Application-Aware Network Coding

Improving Video and TCP Performance over Coded Wireless Networks

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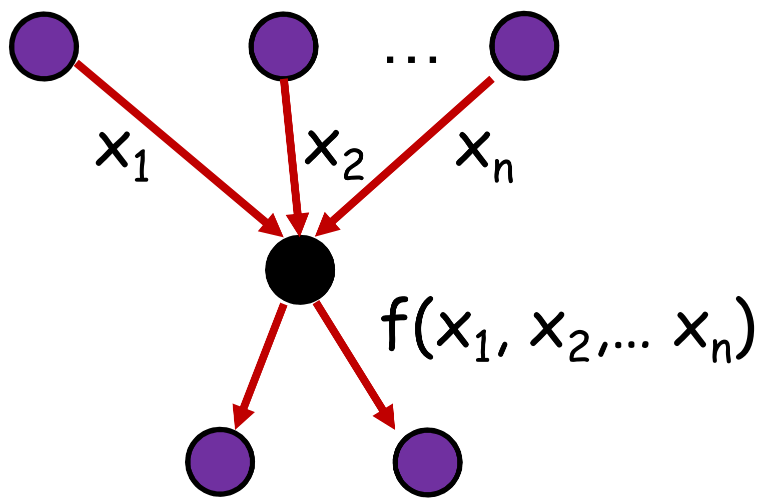
My work

- Interaction and joint optimization of NC and higher layers over wireless mesh networks
  - NC + video streaming
  - NC + TCP
- Dynamic FEC for Video

The network coding paradigm

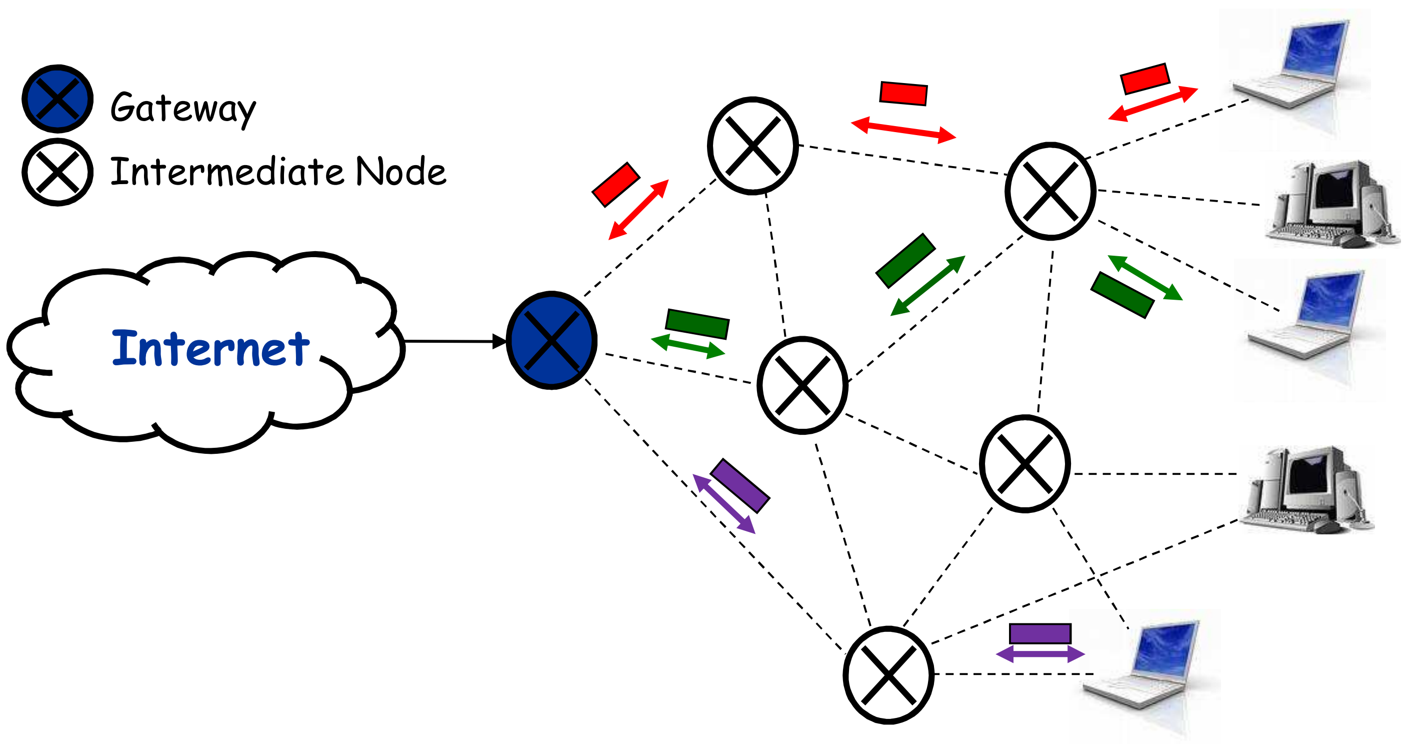
- Idea: allow intermediate nodes to combine incoming packets before forwarding them



- Benefits in throughput and distributed scheduling
- Applications in p2p and wireless mesh networks

Application to 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



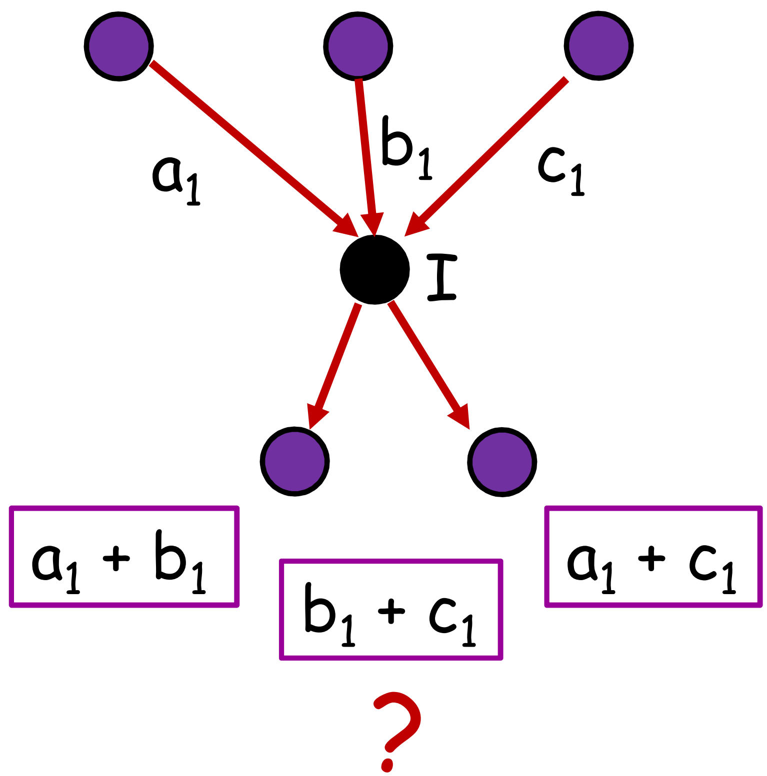
My work

- Interaction and joint optimization of NC and higher layers over wireless mesh networks
  - NC + video streaming
    - Prioritized transmission
    - Delay requirements
    - Rate requirements
  - NC + TCP
- Dynamic FEC for Video

Video-aware opportunistic network coding

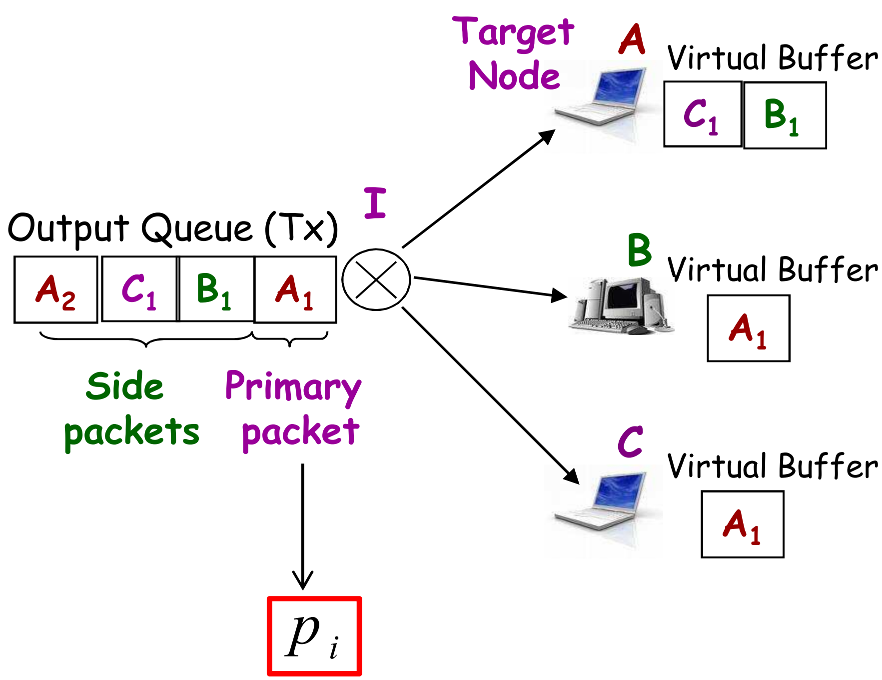
[Seferoglu, Markopoulou, Packet Video 07, JSAC 09]

- NC is agnostic to the contents of network codes
- Key observation: the content (not only the number) of packets matters



Network coding for wireless mesh

[COPE: XORs in the Air, Katti, Katabi et al. Sigcomm 06]



- Candidate codes for $p_1 = A_1$:

  $c^1{}_1 = A_1$

  $c^1{}_2 = A_1 + B_1$

  $c^1{}_3 = A_1 + C_1$

  $c^1{}_4 = A_1 + B_1 + C_1$

- In general, candidate codes for primary packet p_i:

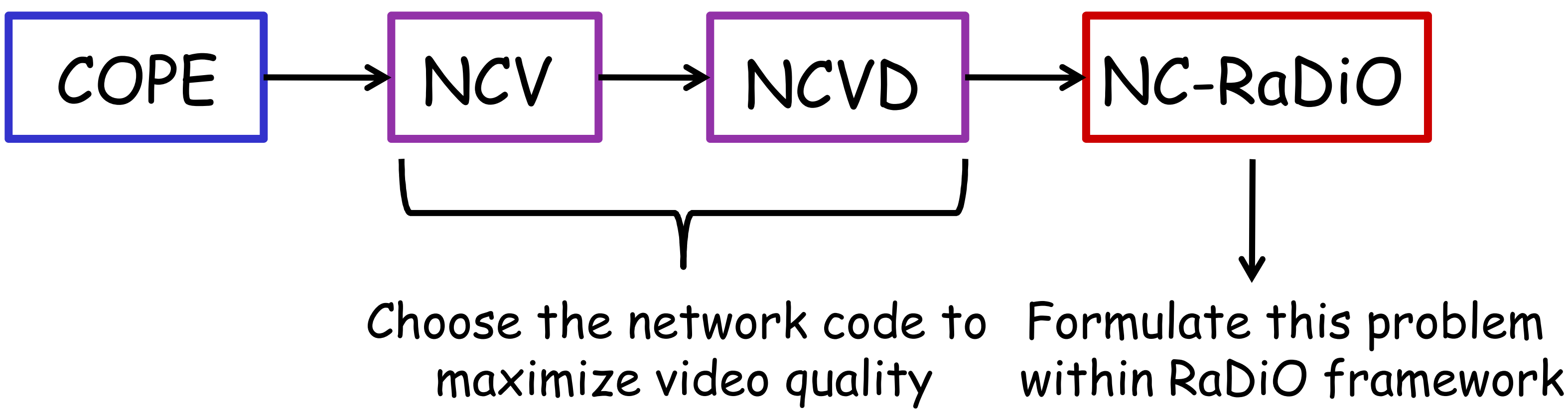
$$c_k^i = p_i \bigcup S_k^{t(p_i)}$$

all subsets of virtual buffer

$$S_k^{t(p_i)} \quad k = 1, \ldots, 2^{\Psi_{t(p_i)}}$$

Which code to choose to maximize total video quality?

Overview


COPE
NCV
NCVD
NC-RaDiO
Choose the network code to maximize video quality
Formulate this problem within RaDiO framework

NCV

Network coding for video

- Primary packet (p_i): 1st packet in the queue
- Choose code c_k^i that brings maximum quality improvement I_k^i

$$\max_k I_k^i = \sum_{n=1}^{N} I_k^i(n)$$

$$I_k^i(n) = \sum_{l=1}^{L_k} (1-P(l))\Delta(l)\gamma(l) g_l^k(n) d_l^k(n)$$

Number of packets in the code: l=1,..L $_k$

Probability of error due to loss & delay

Distortion value of packet l

Flow priority

1 if packet l is targeted to node n

1 if code is decodable at node n

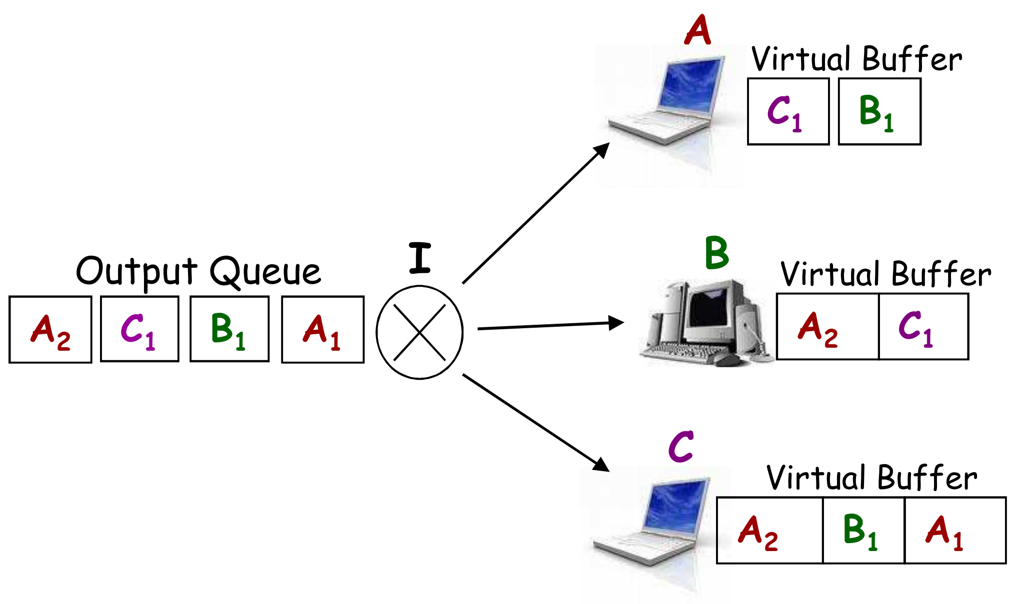
Choose side packets

$$\max_k (I_k^i)$$

NCVD

NCV+depth (choosing the primary packet)

- Primary packet (p_i): Any packet in the queue



A_1 is primary packet

Network Codes	Decodability
$c_1 = A_1$	only A decodes
$c_2 = A_1+B_1$	only A decodes
$c_3 = A_1+C_1$	A and C decode
$c_4 = A_1+B_1+C_1$	A and C decode

B_1 is primary packet

Network Codes	Decodability
$c'_1 = B_1$	only B decodes
$c'_2 = B_1+C_1$	B and C decode
$c'_3 = B_1+A_2$	A and B decode
$c'_4 = B_1+C_1+A_2$	A, B, C decode

Choose primary and side packets

$$\max_{p_i} \max_{k} (I_k^i)$$

NC-RaDiO

Rate-distortion optimized network coding

Distortion Function

$$D(\pi) = \sum_{n=1}^{N} \sum_{p_j \in \Phi_n} \gamma(j)\Delta(j)P_p(j)P_c(\pi_n(j))$$

- $\gamma(j)$: Flow priority
- $\Delta(j)$: Packet Distortion Value
- $P_p(j)$: Probability of Loss in prev. Xmits
- $P_c(\pi_n(j))$: Probability of Loss in curr. Xmit

Rate Function

$$R(\pi) = \sum_{n=1}^{N} \sum_{c_u \in C_n} \max_{p_j \in c_u} \{B(j)\rho(\pi_n(j))\}$$

- $B(j)$: Packet Size
- $\rho(\pi_n(j))$: Avg. cost of Packet xmit

↓ Lagrangian relaxation

Maximize Lagrange parameters:

Choose transmitting node and primary and side packets

$$\max_{\{n,c_u\}} \{\lambda_n(c_u)\} = \max_{\{n,c_u\}} \left\{ \frac{\sum_{p_j \in c_u} \gamma(j)\Delta(j)P_p(j)(1-P_c(\pi_n(j)))}{\max_{p_j \in c_u} \{B(j)\}} \right\}$$

NC-RaDiO

NCVD as a special case

$$\lambda_n(c_u) = \frac{\sum_{p_j \in c_u} \gamma(j)\Delta(j)P_p(j)(1 - P_c(\pi_n(j)))}{\max_{p_j \in c_u}\{B(j)\}}$$

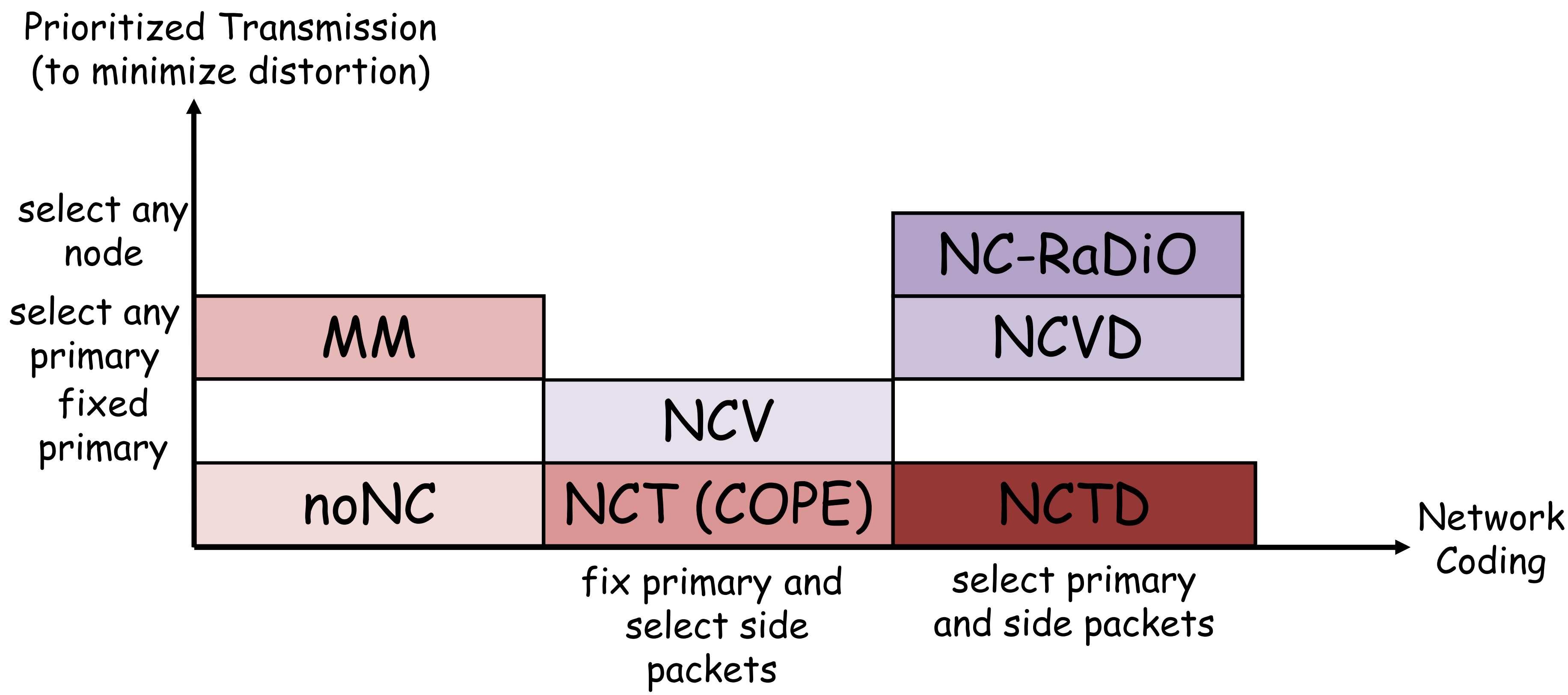
- Equal packet sizes; $B(j) = B$
- Deterministic rules on $P_p(j)$
- $P_c(\pi_n(j))$ is re-written in terms of $P(j)$, $d(\pi_n(j))$

NC-RaDiO ↔ **NCVD**

$$\lambda'_n(c_u) = \sum_{p_j \in c_u \; s.t. T(j) > RTT} \gamma(j)\Delta(j)(1 - P(j))d(\pi_n(j)) \quad \leftrightarrow \quad I_k^i = \sum_{n=1}^{N}\sum_{l=1}^{L_k}(1 - P(l))\gamma(l)\Delta(l)g_l^k(n)d_l^k(n)$$

Performance evaluation

Baseline algorithms

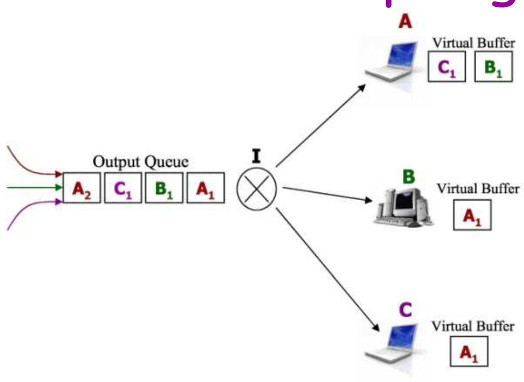


Performance evaluation

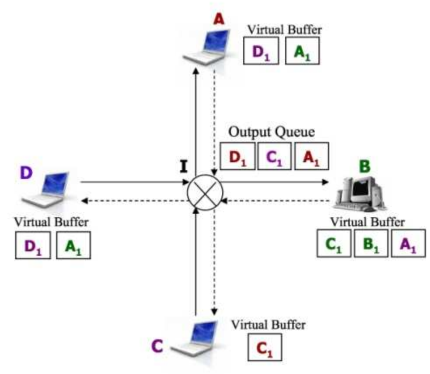
Scenario

[Glomosim + NC]

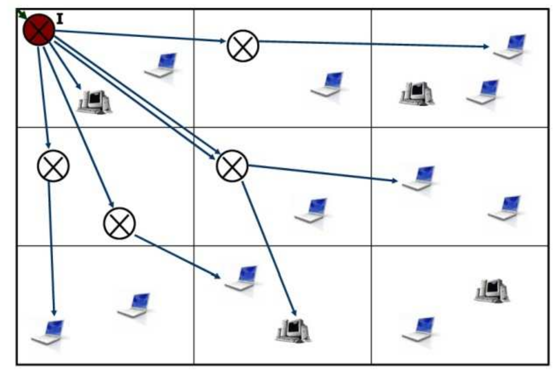
Downlink Topology



Cross Topology



Grid Topology



- Wireless Channel
  - Rayleigh fading channel: Average channel SNR levels; {3,5,7,9,11} dB
- Video Sequences
  - Standard streams: Carphone, Foreman, Mother&Daughter, etc.
  - H.264/AVC, 1I:9P frames
  - 70 kbps, 30 fps, 250B packets on average
  - Delay budget 100 ms. Random delay in forward ch., avg= 4ms.

Performance evaluation

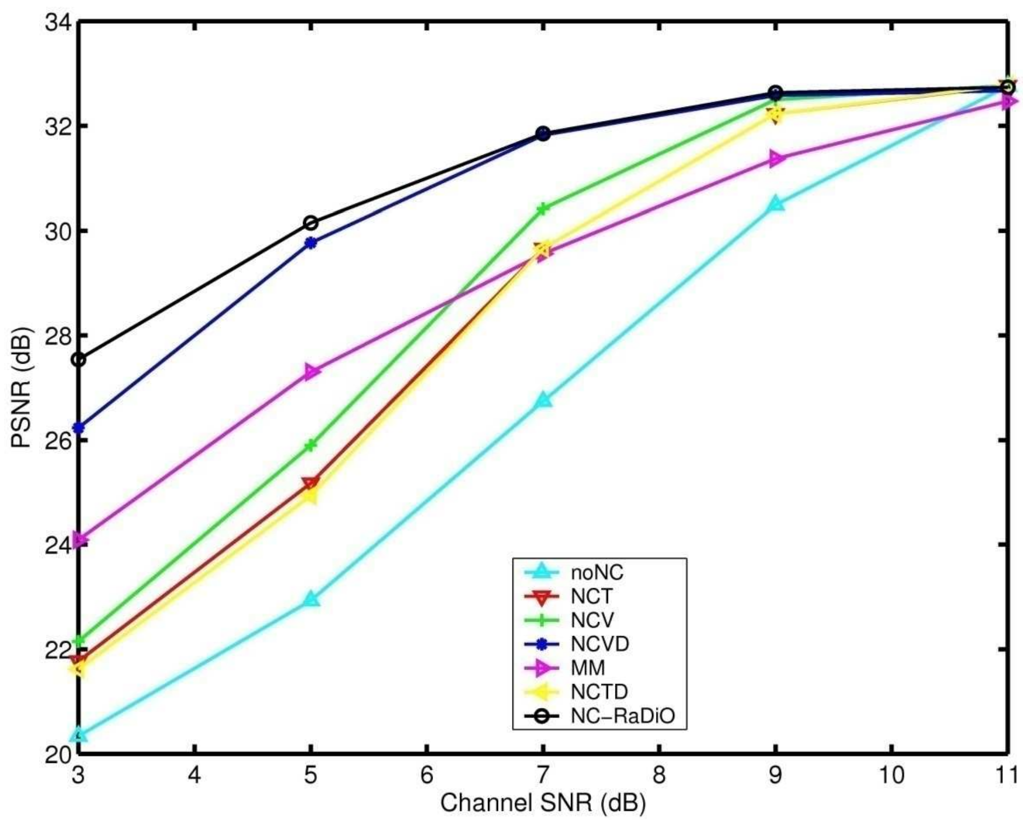
Video quality - downlink topology

Average PSNR for 5 dB channel SNR, 3 Receivers, 100 ms Playout Deadline, 500kbps Tr. Data Rate

avg PSNR (dB)	Carphone	Foreman	Mother&Daughter
Original	29.95	28.70	40.74
NC-RaDiO	28.46	27.51	35.08
NCVD	27.98	26.87	35.36
NCTD	24.91	24.60	28.61
NCV	25.40	25.14	28.66
NCT	23.95	24.38	27.19
MM	25.17	24.61	32.12
noNC	22.32	22.64	23.84

Performance evaluation
Video quality – downlink topology

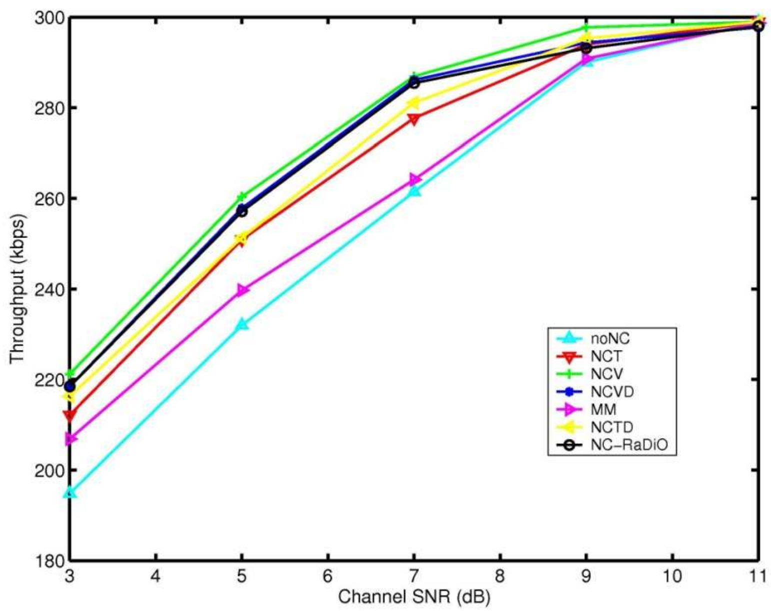
Average PSNR – 100ms Delay Budget, 3 Receivers,
500 kbps Tr. Data Rate.



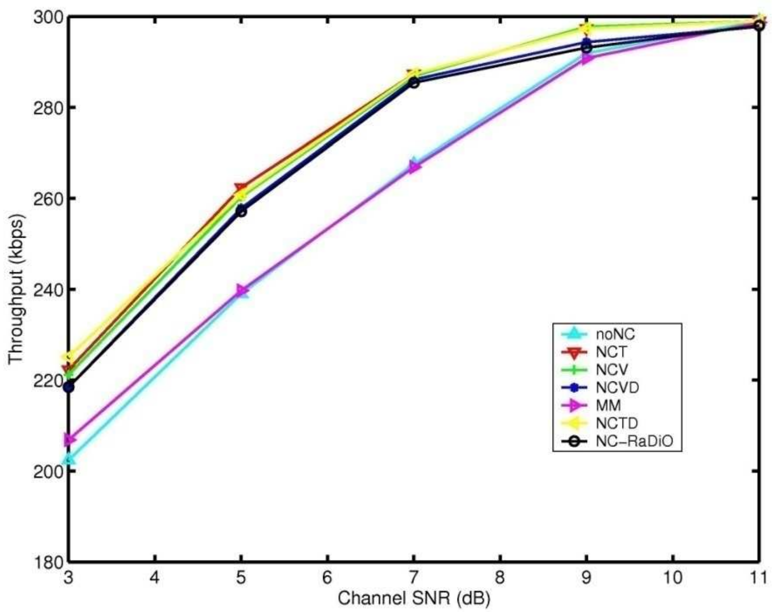
Performance evaluation
Throughput – downlink topology

Throughput – 100ms Delay Budget, 3 Receivers, 500 kbps Tr. Data Rate

Application-level throughput



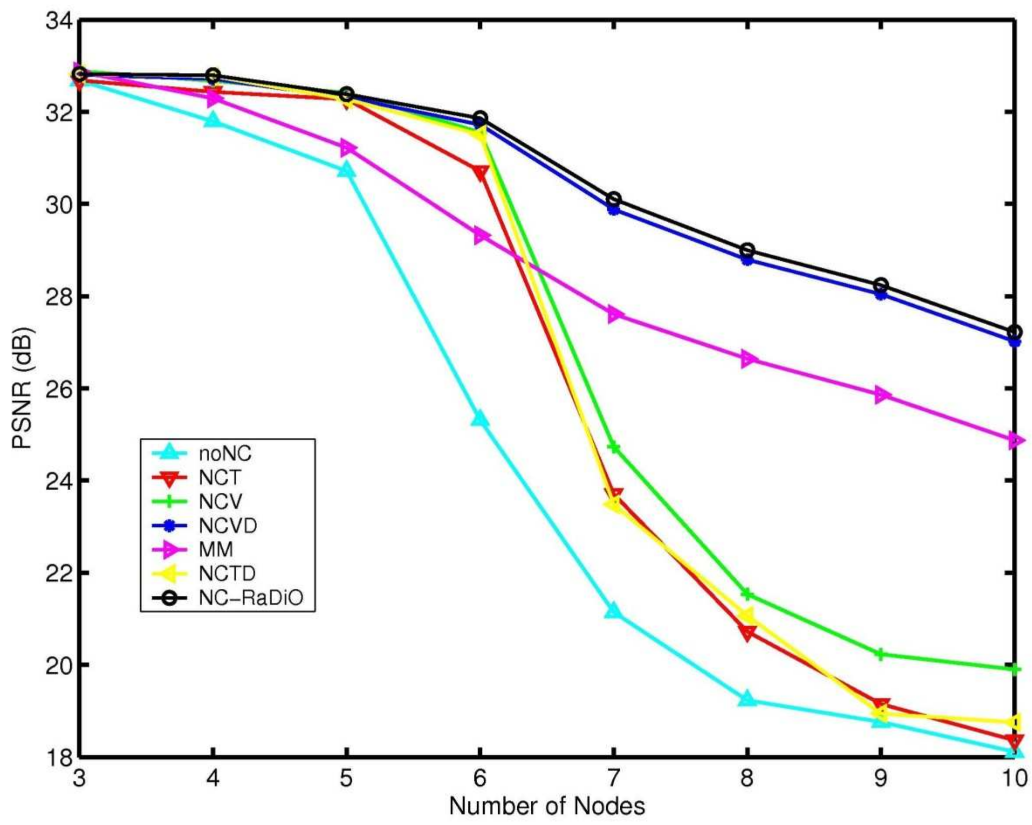
MAC-level throughput



Performance evaluation

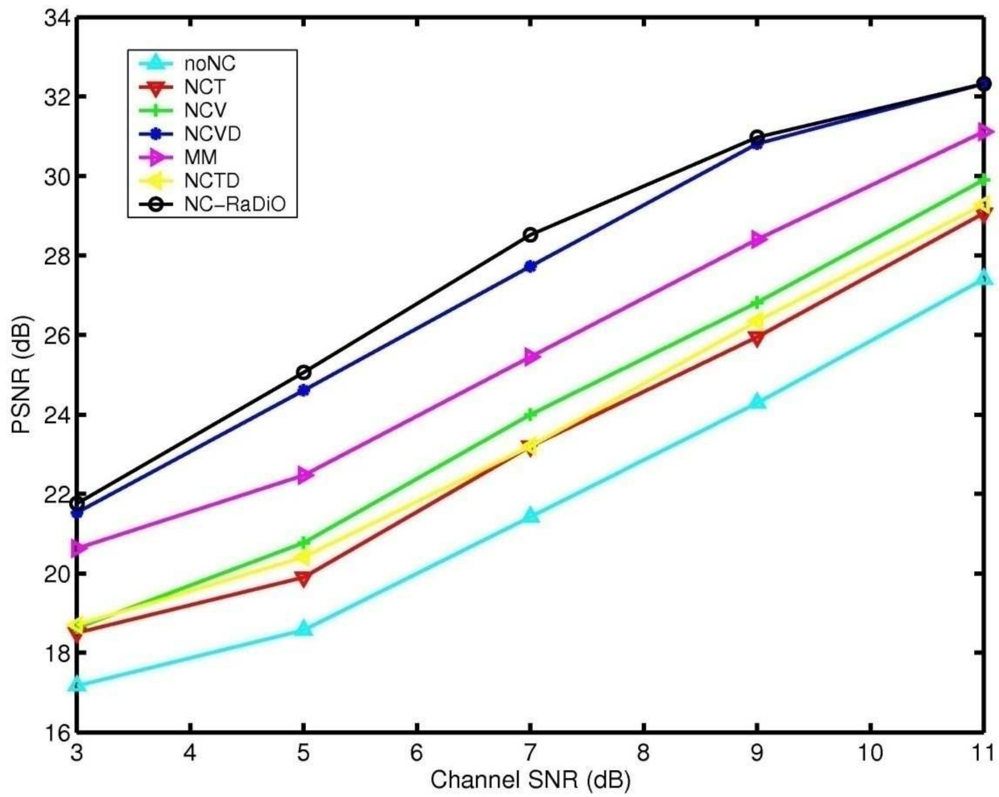
Video quality – downlink topology

Average PSNR – 100ms Delay Budget, 5dB channel SNR, 1 Mbps Tr. Data Rate



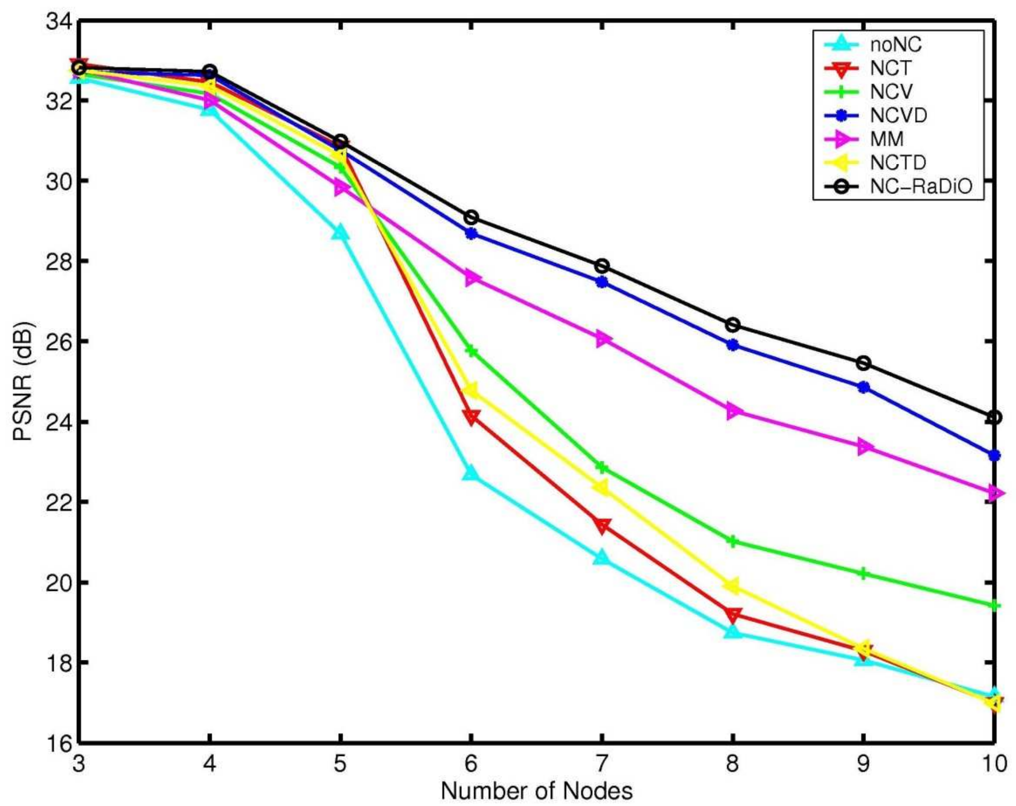
Performance evaluation
Video quality – cross topology

Average PSNR – 100ms Delay Budget, 5dB channel SNR, 1.3 Mbps Tr. Data Rate, 5 number of nodes



Performance evaluation
Video quality – grid topology

Average PSNR – 100ms Delay Budget, 5dB channel SNR, 1 Mbps Tr. Data Rate



Summary

- Designed video-aware network coding algorithms
- Improved video quality up to 5dB
- Without hurting MAC throughput
- Heuristics close to the optimal

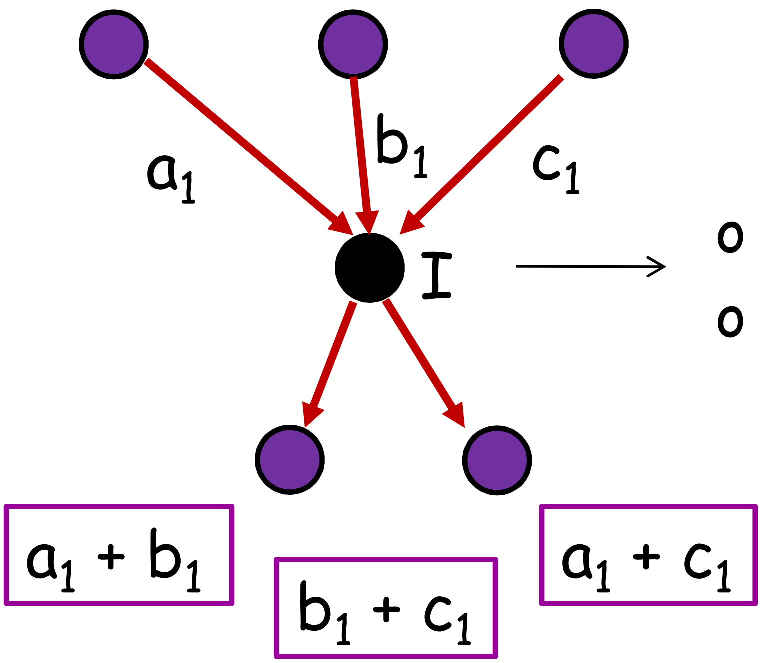
My work

- Interaction and joint optimization of NC and higher layers over wireless mesh networks
  - NC + video streaming
    - Prioritized transmission
    - Delay requirements
    - Rate requirements
  - NC + TCP
- Dynamic FEC for Video

Delay optimized network coding for video

[Seferoglu, Markopoulou, ICC 10]

- Key observation: there is a trade-off between delay and throughput



Introducing delay

- Increases NC opportunities ☺
- Increases end2end delay ☹

How much delay ?

My work

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    - Delay requirements
    - Rate requirements
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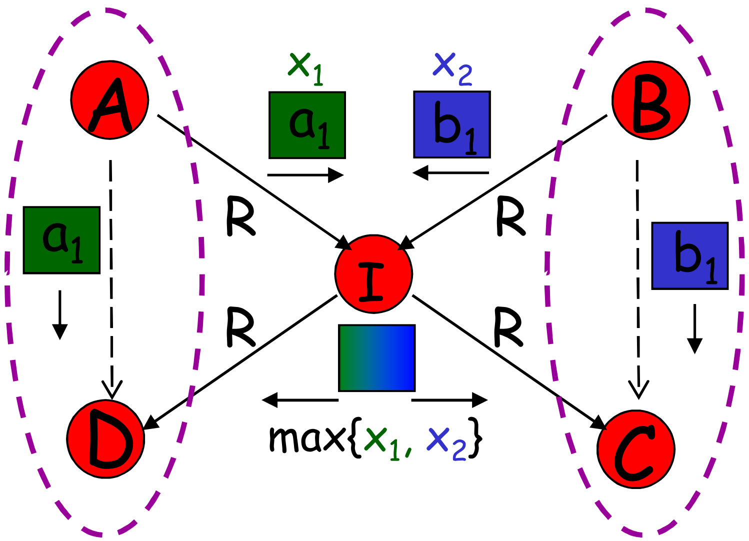
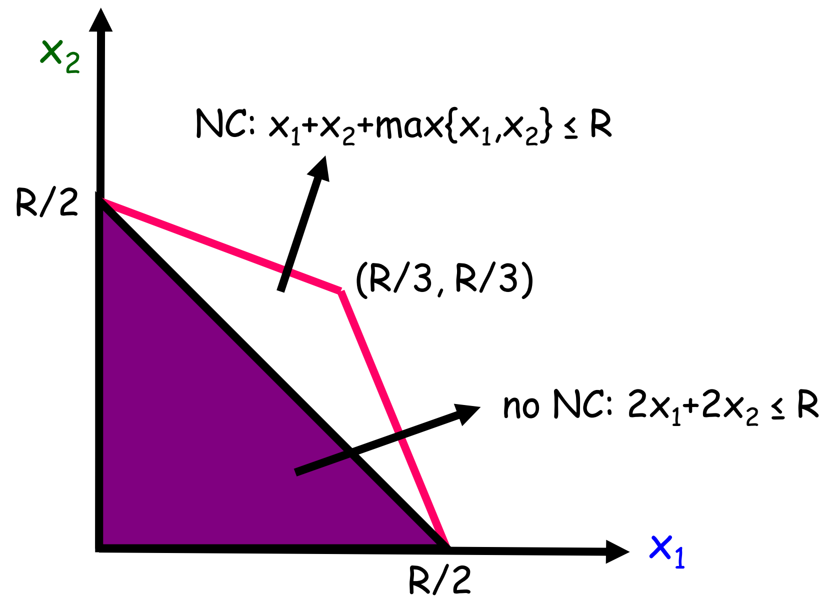
Rate control for video with network coding

[Seferoglu, Markopoulou, Packet Video 09]

- Key observation: video rate affects the network coding opportunities





Delaying some scenes and optimizing the rate allocation create more network coding opportunities.

My work

- Interaction and joint optimization of NC and higher layers over wireless mesh networks
  - NC + video streaming
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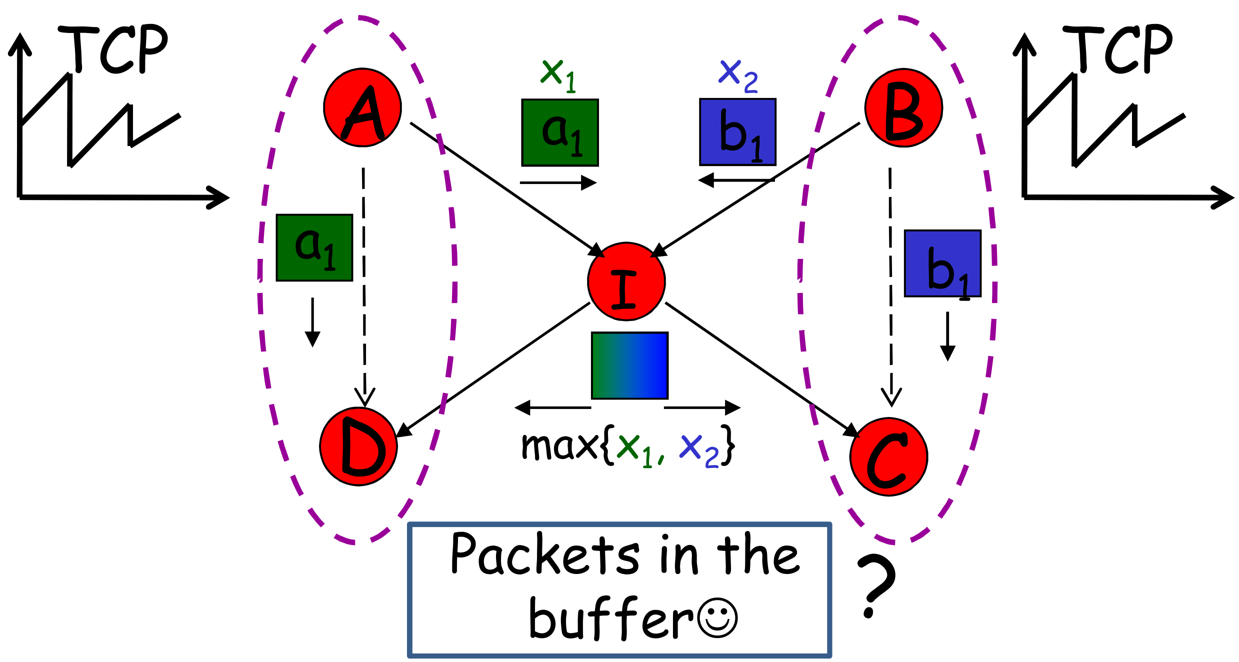
Motivation

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

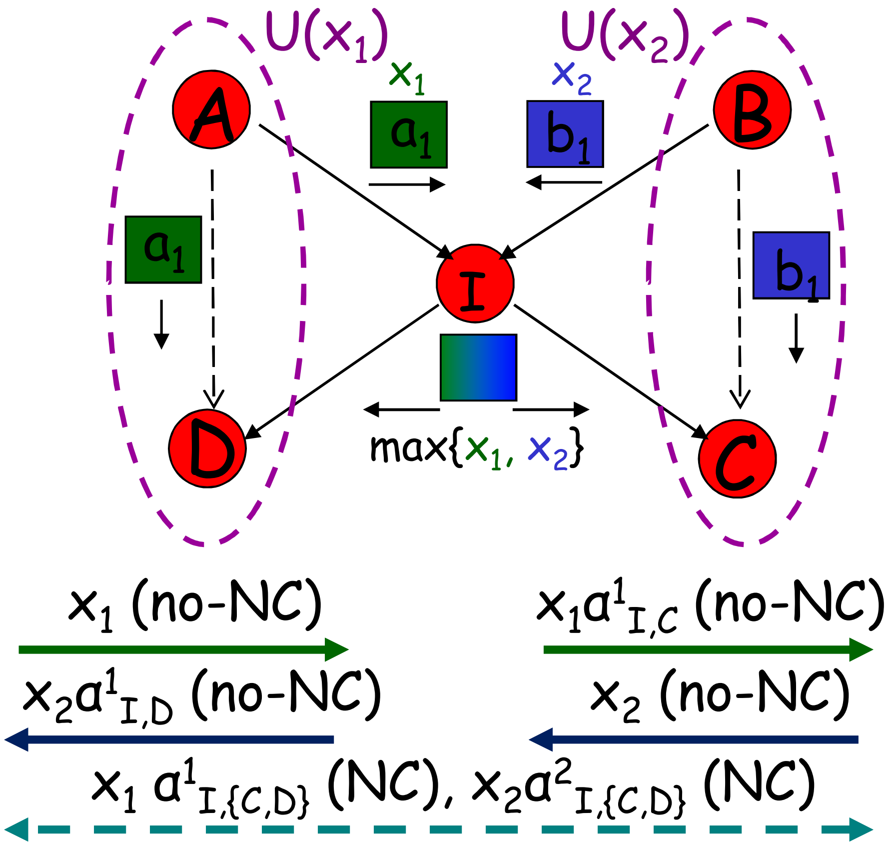


Motivation

- Problem: TCP over COPE does not fully exploit the network coding potential
- Our intuition:
  - Not enough coding opportunities due to TCP burstiness
  - Coded flows do not compete for resources
- Proposed Solution:
  - Formulate network utility maximization (NUM) problem
  - Modify queue management schemes (NCAQM)
  - Make no changes to TCP and MAC
  - TCP + NCAQM doubles the performance of TCP+COPE

Network utility maximization

Formulation



$\max U(x_1) + U(x_2)$

$a^1_{I,C} + a^1_{I,\{C,D\}} = 1$

$a^2_{I,D} + a^2_{I,\{C,D\}} = 1$

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

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:

$$\max_{m} \sum_{s \in S_k} H_h^{s,k} \alpha_h^{s,k} x_s m_h^{s,k}$$
$$s.t. \quad \sum_{s \in S_k} m_h^{s,k} = 1$$

↓

$$\max_{x,\alpha,\tau} \sum_{s \in S} U_s(x_s)$$
$$s.t. \quad \sum_{k \in K_h} \sum_{s \in S_k} H_h^{s,k} \alpha_h^{s,k} x_s (m_h^{s,k})^* \le R_h \tau_h, \ \forall h \in A$$
$$\sum_{h(J)|h \in A} \ \sum_{k \in K_h | s \in S_k} \alpha_h^{s,k} = 1, \ \forall s \in S, i \in P_s$$
$$\sum_{h \in C_q} \tau_h \le \gamma, \ \forall C_q \subseteq A$$

Network utility maximization
Solution II:

Parameter (Queue) Update

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

Rate Control

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

Traffic Splitting

$$\min_{\alpha} \sum_{h(J)|h \in A} \sum_{k \in K_h | s \in S_k} q_h H_h^{s,k} (m_h^{s,k})^* \alpha_h^{s,k}$$

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

Scheduling

$$\max_{\tau} \sum_{h \in A} q_h R_h \tau_h$$

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

Network coding-aware queue management (NCAQM)

Modifications to the protocol stack by mimicking the structure of the optimal solution

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

Minimal and intuitive

NCAQM

Maintaining queues and network coding

Parameter (Queue) Update

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

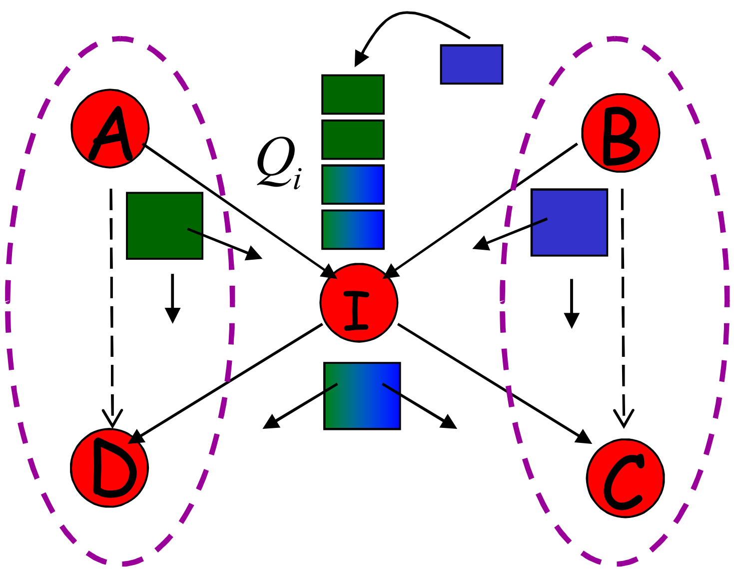
- Maintain state per hyperarc queue
- Store coded packets

NCAQM

Maintaining queues and network coding

Parameter (Queue) Update

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



Implementation

- Store all packets in an output queue Q_i
- If there exists network coding opportunity, packets are coded and stored in the queue
- Hyperarc queue size is determined heuristically;

$$Q_h = \sum_{k \in K_h} \max_{s \in S_k} \left\{ H_h^{s,k} \tilde{\alpha}_h^{s,k} Q_i^s \right\}$$

Estimated traffic splitting parameter

Number of packets at node *i* from flow *s*

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

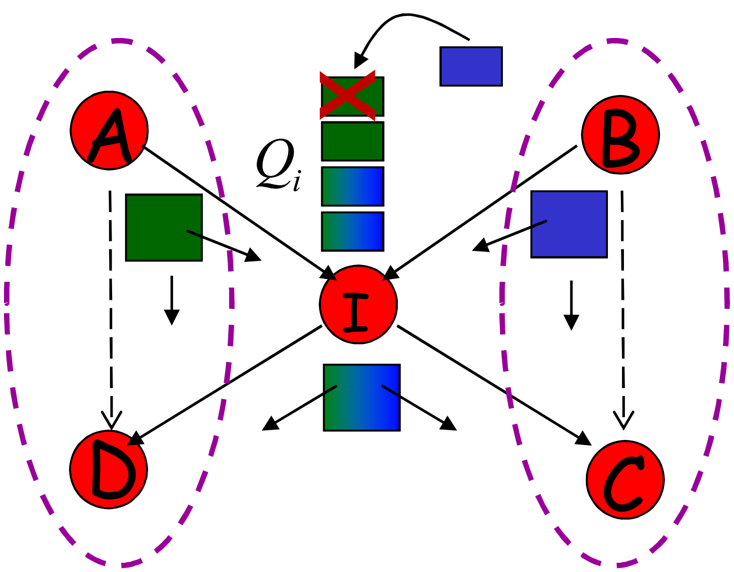
Implementation

Network coded queue size ←

$$\Phi^s_i = \sum_{h(J)|h \in A} Q_h \tilde{w}^s_h$$

$$\tilde{w}^s_h = \sum_{k \in K_h | s \in S_k} H^{s,k}_h \tilde{\alpha}^{s,k}_h \tilde{m}^{s,k}_h$$

→ Estimated dominance indicator



- Upon congestion, flow "lengths" Φ^s_i are compared. A packet from the largest flow is dropped. This mimics the optimal rate control.
- Φ^s_i is the "length" of per flow queues. The "length" counts packets over all Q_h in which a flow is dominant (has the largest number of packets).

Multi-hop network coding

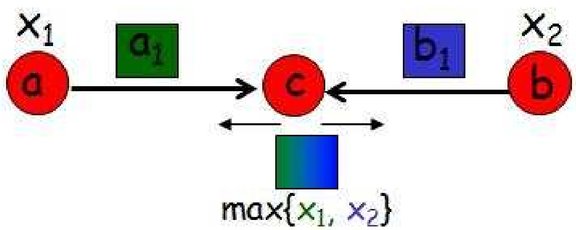
- Network utility maximization problem is extended for multi-hop network coding
- Distributed solutions are derived
  - Only traffic splitting part changes
  - In practice, traffic splitting parameter is estimated
  - NCAQM is directly applied to multi-hop network coding

Performance evaluation

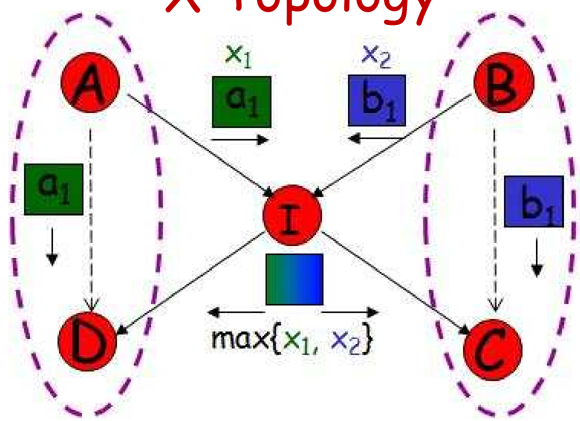
Scenarios

[Glomosim + NC]

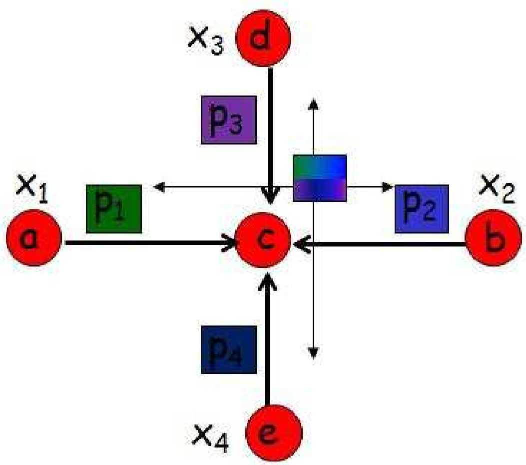
A & B Topology



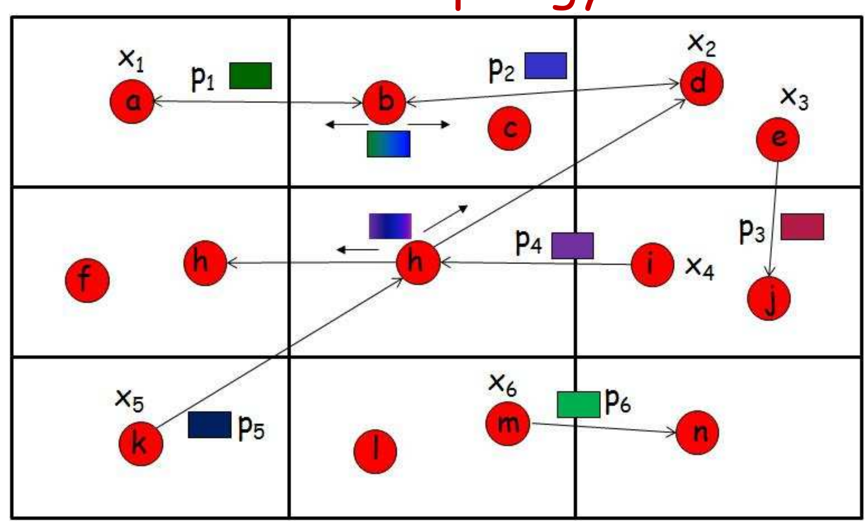
X Topology



Cross Topology



Grid Topology



Performance evaluation

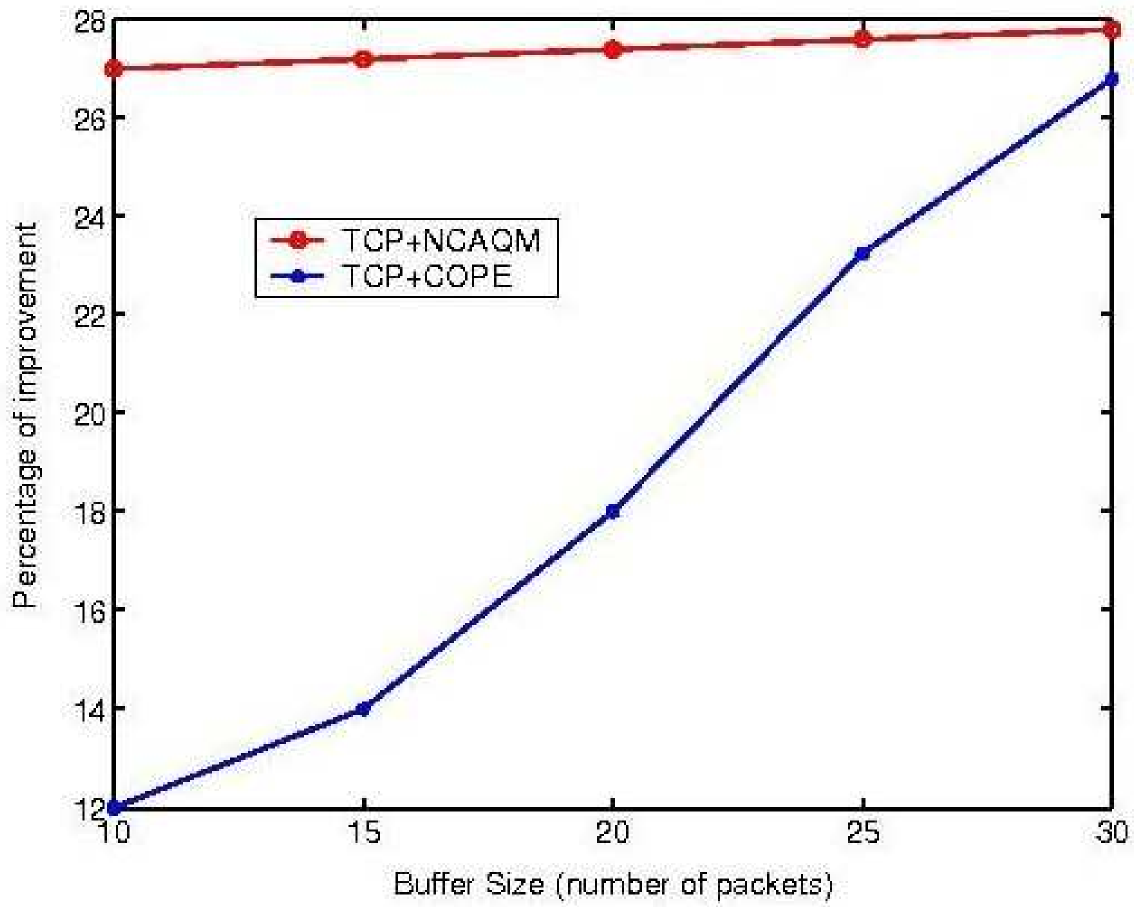
Throughput improvement compared to noNC

	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 queue size



Summary

- Proposed queue management schemes to improve network coding performance of TCP
  - Formulated network utility maximization problem and proposed a decomposed solution
  - Modified queue management schemes considering the structure of the optimal solution
  - Simulations show that our scheme (NCAQM) doubles the improvement of TCP+COPE

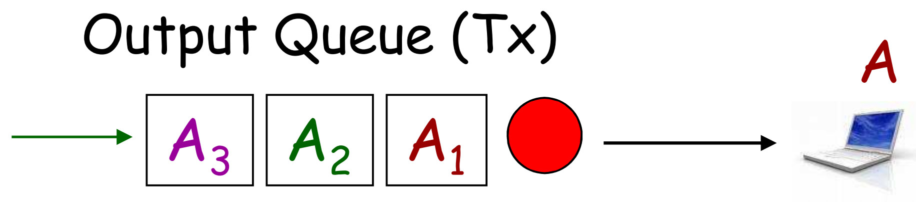
My work

- Interaction and joint optimization of NC and higher layers over wireless mesh networks
  - NC + video streaming
  - NC + TCP
- Dynamic FEC for Video

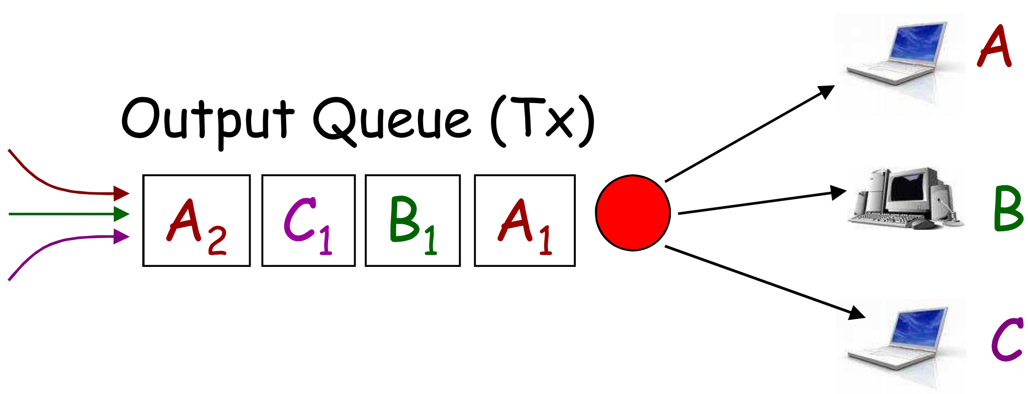
Dynamic FEC for video over WLANs

[Seferoglu, Gurbuz, Ercetin, Altunbasak, ICC 05, ICIP 06, Image Com. 07]

Packet scheduling and dynamic FEC

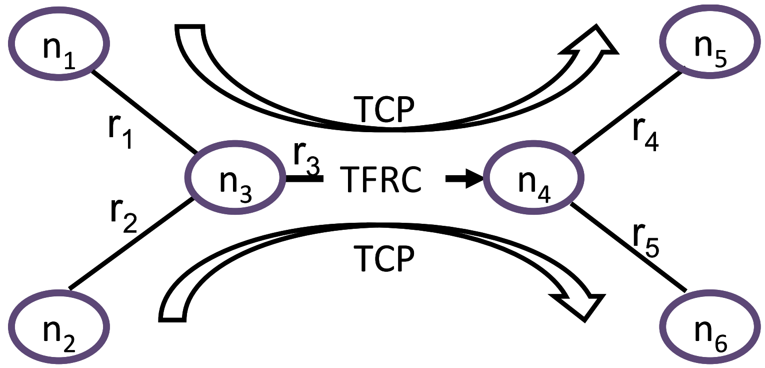


Packet scheduling, dynamic FEC, and rate selection



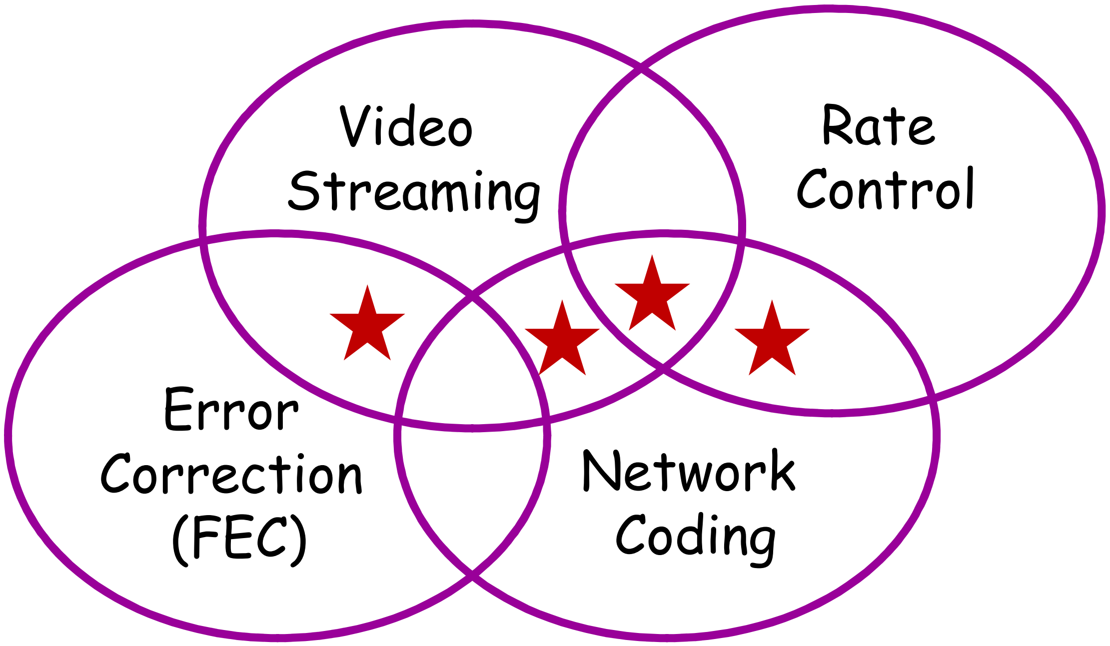
Dynamic FEC for TFRC flows

[Seferoglu, Kozat, Civanlar, Kempf, Packet Video 09]



- Predict congestion induced loss: Loss and delay characteristics (RTT/FTT delays and their derivatives)
- Dynamic FEC algorithms:
  - Media-unaware dynamic FEC: Use the predictor for dynamic FEC protection based on the predicted level of congestion so as to mask congestion losses
  - Media-aware dynamic FEC : Use the predictor output as side information to select the FEC and original media packets within each FEC window in a rate-distortion optimized way

My work



Video Streaming
Rate Control
Error Correction (FEC)
Network Coding

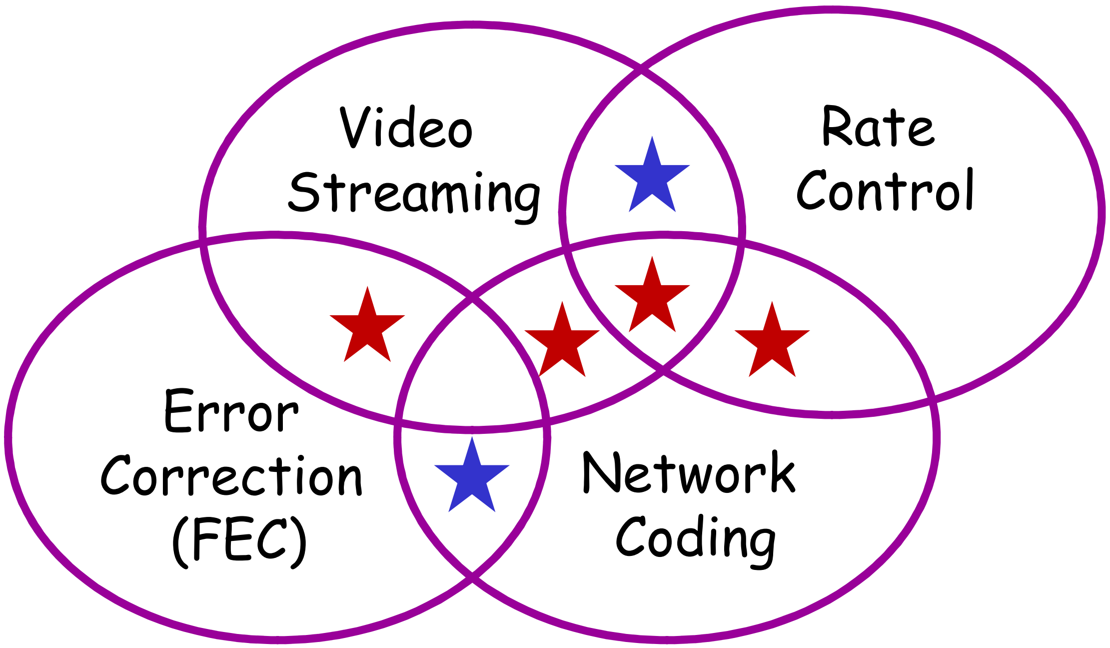
Publications

- NC + video streaming
  - H. Seferoglu, A. Markopoulou, "Delay-Optimized Network Coding for Video Streaming over Wireless Networks," *to appear in Proc. of ICC'10*, South Africa, May 2010.
  - H. Seferoglu, A. Markopoulou, "Video-Aware Opportunistic Network Coding over Wireless Networks," *in IEEE JSAC, Special Issue on Network Coding for Wireless Communication Networks*, vol. 27(5), 2009.
  - H. Seferoglu, A. Markopoulou, "Distributed Rate Control for Video Streaming over Wireless Networks with Intersession Network Coding," *in Proc. of Packet Video'09*, Seattle, May, 2009.
  - H. Seferoglu, A. Markopoulou, "Opportunistic Network Coding for Video Streaming over Wireless," *in Proc. of Packet Video'07*, Lausanne, Switzerland, Nov. 2007.
- NC + TCP (Rate Control)
  - H. Seferoglu, A. Markopoulou, "Network Coding-Aware Queue Management for Unicast Flows over Coded Wireless Networks," *to appear in Proc. of NetCod'10*, Toronto, Canada, June 2010.
  - H. Seferoglu, A. Markopoulou, U. C. Kozat, "Network Coding-Aware Rate Control and Scheduling in Wireless Networks," *in Proc. of ICME'09,* NY, June, 2009.

Publications

- Dynamic FEC for Video
  - H. Seferoglu, U. C. Kozat, M. R. Civanlar, J. Kempf, "Congestion State-Based Dynamic FEC Algorithm for Media Friendly Transport Layer," *in Proc. of Packet Video'07*, Seattle, May, 2009.
  - H. Seferoglu, O. Gurbuz, O. Ercetin, Y. Altunbasak, "Rate-Distortion Based Real-Time Wireless Video Streaming," *Signal Processing: Image Communication.* Vol. 22-6, pp.529-542, July, 2007.
  - H. Seferoglu, O. Gurbuz, O. Ercetin, Y. Altunbasak, "Video Streaming to Multiple Clients over Wireless Local Area Networks," *in Proc. of IEEE ICIP'06*, October 8-11, 2006.
  - H. Seferoglu, Y. Altunbasak, O. Gurbuz and O. Ercetin, "Rate Distortion Optimized Joint ARQ-FEC for Real-Time Wireless Multimedia," *in Proc. of IEEE ICC'05*, May 16-20, 2005.

Current and future work



Thank you!

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