A Framework for Joint Network Coding and Transmission Rate Control in Wireless Networks

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Motivation

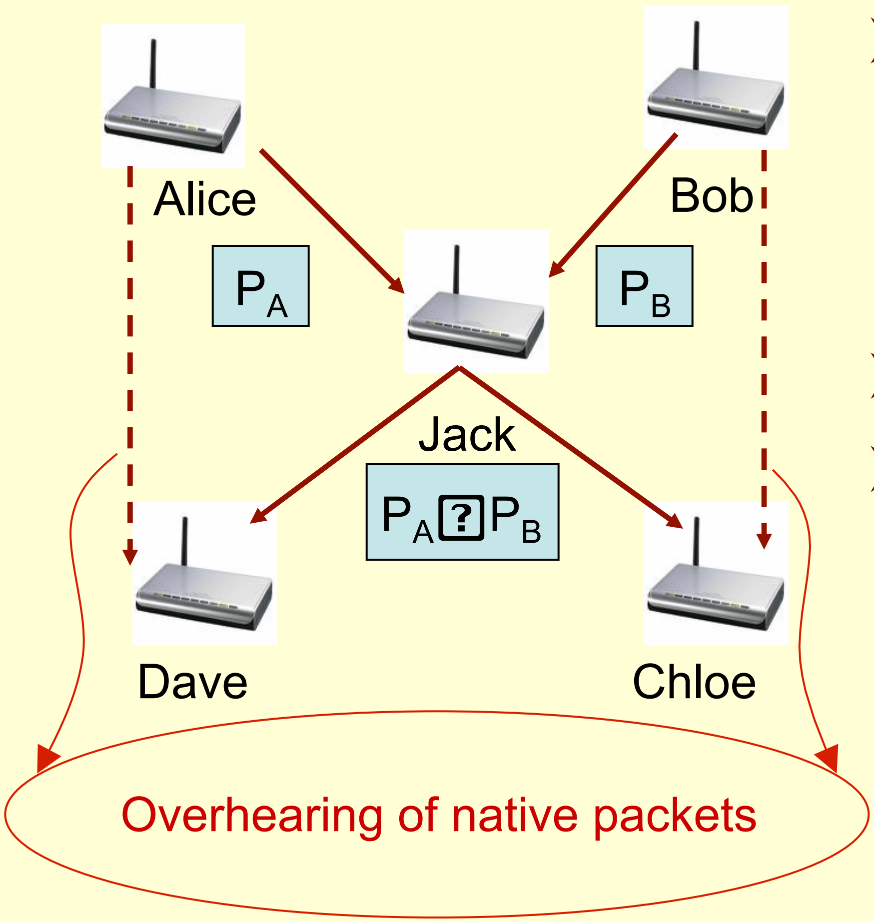
- Network coding is a technique that can potentially increase transport capacity of wireless networks
- Conventional network coding schemes do not consider the effect of using diverse transmission rates
- Higher transmission rates can improve the link-level throughput, but can degrade the encoding capacity by reducing packet overhearing probabilities

Goal

To maximize network throughput by achieving the best trade-off between two contradictory goals:

- To use higher transmission rates for improving link level throughputs
- To ensure effective overhearing at receivers to preserve high encoding gain

Network coding with COPE*



- Encode packets at routers into a single packet to make a single transmission
  - 3 transmissions instead of 4
- Encoding function: XOR
- Based on these functionalities:
  - Packet overhearing (packet pools)
  - "Probe packets" for link quality estimation
  - Periodic "Reception Reports" for native packets received at receivers
  - A fixed transmission rate at all nodes

* S. Katti, H. Rahul, W. Hu, D. Katabi, M. Medard, and J. Crowcroft, XORs in The Air: Practical Wireless Network Coding. In *ACM SIGCOMM*, 2006.

Our Approach

For transmission of native packets:

- Choose rate to maximize throughput to the router
- Consider overhearing probabilities

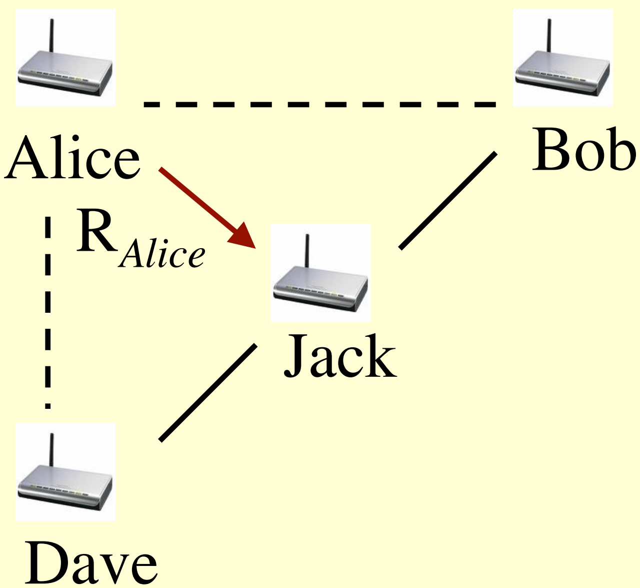
For transmission of encoded packets:

- Choose rate to maximize total throughput at receivers
- Properly choose the primary receiver (ACKer) of the encoded packet

Notations

- Transmission time at rate ***r*** of packet of length ***L***: T_L^r
- Probability of overhearing the transmission of rate ***r*** from ***x*** to ***y*** by ***z*:** $P^r_{\{x,y\},z}$
- Number of transmissions from ***x*** to ***y*** at rate ***r***: $N^r_{x,y}$
- Rate of transmission at node ***x*:** R_x
- Packet length of node ***x***: L_x

Local Transmission Rate Selection Module



- Select a rate to maximize throughput to Jack:

$$\max_{R_{Alice} \in R} \frac{L_{Alice}}{N^{R_{Alice}}_{Alice,Jack} \cdot T^{R_{Alice}}_{L_{Alice}}}$$

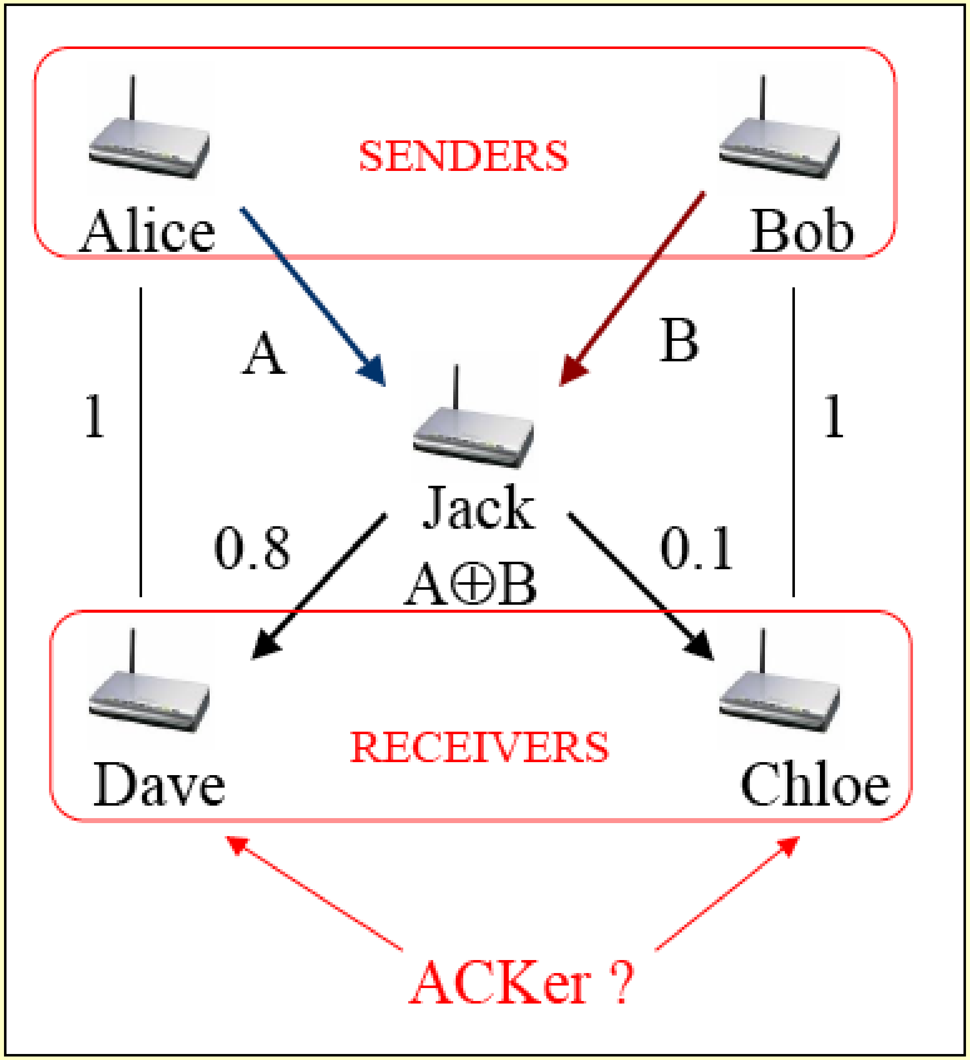
- Constrained by overhearing probabilities at common neighbors of Alice and Jack:

$$s.t. \quad P^{R_{Alice}}_{\{Alice,Jack\},Dave} \geq \beta$$

$$P^{R_{Bob}}_{\{Alice,Jack\},Bob} \geq \beta$$

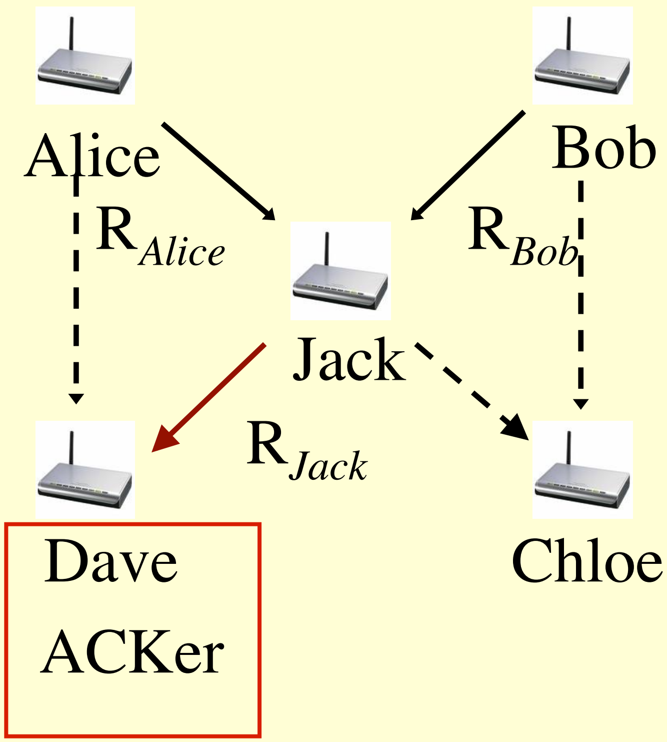
R: Set of transmission rates
(e.g. R: {6, 9, 12, 18, 24, 36, 48, 54} Mbps at 802.11a)

Example (ACKer Selection)



- Perfect overhearing
- Choice 1: ACKer is Chloe:
  - 1 / 0.1 = 10 expected retransmissions before receiving an ACK for A⊕B
  - Total packets: 2
  - Expected throughput:
  - 2/10 = 0.2
- Choice 2: ACKer is Dave:
  - 1/0.8 = 1.25 expected retransmissions before receiving an ACK for A⊕B
  - Total packets: 2
  - Expected throughput:
  - 2/1.25 = 1.6

ACKer Selection Module



- Jack selects one of the next hops of the encoded packet as the primary receiver (ACKer) node
  - Maximize the throughput by considering all next hops as the ACKer over all transmission ranges:

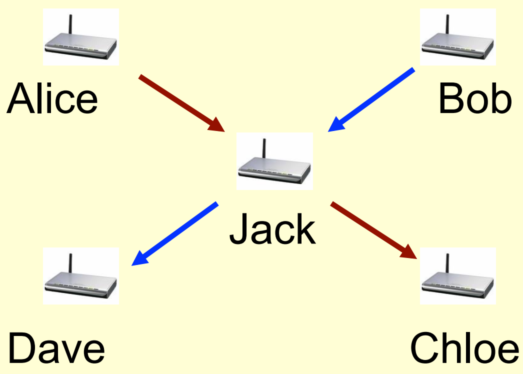
$$\max_{\substack{R_{Jack} \in R \\ ACKer \in \{Chloe, Dave\}}} \frac{L_t^{'}}{D_t^{'}}$$

- Jack unicasts encoded packet to the ACKer :
  - Retransmits until ACK is received
  - Other next hops receive the packet by overhearing
  - $P_{success}$: Probability of successful delivery to ACKer

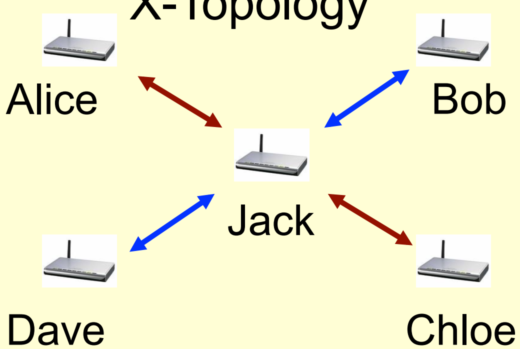
$$L'_t = P^{r_{Jack}}_{\langle Jack, ACKer \rangle, Chloe} \cdot P^{r_{Bob}}_{Bob, Chloe} \cdot L_{Alice} + P^{r_{Jack}}_{\langle Jack, ACKer \rangle, Dave} \cdot P^{r_{Alice}}_{Alice, Dave} \cdot L_{Bob}$$

$$D'_t = N^{r_{Jack}}_{Jack, ACKer} T^{r_{Jack}}_{max(L_{Alice}, L_{Bob})} \quad .$$

Experiments



X-Topology

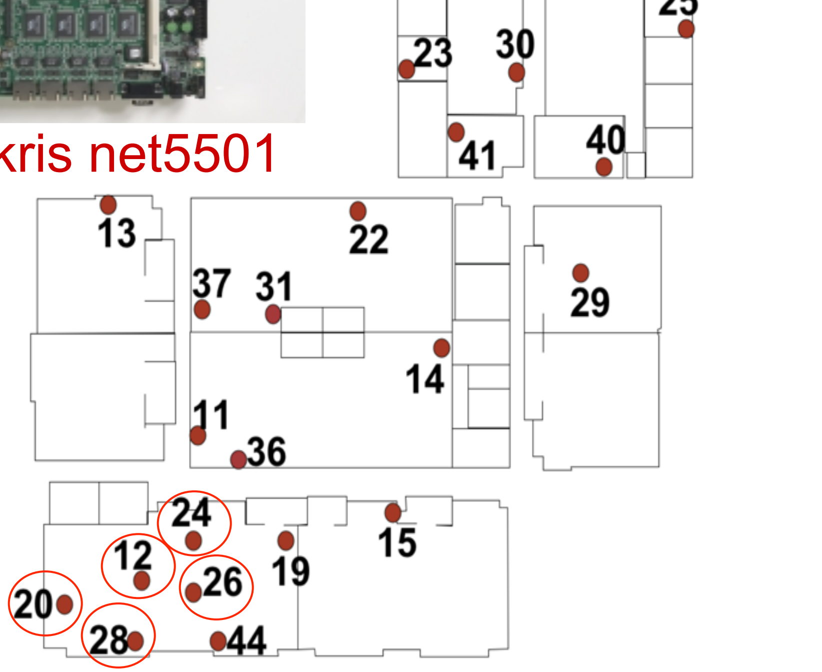


Cross Topology

- Click Router v.1.4.2 (as in COPE)
- Madwifi-2005 wireless driver
- 802.11b (4 bit rates: 1, 2, 5.5, 11 Mbps)
- Our scheme on top of COPE
  - COPE operates by default at 1 Mbps
- Probing mechanism of Roofnet routing protocol (SRCR)
- Two topologies:
  - X-Topology
  - Cross Topology

UCR Testbed

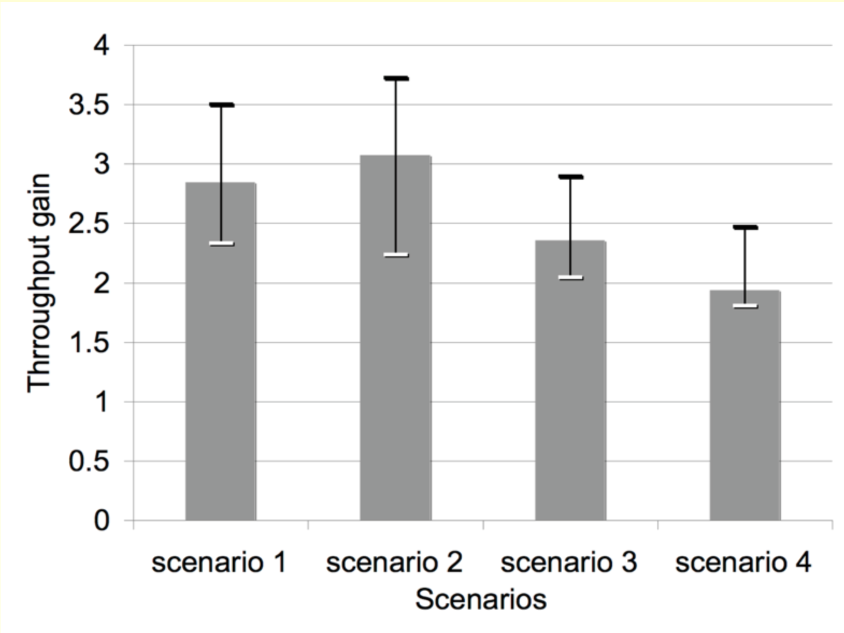
Soekris net5501



Sample topology for experiments

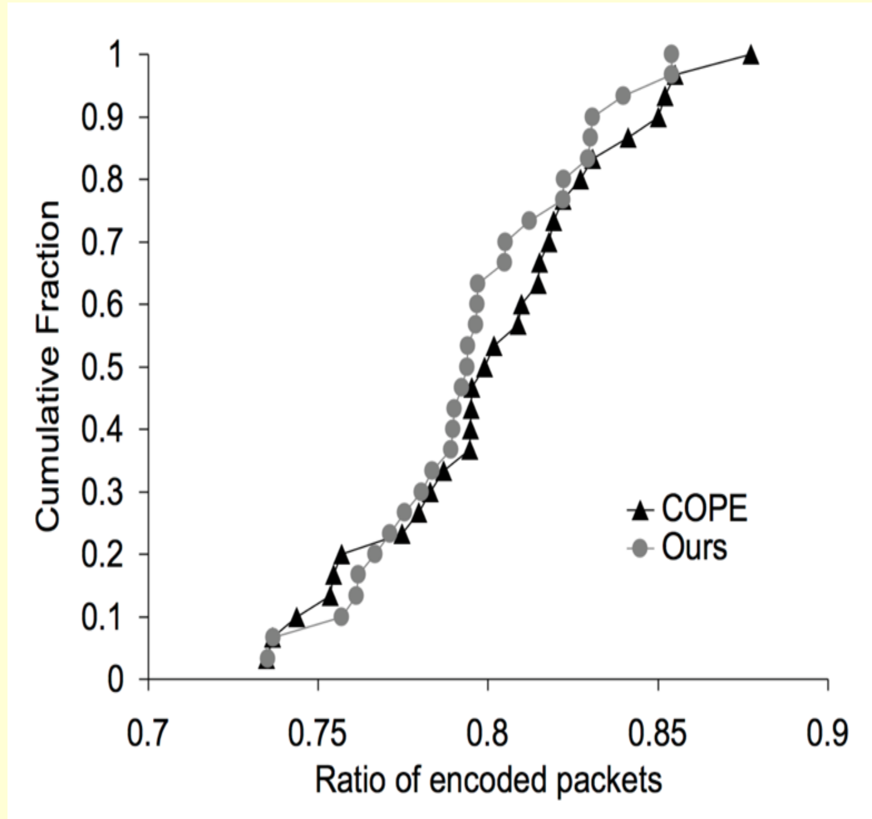
- Both indoor and outdoor links
- Soekris net5501 nodes
- Debian Linux distribution
- Kernel v2.6.16.19 over NFS
- 500 MHz CPU, 512 Mbytes of memory
- WN-CM9 wireless mini-PCI card
- AR5213 Atheros as main chip
- 5dBi omnidirectional antenna
- Transmission power set to 10 dBm
- RTS/CTS disabled

Gain in Throughput wrt COPE



➢ Significant improvement in throughput over COPE

Ratio of encoded packets at router



Scenario 1

- Good-channel quality links

(PDR of links are 70% or above)

- Up to 250% improvement
- Our scheme efficiently exploits good channel conditions by utilizing higher transmission rates
- Our scheme does not hurt encoding gain while using higher transmission

rates

Scenario 2

- Good channel quality links

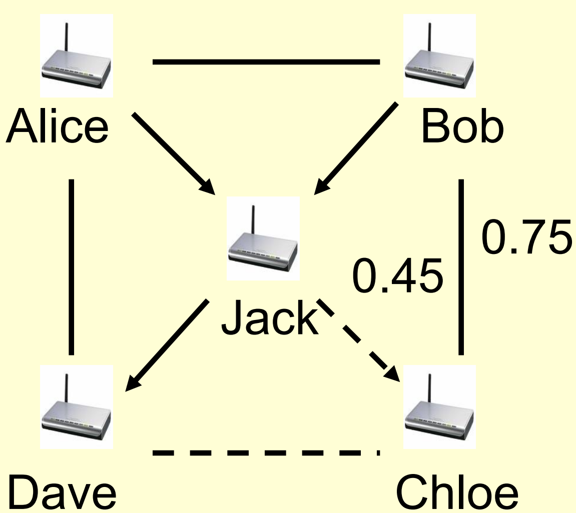
(PDR of links are 70% or above)

- Bi-directional traffic flows
    - Can encode up to 4 packets
- Up to 272% improvement
- We can obtain 20% higher throughput

than X topology since higher encoding opportunities occur with 4 traffic flows.

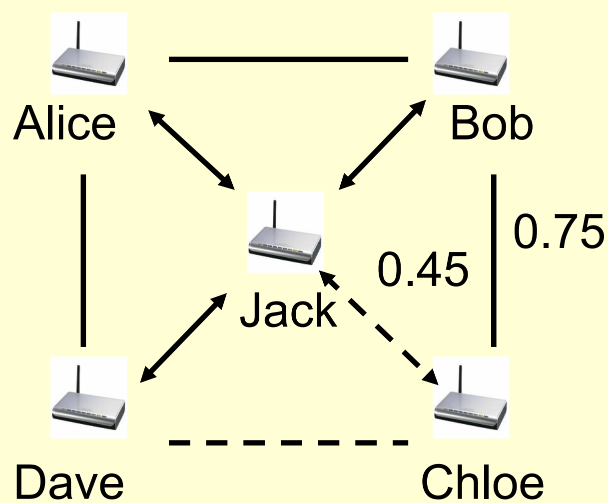
Scenario 3

- Poor quality links:
  - < Jack to Chloe >
  - < Chloe to Dave >
- Up to 189% improvement
- To increase probability of reception by Chloe, Bob uses lower transmission rates compared to Scenarios 1&2 : Less gain is obtained



Scenario 4

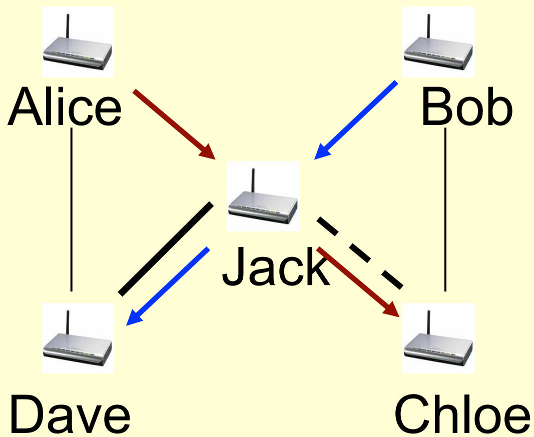
- Poor quality links:
  - < Chloe to Jack >
  - < Chloe to Dave >
- Up to 150% improvement
- Both Alice and Bob use lower transmission rates <u>to increase overhearing probabilities</u>. Hence, throughput gain is lower than Scenario 3



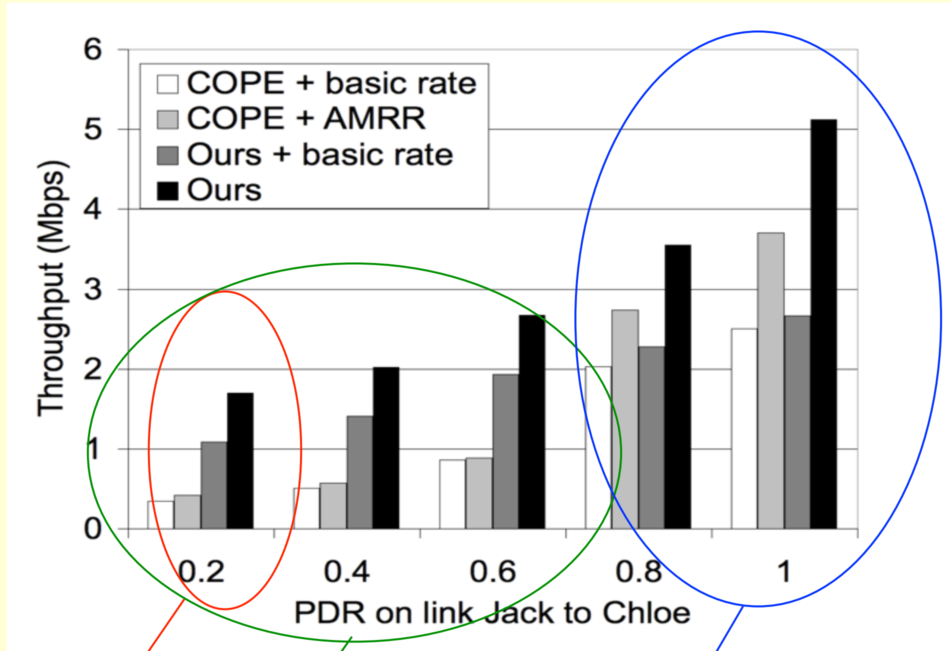
Simulations

- Network Simulator 2 (ns2)
- 802.11a (8 bit rates: 6, 9, 12, 18, 24, 36, 48, 54 MBps)
- Performance results of the following schemes are compared:
  - COPE (basic rate)
  - COPE + rate adaptation
  - Our scheme with only ACKer Selection
  - Our scheme with both ACKer Selection and Rate Selection

Small-Scale Topologies



X Topology



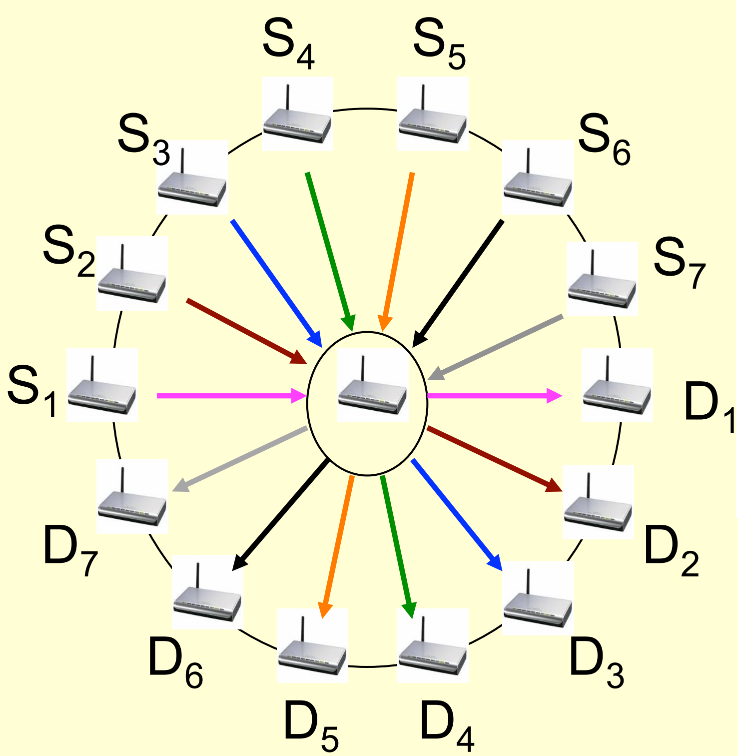
$\text{PDR}_{\text{<Jack to Dave>}} = 1$

$\text{PDR}_{\text{<Jack to Chloe>}}$: varied

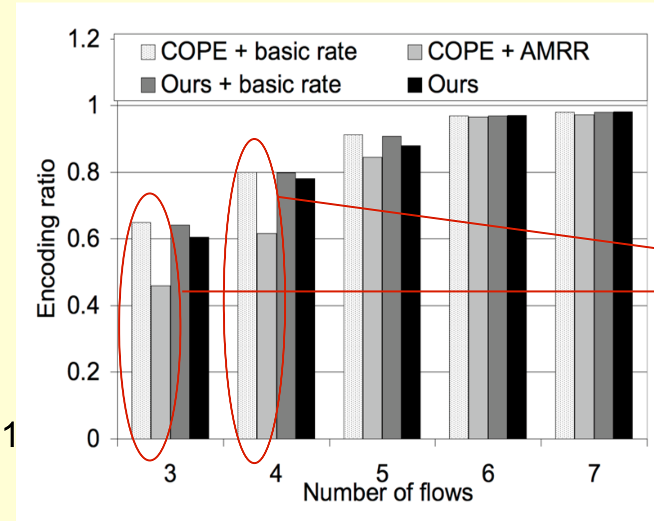
- With this topology, up to 390% improvement is obtained over COPE
- ACKer selection is important when link qualities to receivers are diverse
- Rate Selection is important when link qualities are similar

Gain in throughput: 75% over COPE, 30% over COPE + Rate Adaptation

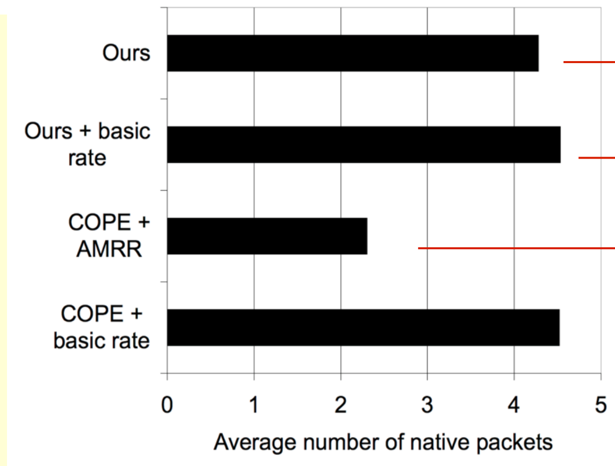
Dense "Wheel" Topologies



$$Encoding\ Ratio = \frac{Total\ number\ of\ encoded\ packets\ sent}{Total\ number\ of\ packets\ sent}$$



COPE + Rate Adaptation is coding unaware

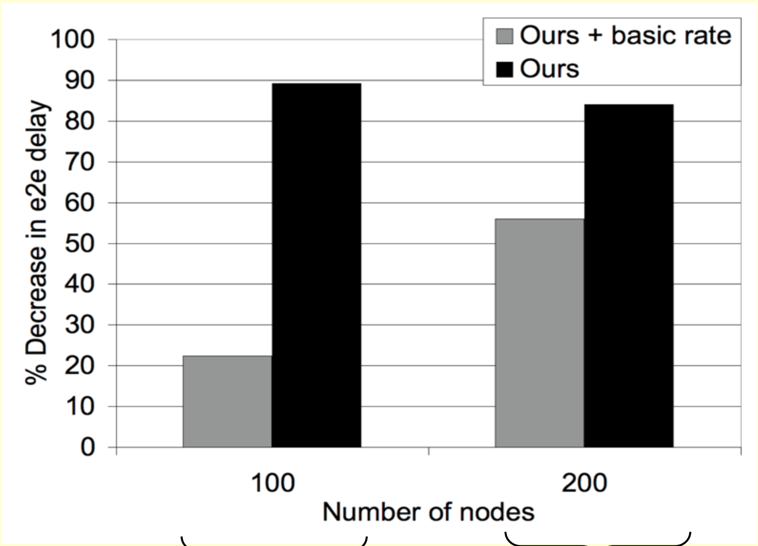


Slightly less than COPE

Similar to COPE

~ Half of COPE

Larger-scale Multihop Settings



- $1000 \times 1000\ m^2$
- Random node locations
- Randomly selected source-destination pairs
- Paths established by DSR
- Fully-saturated UDP flows

Less Interference → Higher transmission rates possible → Delay is reduced mostly by transmission rate increase

Higher interference → Higher and more diverse packet loss rates → ACKer selection is predominant factor In delay reduction

Conclusions

- Performance gain of our framework in throughput with network coding as much as 390% compared to COPE
- A coding-unaware rate adaptation scheme degrades coding gain and achievable throughput
- Our scheme conserves the coding gain of COPE even with higher transmission rates
- Routers can boost throughput performance by intelligently choosing the recipient of the encoded packets