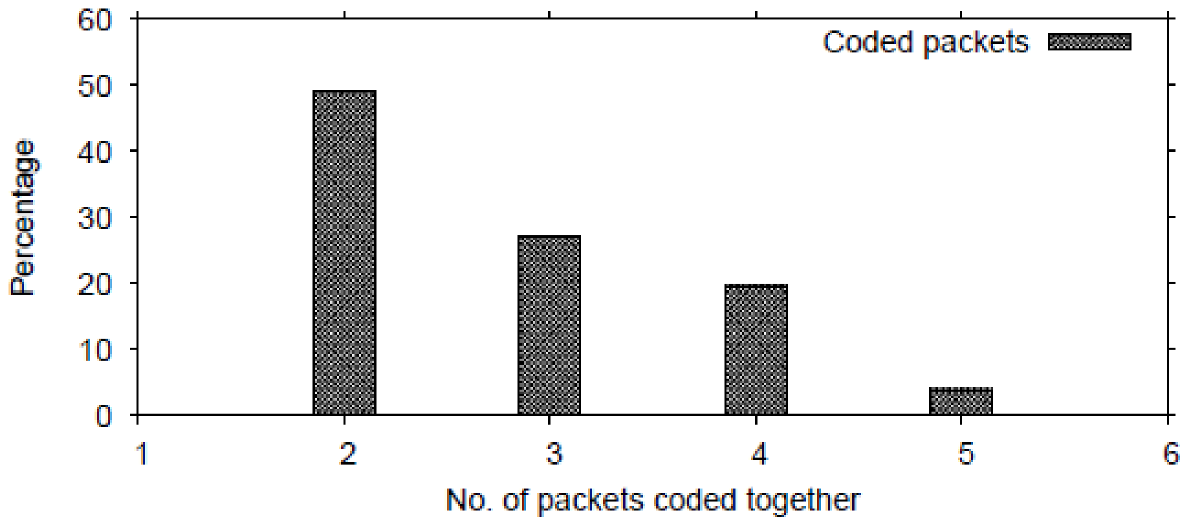


3-4x improvement in throughput

Ad-hoc network - UDP

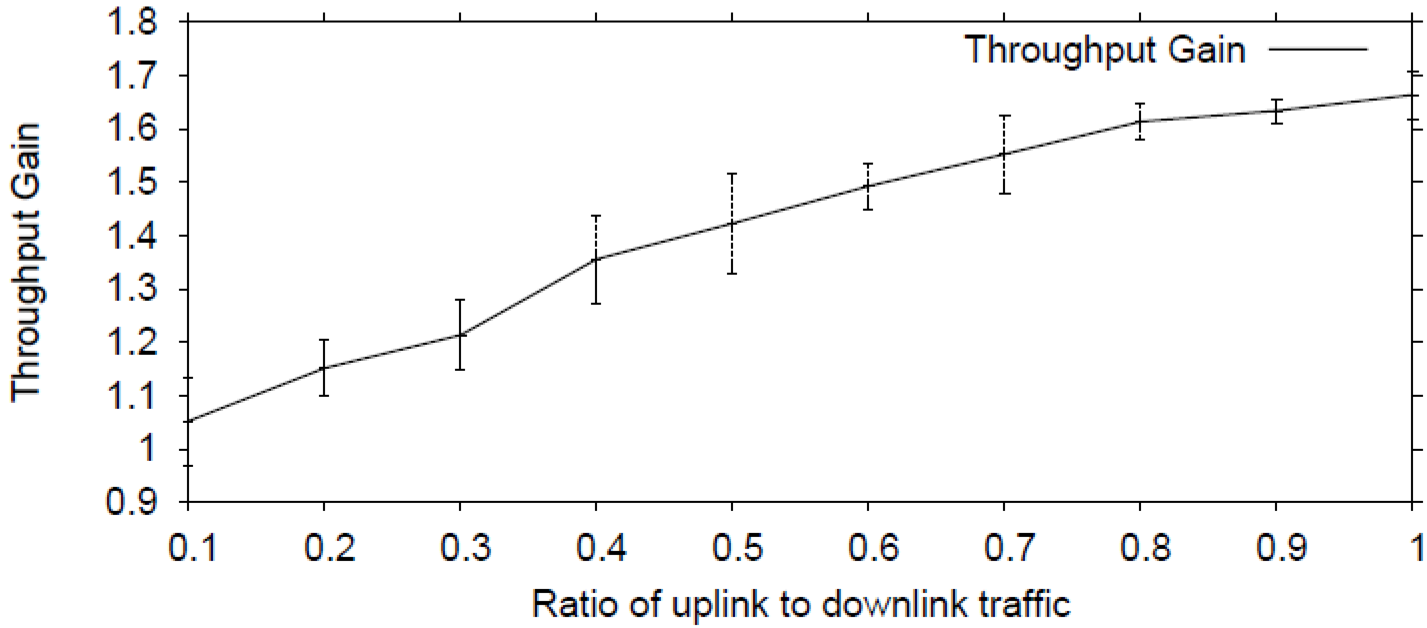


Ad-hoc network - UDP



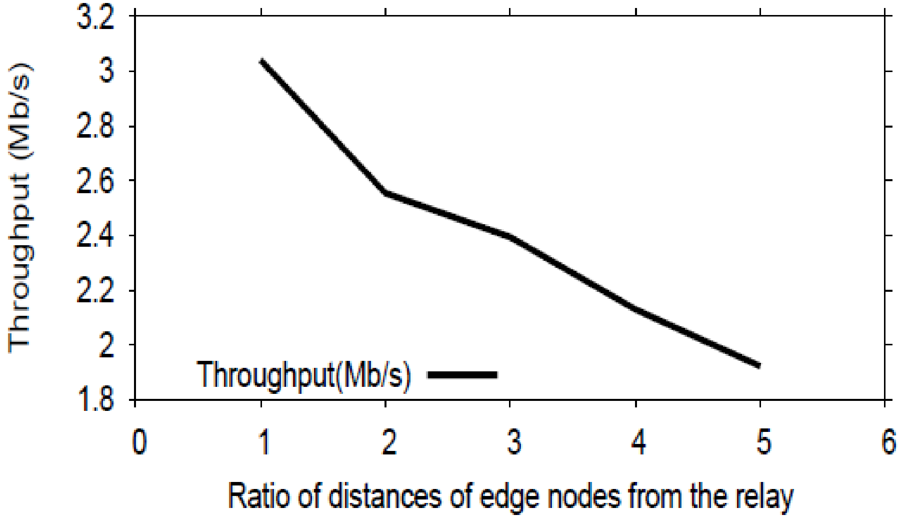
On an average 3 packet are coded together

Mesh network

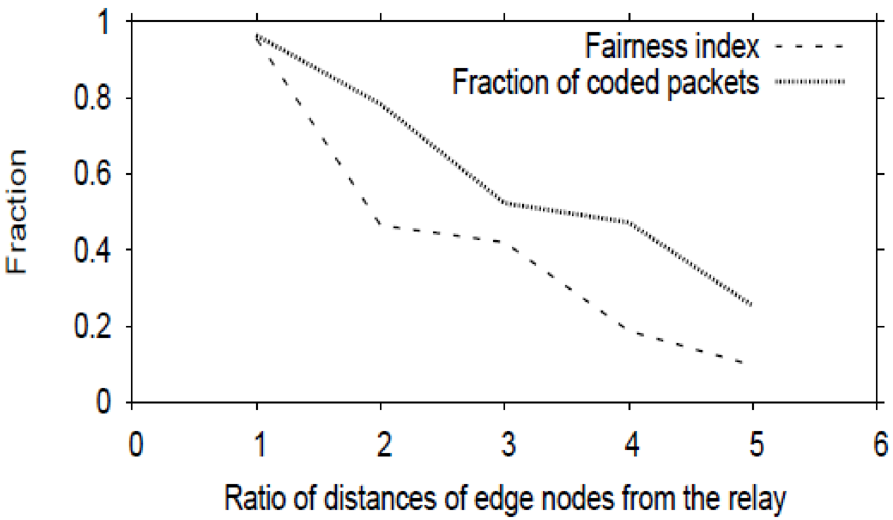


- COPE throughput gain relies on coding opportunities
  - Depends on diversity of packets in the queue of the bottleneck node

Fairness



More fair – more opportunities to code



Conclusion

- Network coding to improve the throughput of wireless networks
- COPE -Implementation of first system architecture for wireless network coding
- COPE improves the UDP throughput by 3-4x
- 5% to 70% throughput improvement in mesh networks depending on downlink-uplink ratio

Thank You

Questions?