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,
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 $z$: $P_{\{x,y\},z}^{r}$
- Number of transmissions from $x$ to $y$ at rate $r$: $N_{x,y}^{r}$
- 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:
\[
\text{s.t. } P^{R_{Alice}}_{\{Alice, Jack\}, Dave} \geq \beta
\]
\[
P^{R_{Bob}}_{\{Alice, Jack\}, Bob} \geq \beta
\]

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 $A\oplus B$
  - 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 $A\oplus B$
  - 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:

$$\max_{R_{Jack} \in R, \text{ACKer} \in \{Chloe, Dave\}} \frac{L'_t}{D'_t}$$

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

\[
L'_t = P_{\text{Jack}}^{r_{Jack}, \text{ACKer}, Chloe} \cdot P_{\text{Bob}, Chloe}^{r_{Bob}} \cdot L_{Alice} \\
+ P_{\text{Jack}}^{r_{Jack}, \text{ACKer}, Dave} \cdot P_{\text{Alice}, Dave}^{r_{Alice}} \cdot L_{Bob} \\
D'_t = N_{Jack, \text{ACKer}}^{r_{Jack}} T_{\text{max}}^{r_{Jack}}(L_{Alice}, L_{Bob})
\]
Experiments

- 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
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

Sample topology for experiments
Gain in Throughput wrt COPE

Ratio of encoded packets at router

- Significant improvement in throughput over COPE
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 to increase overhearing probabilities. 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

- PDR_{Jack to Dave} = 1
- PDR_{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{\text{Total number of encoded packets sent}}{\text{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 x 1000 m²
- 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 ACKer selection is predominant

Higher interference
Higher and more diverse packet loss rates
Transmission rate increase 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