# Network Coding-Aware Queue Management for Unicast Flows over Coded Wireless Networks

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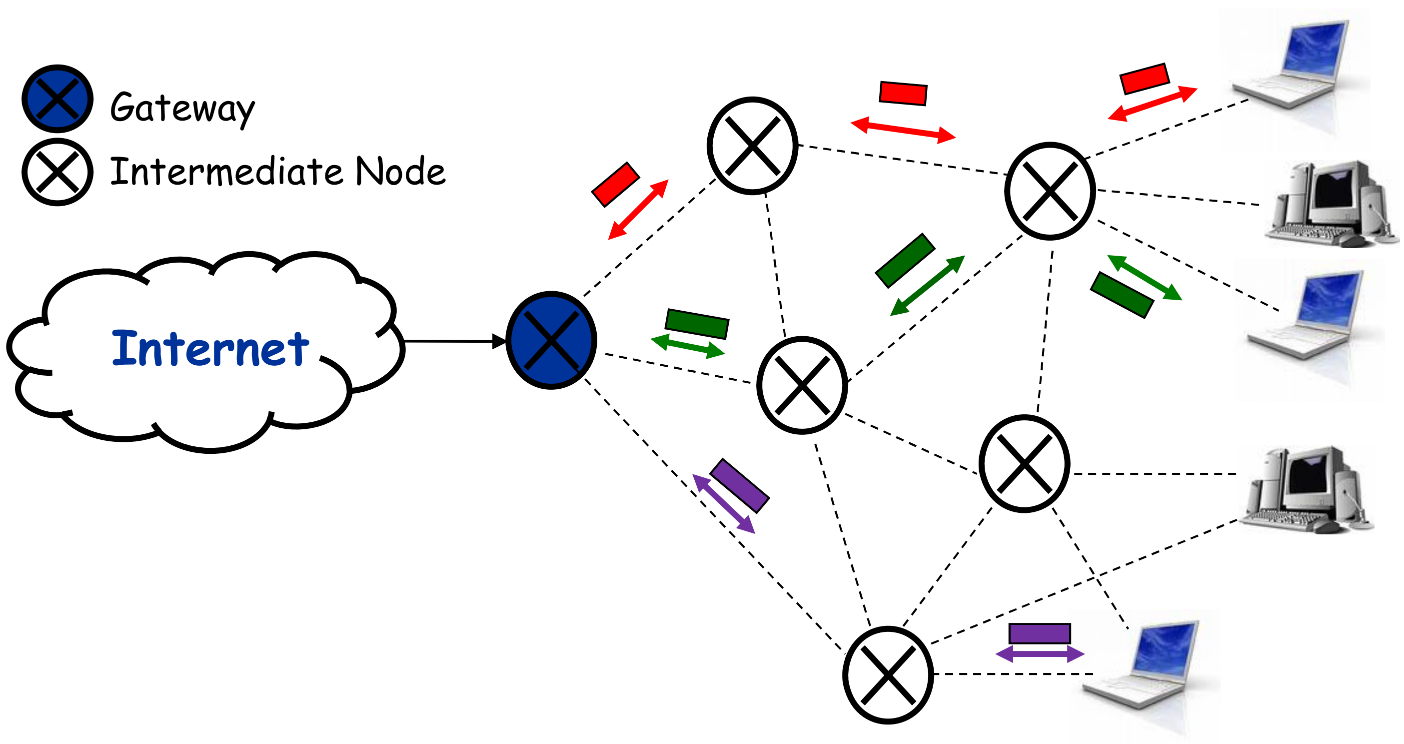
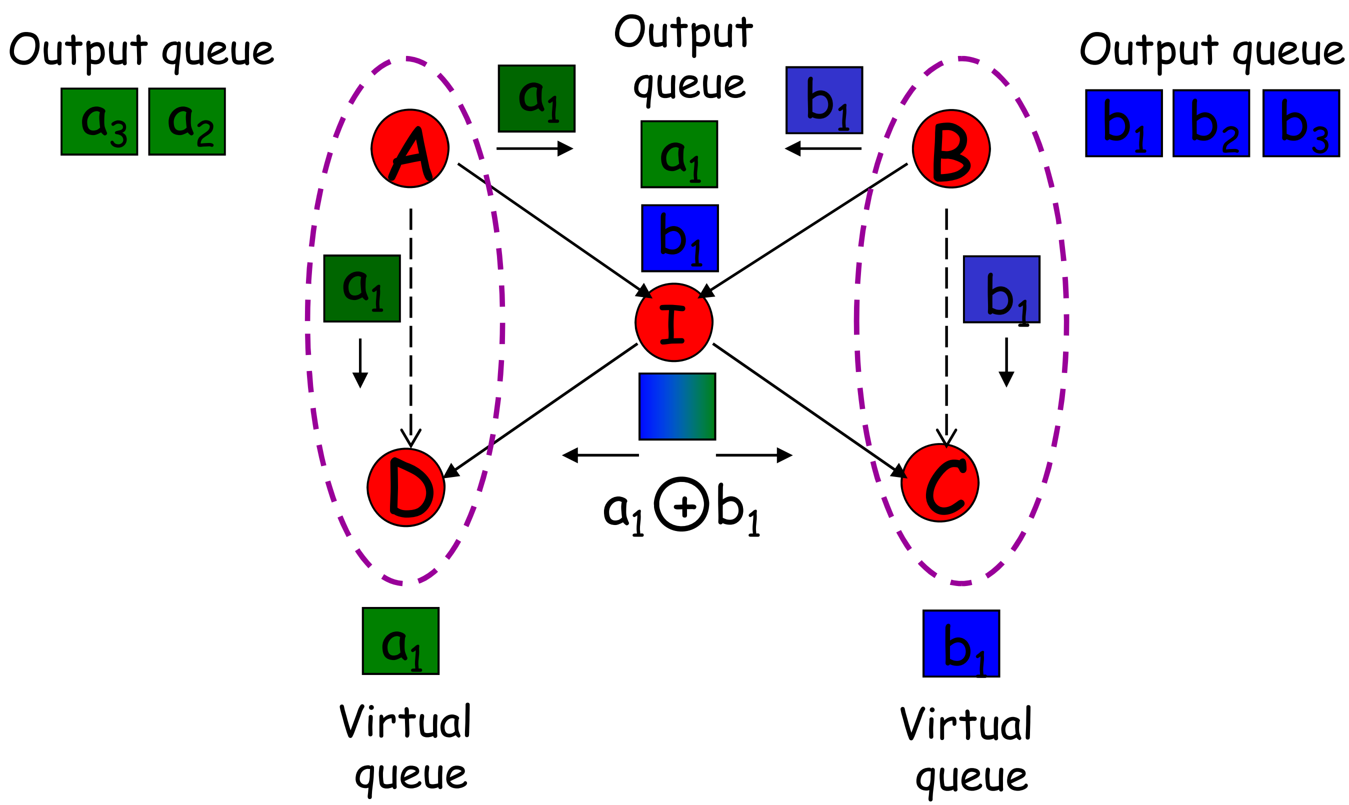
# Wireless Mesh Networks

- Y. Wu, P. A. Chou, S. Y. Kung, "Information exchange in wireless network coding and physical layer broadcast", CISS '05.
- S. Katti, H. Rahul, W. Hu, D. Katabi, M. Medard, J. Crowcroft "XORs In The Air: Practical Wireless Network Coding, (COPE)", ToN '08.
- Throughput increases by mixing packets

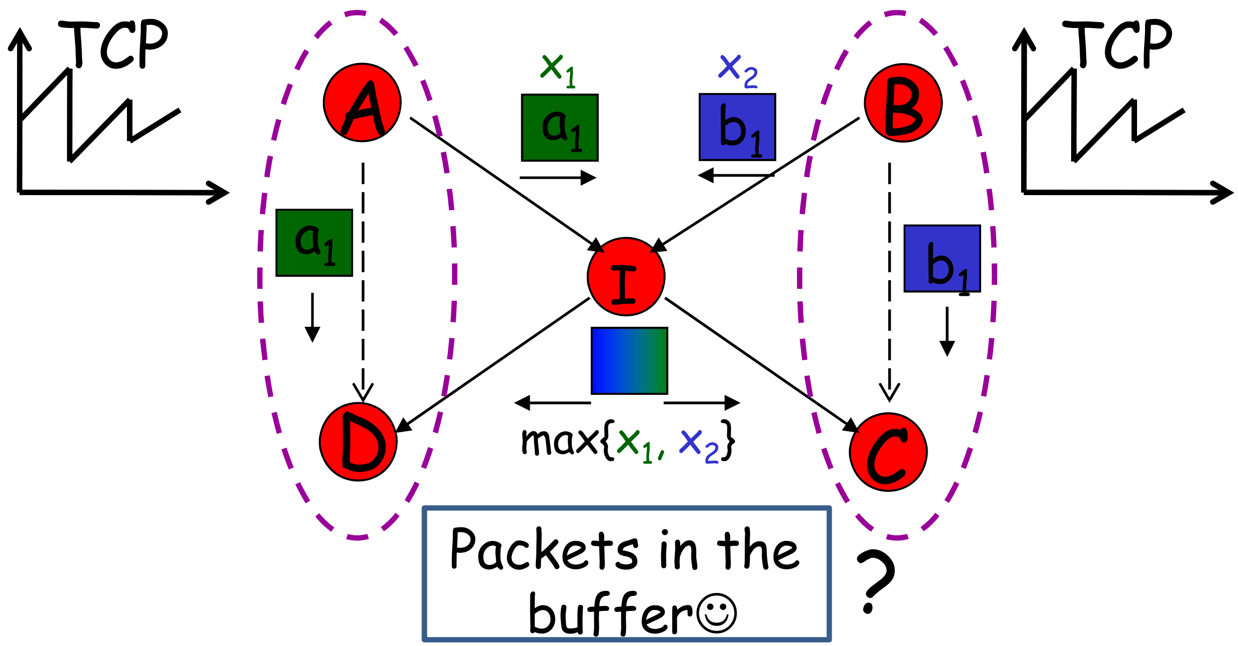


# One-hop network coding



# Motivation

- Problem:
  - TCP over COPE does not fully exploit the NC potential
- Intuition:
  - Not enough coding opportunities due to TCP burstiness
  - Coded flows do not compete for resources



# Motivation

- Problem:
  - TCP over COPE does not fully exploit the NC potential
- Intuition:
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  - Coded flows do not compete for resources
- *A* Possible Solution:
  - Artificially delay packets at intermediate nodes

    Y. Huang, M. Ghaderi, D. Towsley, and W. Gong, "TCP performance in coded wireless mesh networks," SECON '08.
  - Throughput increases with small delay, but decreases with large delay
  - Optimal delay depends on the network topology and the background traffic, and may change over time
  - Not practical

# Motivation

- Problem:
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- Proposed Solution:
  - Network Coding-Aware Queue Management (NCAQM)
  - No changes to TCP and MAC
  - Formulate network utility maximization (NUM) problem
  - TCP+NCAQM doubles the network coding benefit of TCP+COPE

# Previous Work
## Intra-session Network Coding

- Minimum  cost multicast for wired and wireless:
  - D. S. Lun, N. Ratnakar, M. Medard, R. Koetter, D. R. Karger, T. Ho, E. Ahmed, and F. Zhao, “Minimum-cost multicast over coded packet networks,” ToIT'06.
  - L. Chen, T. Ho, S. Low, M. Chiang, and J. C. Doyle, “Optimization based rate control for multicast with network coding,” Infocom'07.
- Minimum cost unicast with for wireless:
  - B. Radunovic, C. Gkantsidis, P. Key, P. Rodriguez, and W. Hu, “Toward Practical Opportunistic Routing with Intra-session Network Coding for Mesh Networks,” ToN’09.

# Previous Work
## Inter-session Network Coding

- Optimal Scheduling and Routing:
  - P. Chaporkar and A. Proutiere, "Adaptive network coding and scheduling for maximizing througput in wireless networks," Mobicom'07.
  - S. Sengupta, S. Rayanchu, and S. Banarjee, "An Analysis of Wireless Network Coding for Unicast Sessions: The Case for Coding-Aware Routing," Infocom'07.
- Energy efficient network coding:
  - T. Cui, L. Chen, and T. Ho, "Energy Efficient Opportunistic Network Coding for Wireless Networks," Infocom'08.
- End2end pairwise network coding:
  - A. Khreishah, C. C. Wang, and N. B. Shroff, "Cross-layer optimization for wireless multihop networks with pairwise intersession network coding," JSAC'09.

# Motivation

- Proposed Solution:
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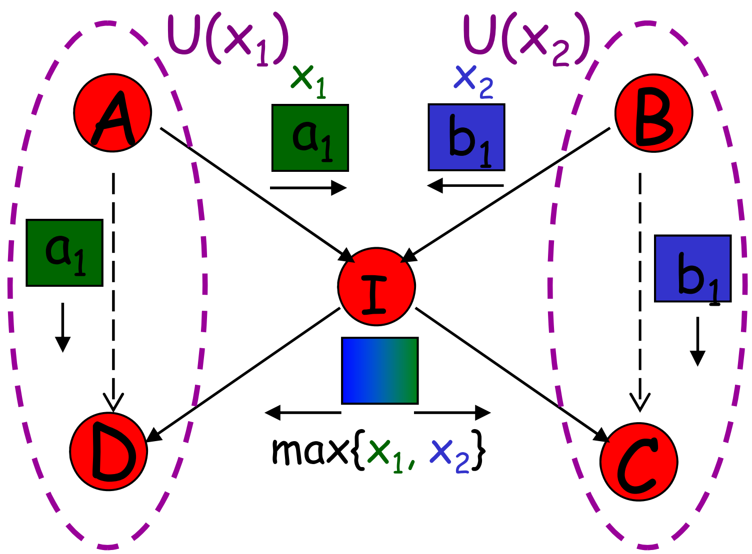
- Our work in perspective:
  - Multiple unicast flows over wireless with given network coding scheme and pre-determined routing paths
  - Connection between optimization and protocol design
  - Intuition for practical implementation

# Outline

- Introduction
- Network Utility Maximization (NUM)
- Network Coding-Aware Queue Management (NCAQM)
- Performance Evaluation
- Extensions & Summary

# Network utility maximization
## Formulation




$$\max_{x,\alpha,\tau} \sum_{s\in S} U_s(x_s)$$

Optimize total utility

$$s.t. \quad \sum_{k\in K_h} \max_{s\in S_k}\{H_h^{s,k}\alpha_h^{s,k}x_s\} \le R_h\tau_h, \quad \forall h \in A$$

Capacity constraint

$$\sum_{h(J)|h\in A} \; \sum_{k\in K_h|s\in S_k} \alpha_h^{s,k} = 1, \quad \forall s \in S, i \in P_s$$

Flow Conservation

$$\sum_{h\in C_q} \tau_h \le \gamma, \quad \forall C_q \subseteq A$$

Interference

# Network utility maximization

## Solution I:

$$\max_{s \in S_k} \{ H_h^{s,k} \alpha_h^{s,k} x_s \} \equiv \begin{array}{ll} \max\limits_{m} & \sum\limits_{s \in S_k} H_h^{s,k} \alpha_h^{s,k} x_s m_h^{s,k} \\ s.t. & \sum\limits_{s \in S_k} m_h^{s,k} = 1 \end{array}$$

$$\max_{x,\alpha,\tau} \sum_{s \in S} U_s(x_s)$$

$$s.t. \quad \sum_{k \in K_h} \sum_{s \in S_k} H_h^{s,k} \alpha_h^{s,k} x_s (m_h^{s,k})^* \le R_h \tau_h, \quad \forall h \in A$$

$$\sum_{h(J)|h \in A} \sum_{k \in K_h | s \in S_k} \alpha_h^{s,k} = 1, \quad \forall s \in S, i \in P_s$$

$$\sum_{h \in C_q} \tau_h \le \gamma, \quad \forall C_q \subseteq A$$

# Network utility maximization
## Solution II:

**Rate Control**

$$x_s = (U_s')^{-1}\left(\sum_{h\in A}\sum_{k\in K_h|s\in S_k} q_h H_h^{s,k}\alpha_h^{s,k}(m_h^{s,k})^*\right)$$

**Queue Size**

$$q_h(t+1) = \left\{q_h(t) + c_t\left[\sum_{k\in K_k}\sum_{s\in S_k} H_h^{s,k}\alpha_h^{s,k}(m_h^{s,k})^* x_s - R_h\tau_h\right]\right\}^+$$

**Traffic Splitting**

$$\min_{\alpha} \sum_{h(J)|h\in A}\sum_{k\in K_h|s\in S_k} q_h H_h^{s,k}(m_h^{s,k})^*\alpha_h^{s,k}$$
$$s.t. \sum_{h(J)|h\in A}\sum_{k\in K_h|s\in S_k}\alpha_h^{s,k} = 1,\ \forall i\in P_s$$

**Scheduling**

$$\max_{\tau}\sum_{h\in A} q_h R_h \tau_h$$
$$\sum_{h\in C_q}\tau_h \le \gamma,\ \forall C_q \subseteq A$$

# Network Coding-Aware Queue Management (NCAQM)

Protocol modifications, mimicking the optimal solution

| | Implementation Summary |
|---|---|
| Queue management (NCAQM) | • Network coding<br>• Packet dropping |
| TCP | No change (TCP-SACK) |
| MAC | No change (802.11) |

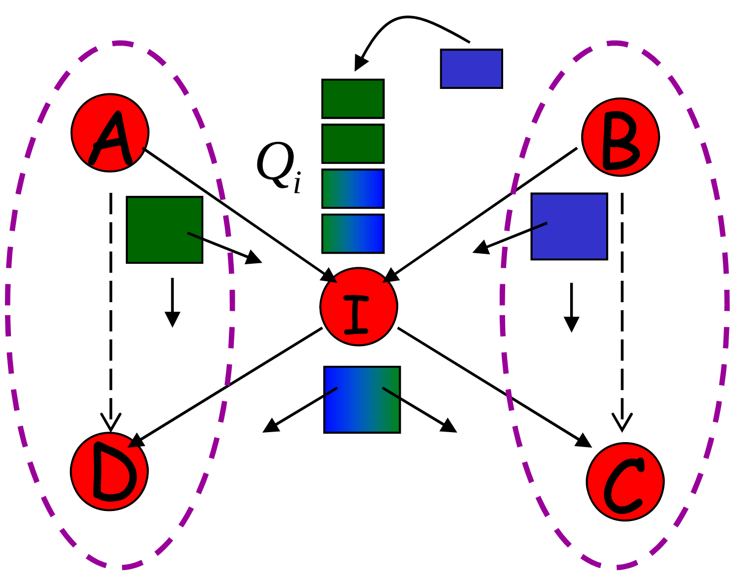
Minimal and intuitive

# NCAQM

## Maintaining queues and packet transmission

Queue Size

$$q_h(t+1) = \left\{ q_h(t) + c_t \left[ \sum_{k \in K_k} \max_{s \in S_k} \left\{ H_h^{s,k} \alpha_h^{s,k} x_s \right\} - R_h \tau_h \right] \right\}^+$$




### Modification I

- $Q_i$ is the output queue at node $i$
- Store network coded packets (when an opportunity arises) instead of uncoded packets
- Keep track of hypearc queues
- Estimate traffic splitting parameters
- Packet scheduling is according to FIFO queue

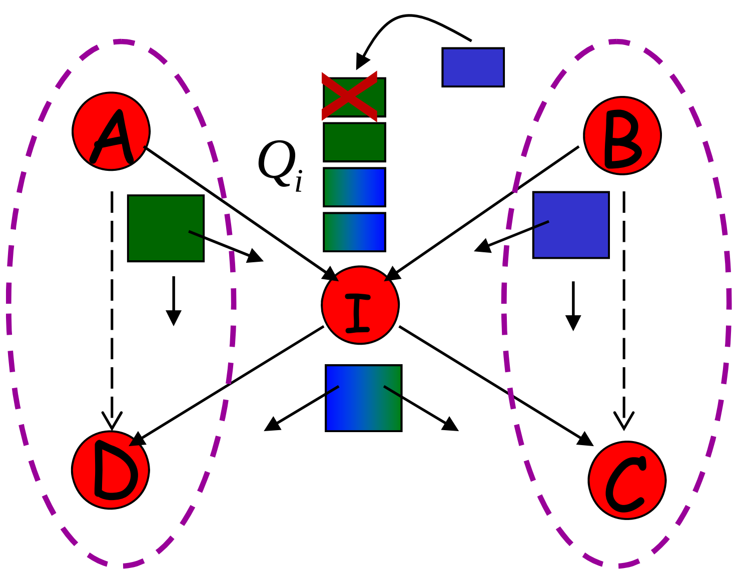
# NCAQM

## Rate control and packet dropping

Optimal Rate Control

$$x_s = \left( \sum_{h(i) \in P_s} q^s_{h(i)} \right)^{-1}$$

→ Sum of network coded queue sizes across all nodes on the path




### Modification II

- Upon congestion, compare $Q_i^s$ for all flows s. Drop an uncoded packet from the largest flow
- How to calculate $Q_i^s$?
  - Determine hyperarc queues that flow s is dominating (has the largest number of packets)
  - Sum the number of packets of flow s over these hyperarc queues

# NCAQM

## Implementation Summary

- Problem:
  - TCP over COPE does not fully exploit the NC potential
- Intuition:
  - Flows coded together do not compete for resources
  - Not enough coding opportunities due to TCP burstiness
- Modifications
  - Store network coded packets (when an opportunity arises) instead of uncoded packets.
  - Compare $Q_i^s$ for all s. Drop an uncoded packet from the "largest" flow.

# Outline

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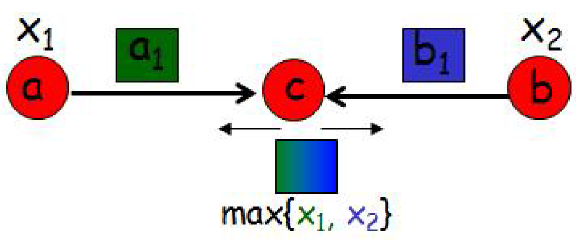
# Performance evaluation

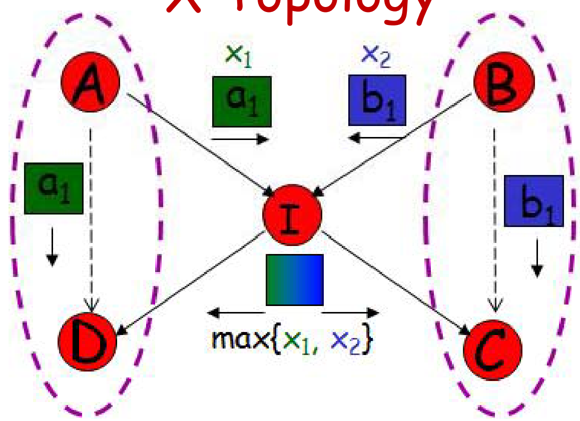
## Scenarios

[Glomosim + NC]

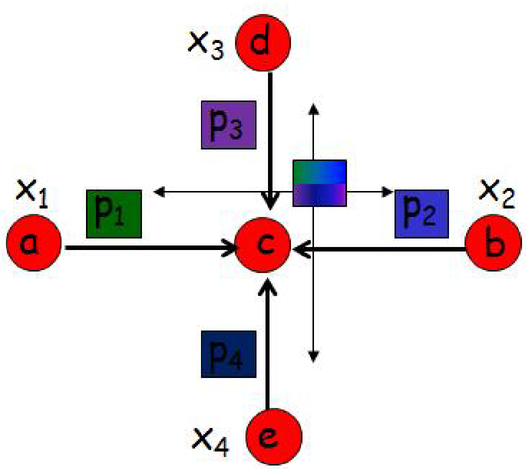
### A & B Topology



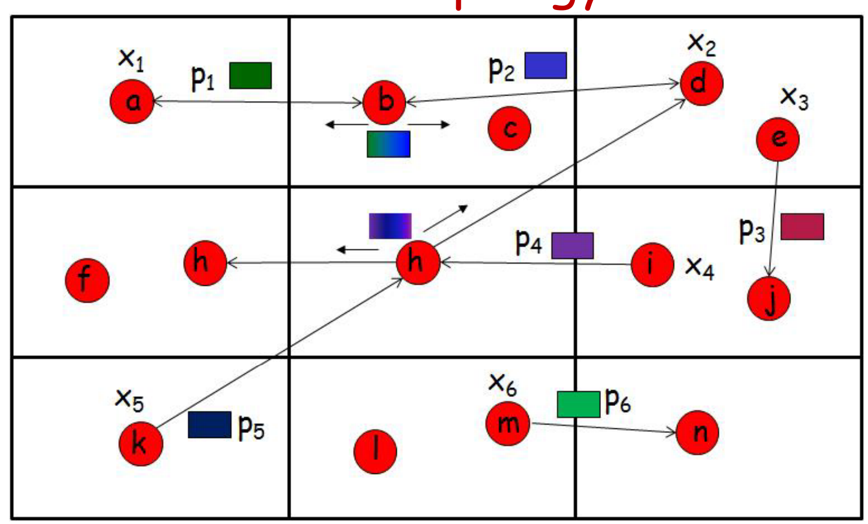

### X Topology




### Cross Topology




### Grid Topology



# Performance evaluation

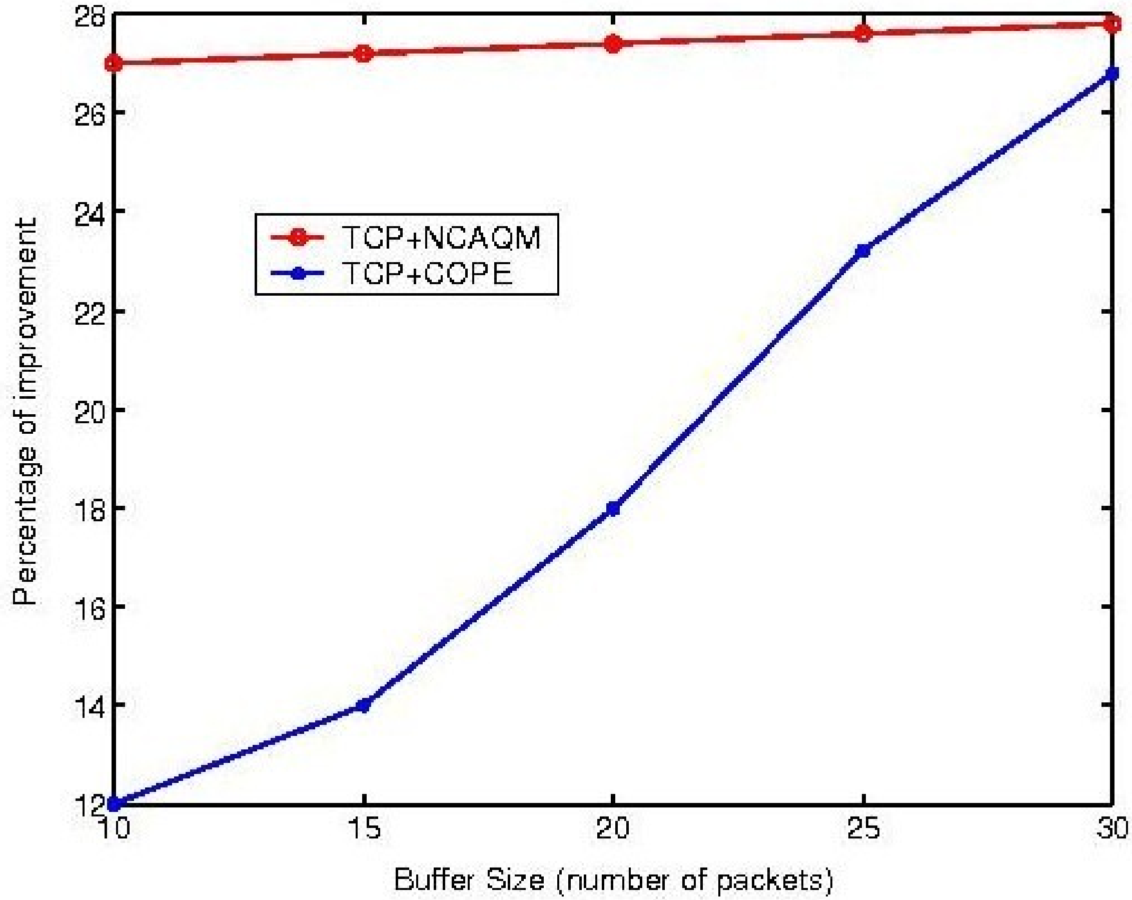
## Throughput improvement compared to noNC

| | TCP+COPE (%) | TCP+NCAQM (%) | Optimal (%) |
|---|---|---|---|
| A & B | 12 | 27 | 33 |
| Cross | 16 | 31 | 60 |
| X | 10 | 22 | 33 |
| Grid | 8 | 19 | - |

TCP+NCAQM doubles the improvement of TCP+COPE

# Performance evaluation

## Throughput improvement vs buffer size



# Extensions

## Multi-hop network coding

- Network utility maximization problem is extended for multi-hop network coding
- Distributed solutions are derived
  - Only traffic splitting part changes
  - In practice, traffic splitting parameter is estimated
  - NCAQM is directly applied to multi-hop network coding

# Summary

- Proposed queue management schemes to improve the performance of TCP over coded wireless networks
  - Formulated network utility maximization problem and proposed a distributed solution
  - Designed NCAQM scheme, mimicking the structure of the optimal solution. No changes TCP and MAC.
  - Simulations show that TCP+NCAQM doubles the improvement of TCP+COPE as compared to noNC.

# Thank you!

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