RESILIENT Priority-Based Data Transmission Using NETWORK CODING

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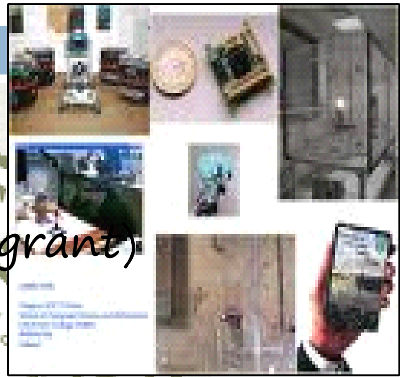
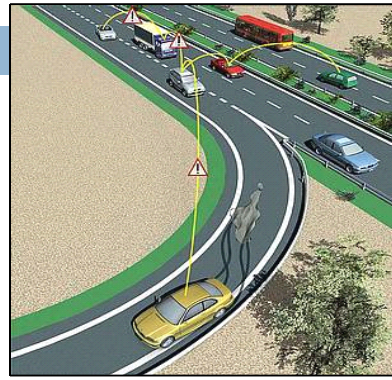
Wireless and mobile networks

- Mesh networks (CRI and GENI grants)
- Sensor networks (NeTS and TF grants)
- Content sharing networks (NeTS medium grant)
- Network coding (CCSS grant)
- Vehicle networks





Network security and privacy

- Wireless networks (ARO and CCSS grants)
- Cloud comp. (Microsoft and Amazon grants)
- Medical applications (Tobacco fund)

High performance computing

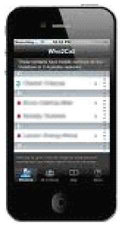
- NSF GPU/CPU supercomputer (MRI g

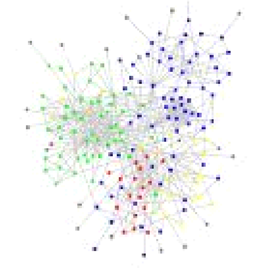
Economic development

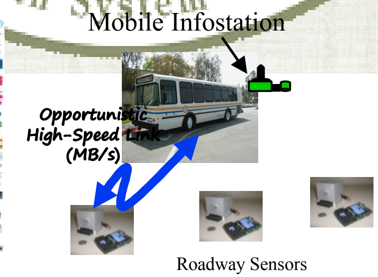
- Urban Maps & Apps Studio (EDA gra

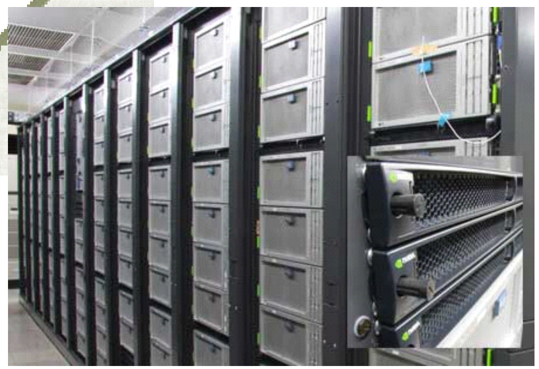
Social networks

- Online social networks









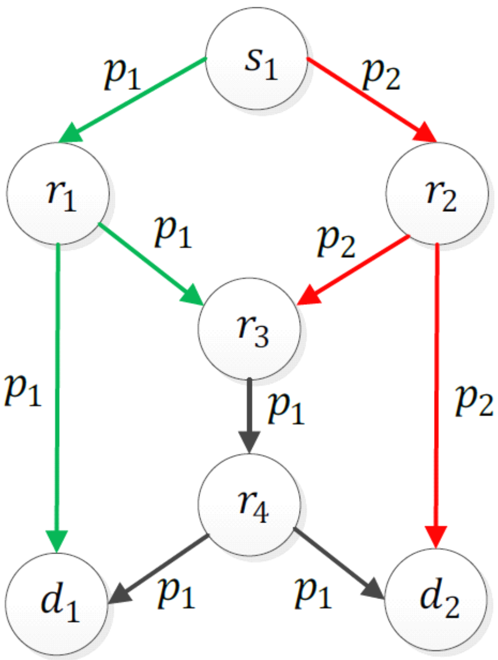
Agenda

- Network Coding Background
- Priority-Based Network Coding
  - Symbol-level transmission
  - Layered video streaming
- Conclusions
- Other Recent Works

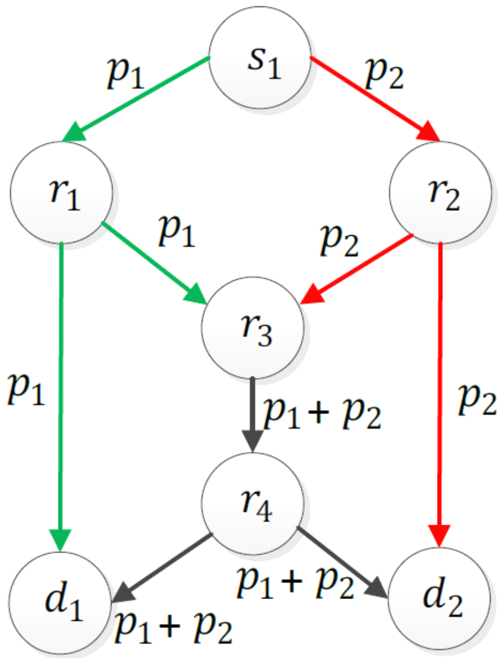
Network Coding Background

Network Coding in Wired Networks

- Single multicast session
  - Bottleneck problem (Ahlswede'00)



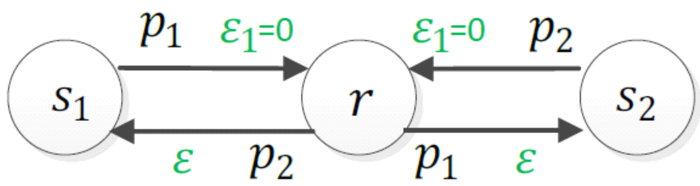
No coding



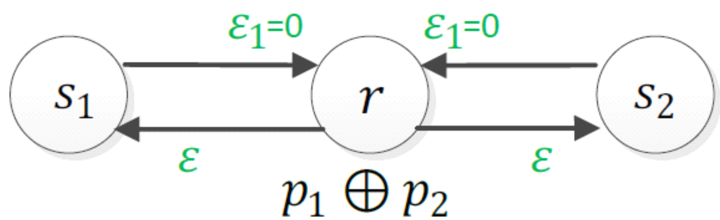
Coding

Network Coding in Wireless Networks

- No coding
  - 4 transmissions
  - delivery rate = $(1-\varepsilon)/4$



- COPE (coding, Katty'06)
  - 3 transmissions (broadcast channel)
  - delivery rate = $(1-\varepsilon)/3$

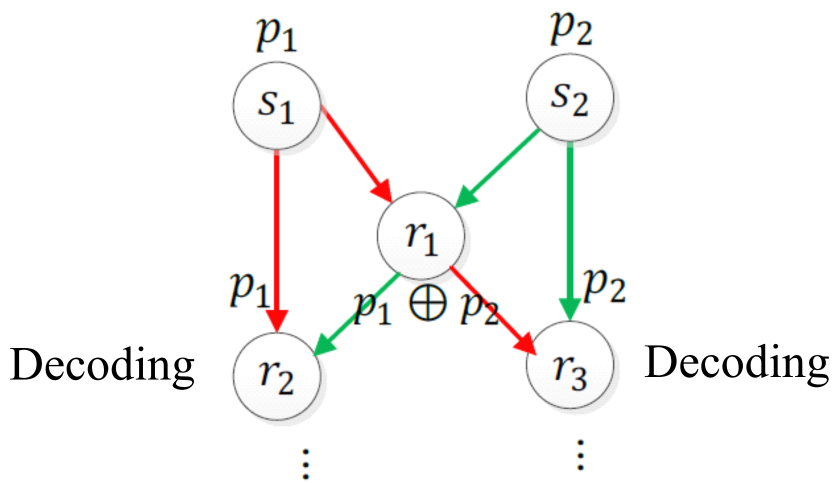


- COPE-dup (double transmission by relay, Rayanchu'08)
  - 4 transmissions
  - delivery rate = $(1-\varepsilon^2)/4$

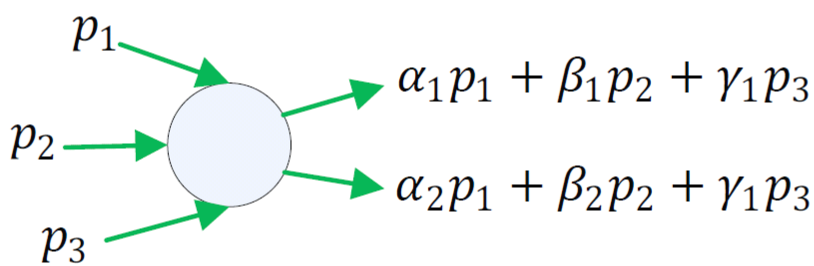
Scheme	=0	=0.1	=0.3	=0.5	=0.7
No coding	0.25	0.225	0.175	0.125	0.075
COPE	**0.333**	**0.3**	**0.233**	0.167	0.1
COPE-dup	0.25	0.247	0.227	**0.187**	**0.127**

Network Coding Classification

- Local
  - Hop-by-hop decoding
  - XOR operation

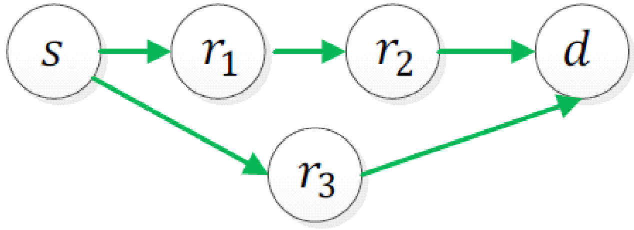


- Global
  - Decoding at the destination
  - Linear network coding (on a finite field)

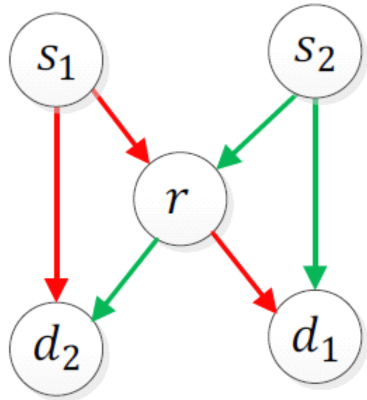


Network Coding Classification

- Intra-flow
  - Within a flow
  - Robustness enhancement



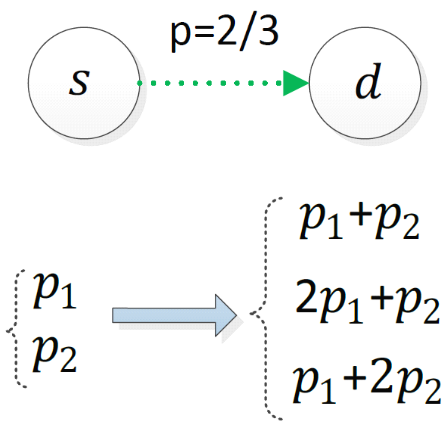
- Inter-flow
  - Between different flows
  - Throughput/capacity enhancement



- Joint inter- and intra-flow
  - Within flow and between flows

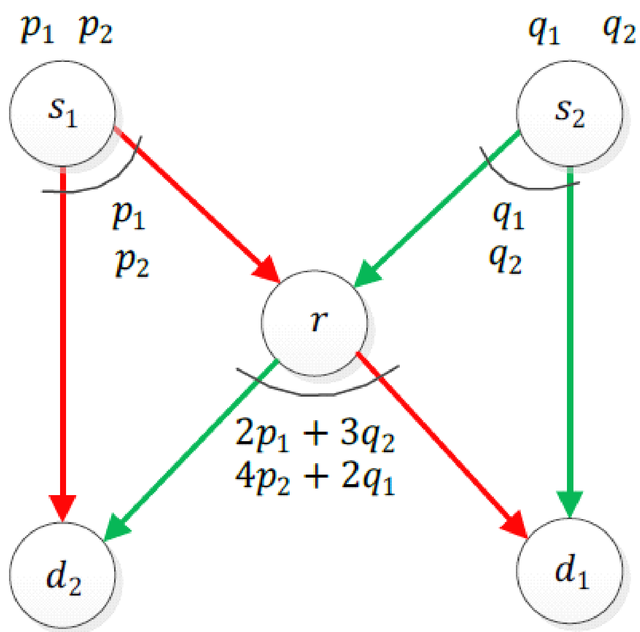
Network Coding in Wireless Networks

Intra-flow coding



- Reliability=2/3
- **3** transmissions

Inter-flow coding

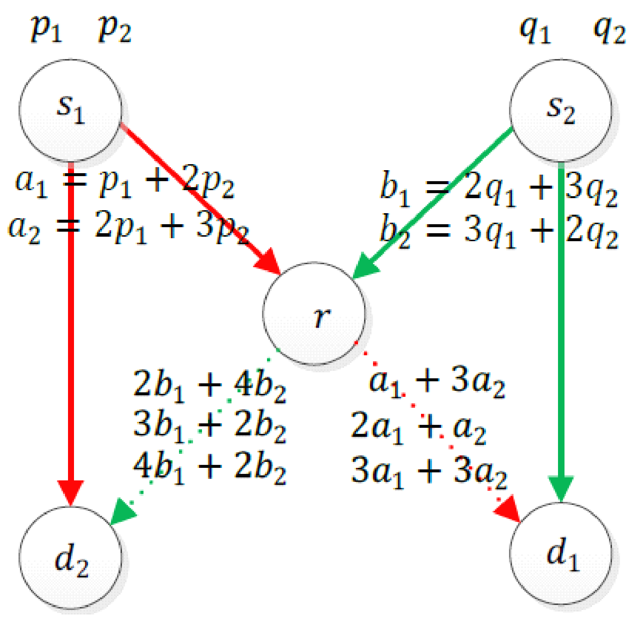


- Reliable links
- **2** transmissions by the relay

Network Coding in Wireless Networks

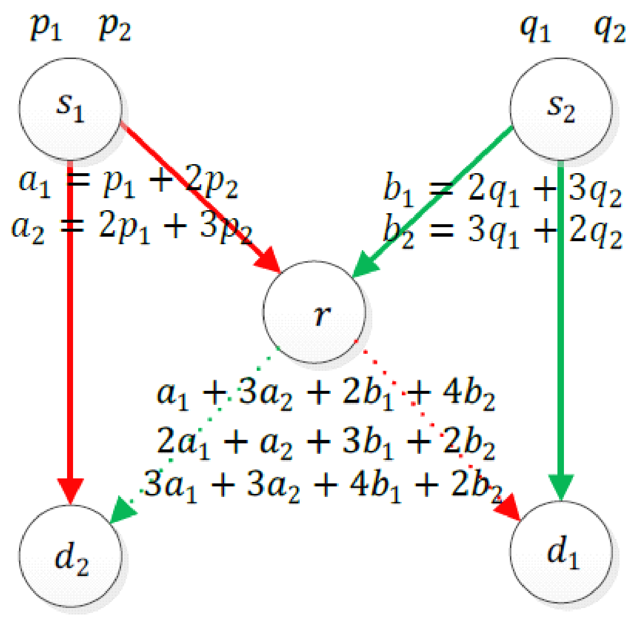
- Reliability from r to d_1 and d_2 is 2/3
- Other links are reliable

Intra- flow coding



6 transmissions by the relay

Joint inter- and intra-flow coding

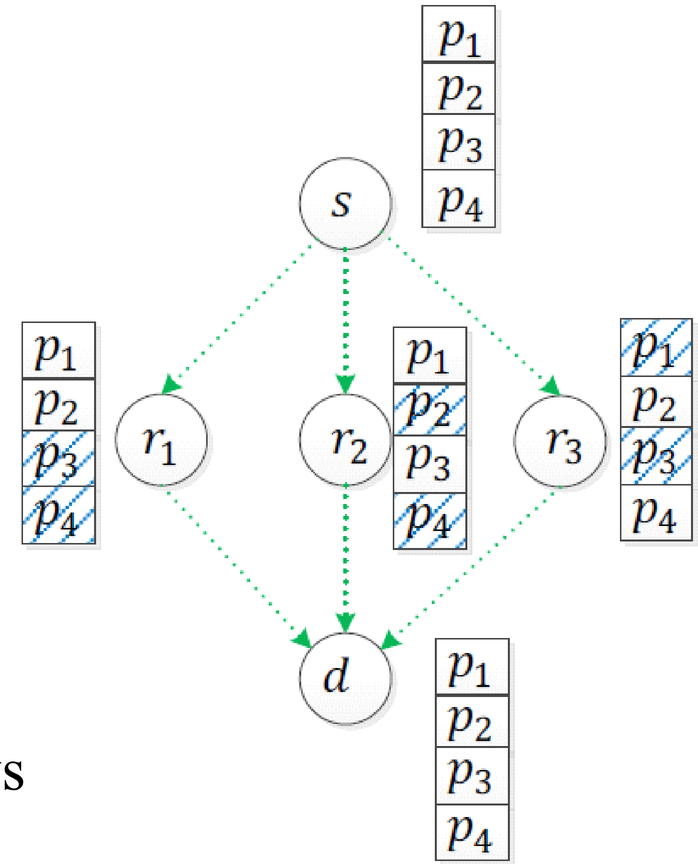


3 transmissions by the relay

Opportunistic Routing (OP)

- OP: no fixed path
  - Relays jointly having all packets
  - Coordination needed among relays
  - Which packets should be sent?

    (coupon collection problem)



- OP with network coding
  - Linear coded transmissions at relays
  - No coordination needed among relays

Network Coding Applications

- Robustness Enhancement
  - Error correcting code
    - Physical layer: improving error performance on wireless link using intra-packet coding
  - Erasure correction
    - Spatial redundancy: handle lost packets on the end-to-end connection level using inter-packet coding
  - Joint error and erasure correction
  - Robust linear network coding for link failures

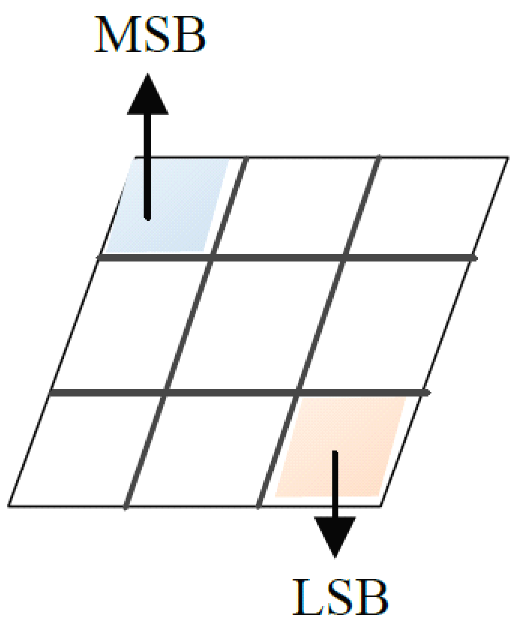
    (Koetter and Medard 2003)

Network Coding Applications

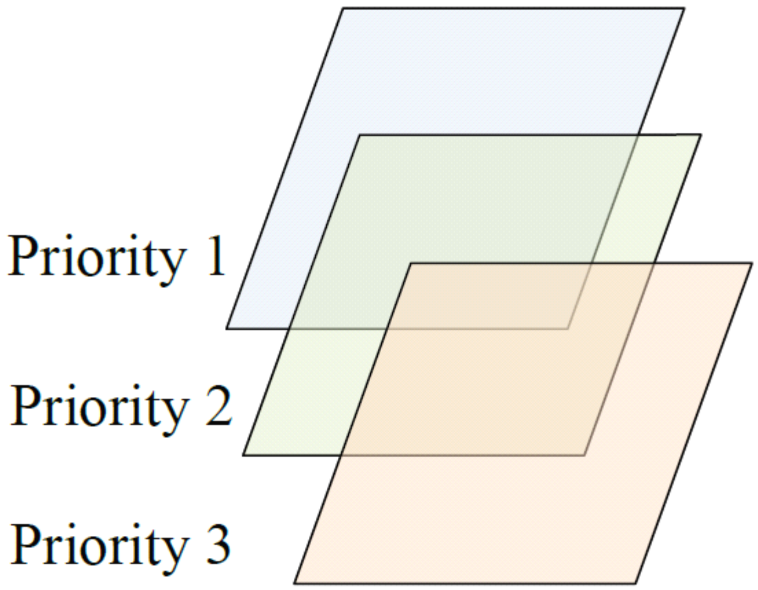
- Throughput/Capacity Enhancement
  - Overlay networks
    - Distributed storage systems
    - Content distribution
    - Layered multicast
  - Wireless networks
    - Throughput enhancement
    - Broadcast storm problem
- Network Tomography: infer network characteristics
  - Link loss rate inference
  - Topology inference

Priority-Based Approaches

- New twist on the classic unequal error protection



Symbol-Level NC



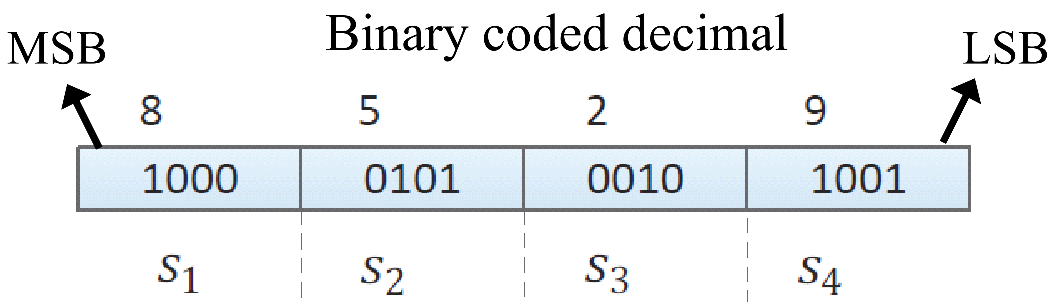
Video Streaming NC

Priority-Based Network Coding

Symbol-Level Transmission

Priority-Based Transmission

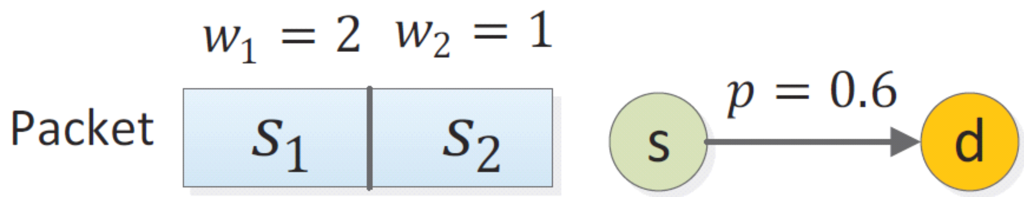
- Numeric data
  - Sensed data by sensors
  - Different priorities (utility values) for symbols s_i



- Approaches
  - Reliable transmissions
  - Maximizing the expected utility with a given number of transmissions

Motivation

- u : utility
- p : loss rate
- w_i : weight of s_i
- x_i : number of transmissions of s_i



$$u = w_1 \times (1 - p^{x_1}) + w_2 \times (1 - p^{x_2})$$

x_1	x_2	Utility
2	0	1.28
1	1	1.2
0	2	0.64

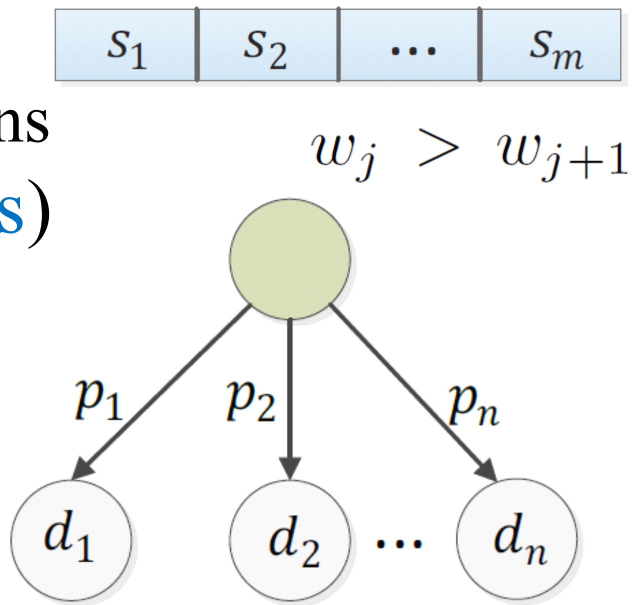
2 transmissions

x_1	x_2	Utility
3	0	1.568
2	1	1.68
1	2	1.44
0	3	0.78

3 transmissions

Setting and Objective

- One-hop wireless (WiFi) network
  - One source with multiple destinations
- Lossy links (randomness in wireless)
  - $p_1, p_2, \cdots, p_n$
- Transmission window size
  - X slots for a packet



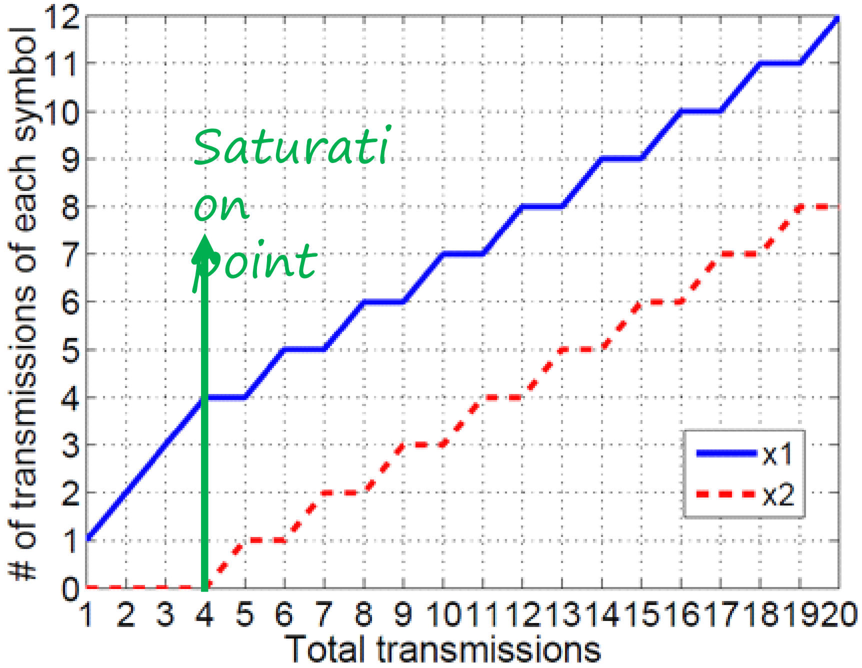
- Objective: maximizing the total expected utility of the received symbols

Single Packet (Homogenous Destinations)

- The case of a packet with 2 symbols

$$u = w_1 \times (1 - p^{x_1}) + w_2(1 - p^{x_2})$$

$$st. \quad x_1 + x_2 = X$$



$w_1 = 5$

$w_2 = 1$

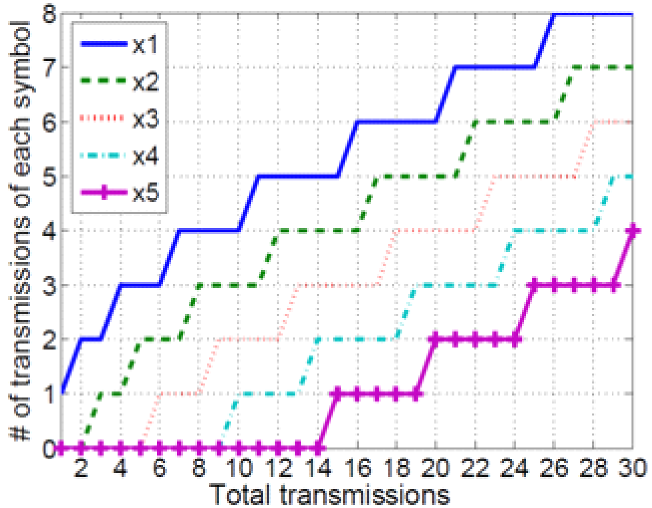
Single Packet (Homogeneous Destinations)

- *m* symbols
  - Assign the transmissions to x_1 while $p^{x_1} < \frac{w_2}{w_1}$
  - Then, distribute the transmissions between x_1 and x_2 while $p^{x_1} < \frac{w_3}{w_1}$ and $p^{x_2} < \frac{w_3}{w_2}$
  - Assign round-robin pattern among x_1, x_2, and x_3

Start increasing while x_j

$$p^{x_i} < \frac{w_j}{w_i}, \forall i : 1 \le i \le j-1$$

$w_i = 2^{5-i}$



Single Packet (Heterogeneous Destinations)

- The round-robin pattern does not exist
- Iterative algorithm
  - Δ_{x_i} : utility changes for increasing x_i to $x_i + 1$

$$\Delta_{x_i} = w_i \times \sum_{l=1}^{n} \left[p_l^{x_i} - p_l^{x_i+1} \right]$$

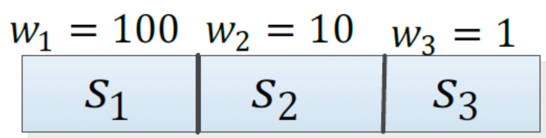
- At each iteration, assign the current transmission to the symbol s_i with the maximum Δ_{x_i}

Single Packet (Heterogeneous Destinations)

- Iteration 1

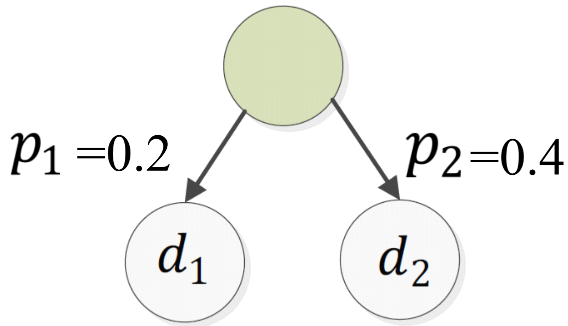
x_1 0	**Δ_{x_1}=140**	x_1 1
x_2 0	Δ_{x_2}=14	x_2 0
x_3 0	Δ_{x_3}=1.4	x_3 0

Binary coded decimal



- Iteration 2

x_1 1	**Δ_{x_1}=40**	x_1 2
x_2 0	Δ_{x_2}=14	x_2 0
x_3 0	Δ_{x_3}=1.4	x_3 0

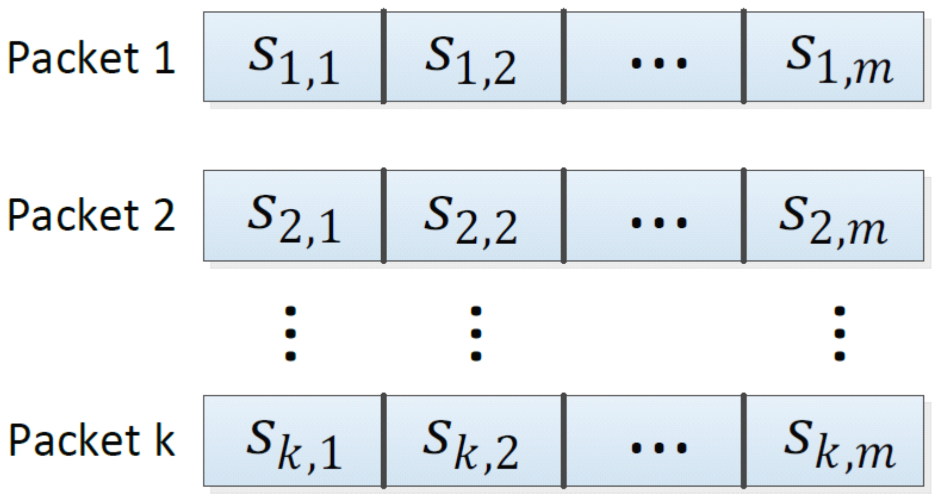


- Iteration 3

x_1 2	Δ_{x_1}=12.8	x_1 2
x_2 0	**Δ_{x_2}=14**	x_2 1
x_3 0	Δ_{x_3}=1.4	x_3 0

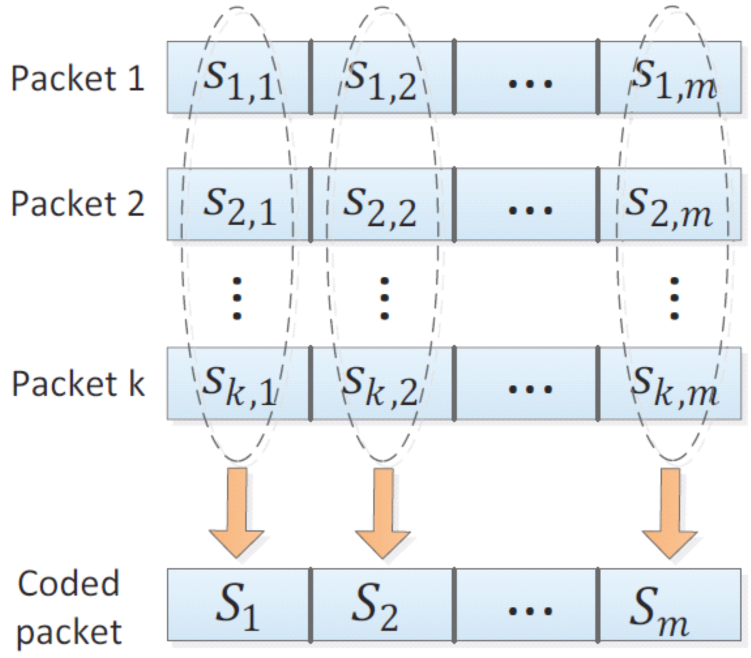
Multiple Packets (No Coding)

- Our model
  - The size of the packets is equal
  - Each packet has the same weight
- *k* independent packets with no coding



Multiple Packets (with Network Coding)

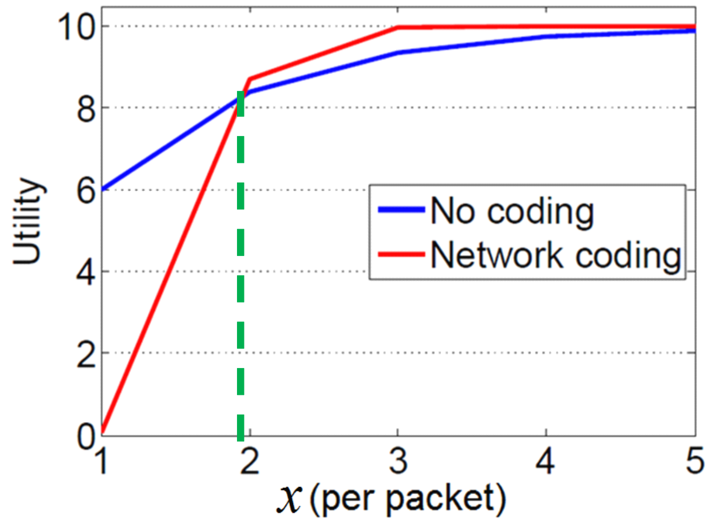
- Heuristic
  - First find the optimal x_i
  - Code all s_i of the k packets together
  - Send $x_i \times k$ coded symbols



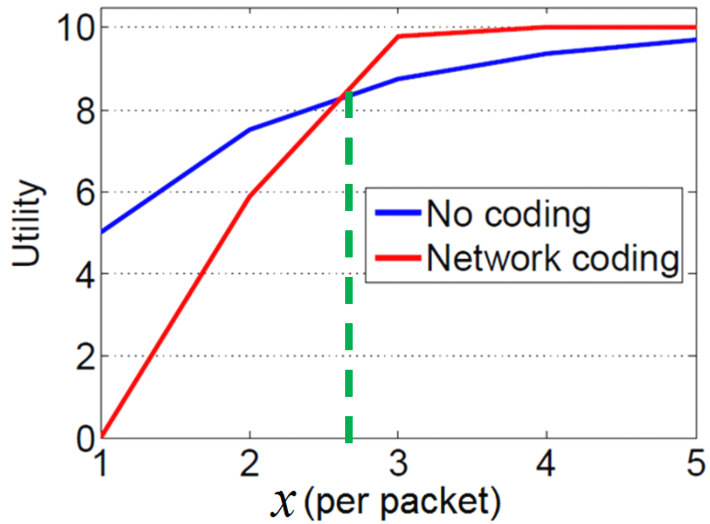
$$S_i = \sum_{j=1}^{k} \alpha_j \times s_{j,i}$$

Multiple Packets (with Network Coding)

- Network coding may or may not improve the utility
  - Since partial decoding is not possible
- Compute utility of coding/non-coding
  - Decision for coding/non-coding at each symbol



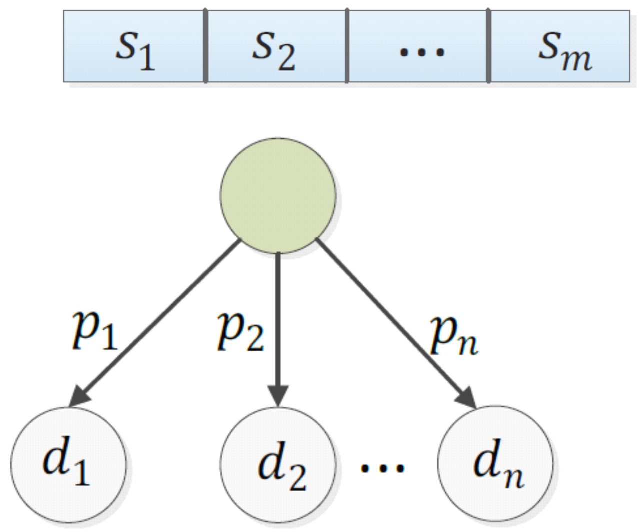
- 10 packets
- Error rate: 0.4



- 10 packets
- Error rate: 0.5

Simulations Setting

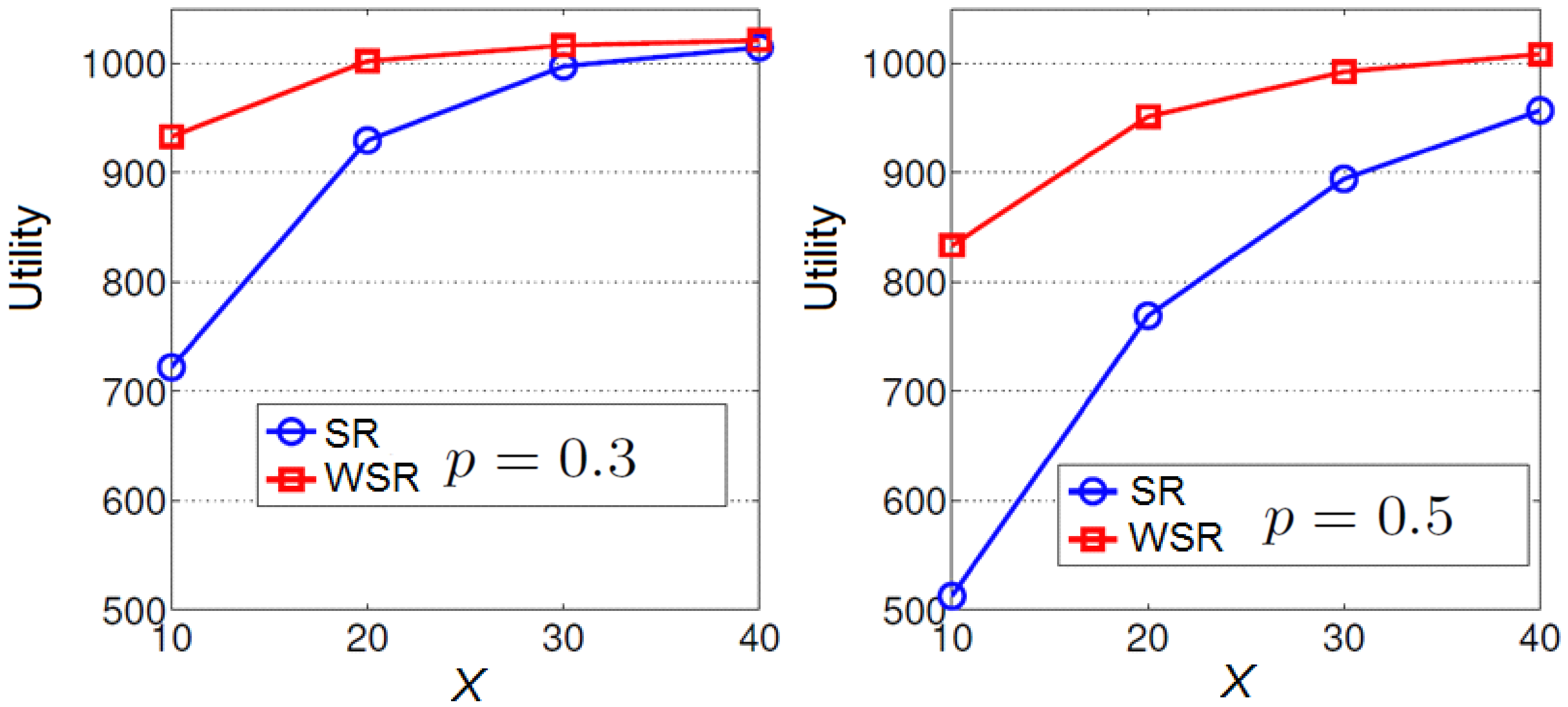
- MATLAB environment
- 1,000 rounds
  - Different error rates for links
- Weight of s_i : 2^{m-i}



- Comparing with simple retransmission method
  - Distribute transmissions equally to the different s_i

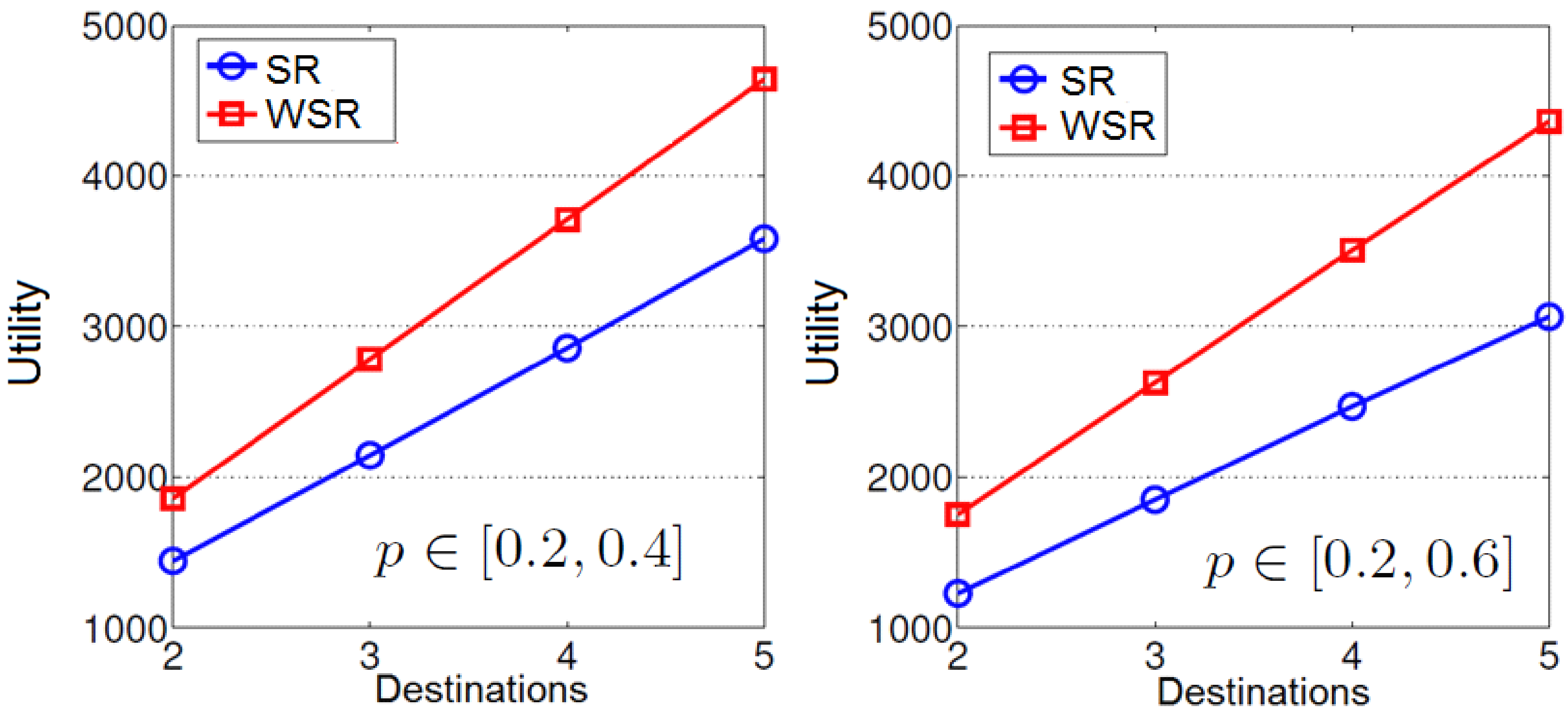
Simulations (Homogenous Destinations)

- Single packet: 10 symbols
- SR: simple retransmission
- WSR: weighted symbol retransmission



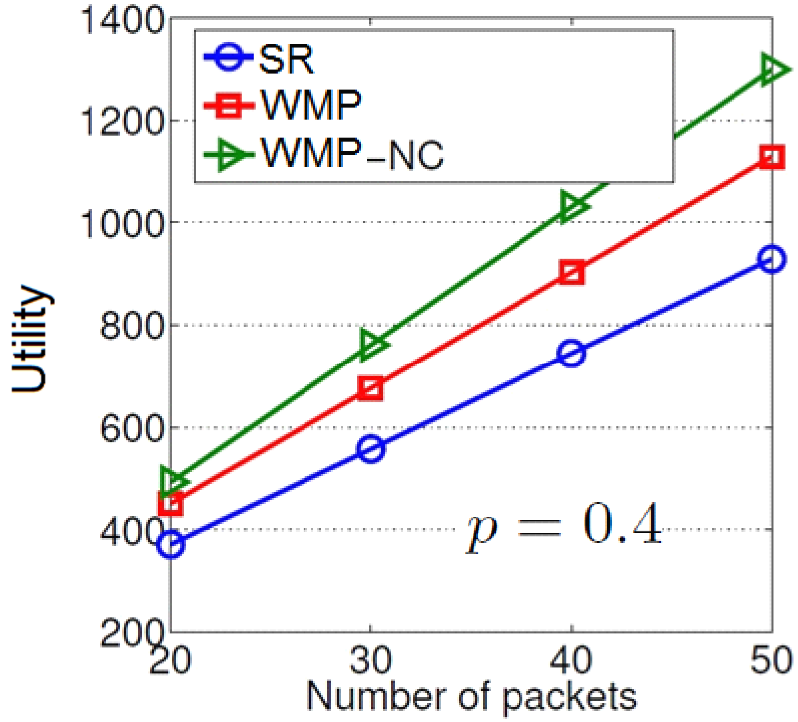
Simulations (Heterogeneous Destinations)

- Single packet- 10 symbols
- 10 transmissions
- Variable destinations and error rates

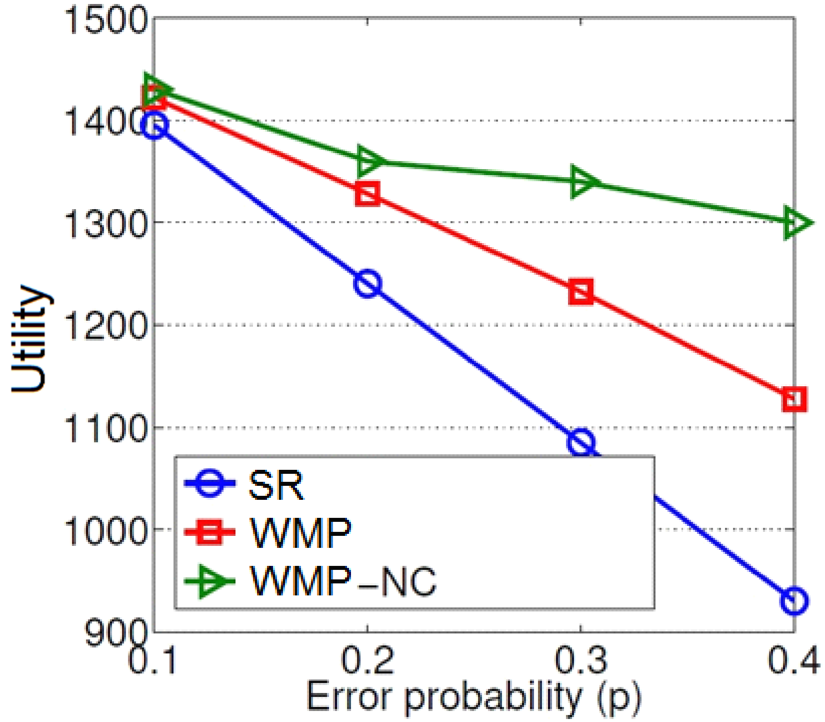


Simulations (Homogenous Destinations)

- Packet size: 5 symbols
- WMP: weighted multiple packets
- WMP-NC: weighted multiple packets with network coding



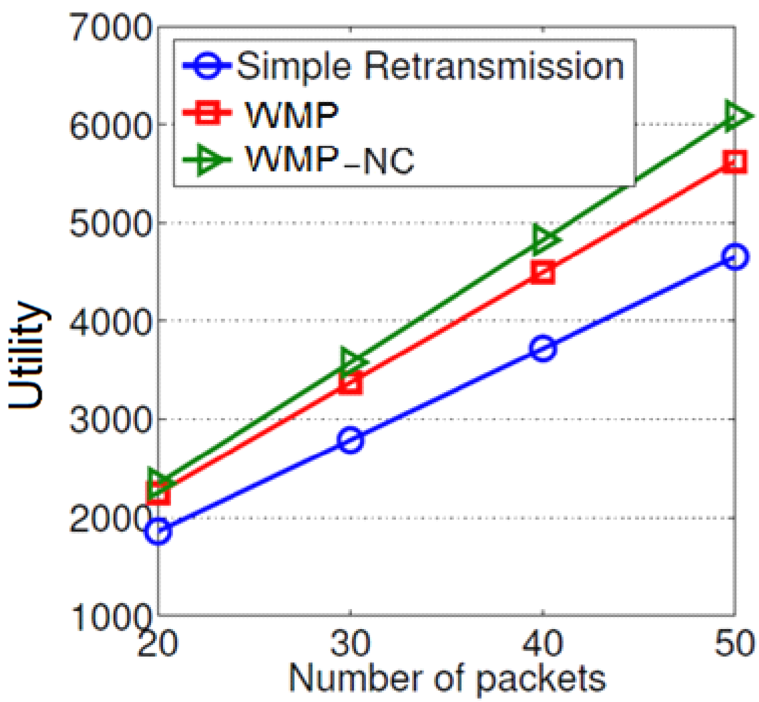
10 transmissions



50 packets

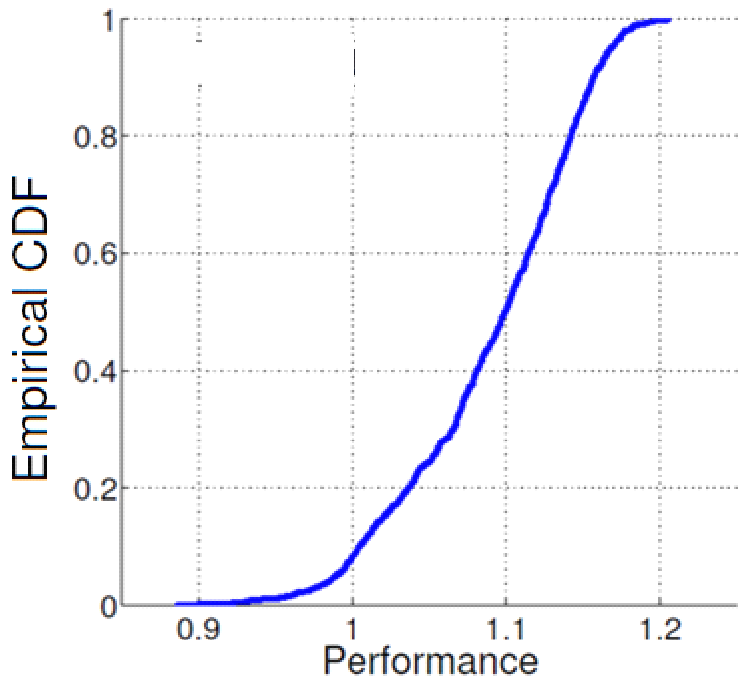
Simulations (Heterogeneous Destinations)

- Packet size: 5 symbols
- 5 destinations



$p \in [0.3, 0.5]$

CDF of WMP-NC's utility divided by WMP's utility



Number of packets=50

Simulations Summary

- WMP increases utility up to 22% compared to SR
- Utility of WMP-NC is up to 45% more than SR
- In 50% of the cases the utility of WMP-NC is 10-20% more than WMP
- As error rate increases, the performance of WMP-NC over the other methods increases

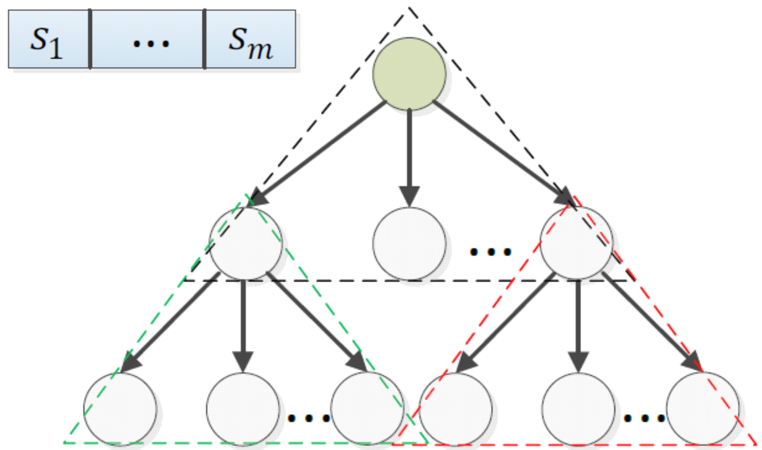
Current and Future Work

Current Work

- Optimal solution for network coding with multiple packets
- Multiple-hop network extensions with weighted destinations (based on the number of leaf nodes)

Future Work

- Extensions to DAG
- Real implementation



Priority-Based Network Coding

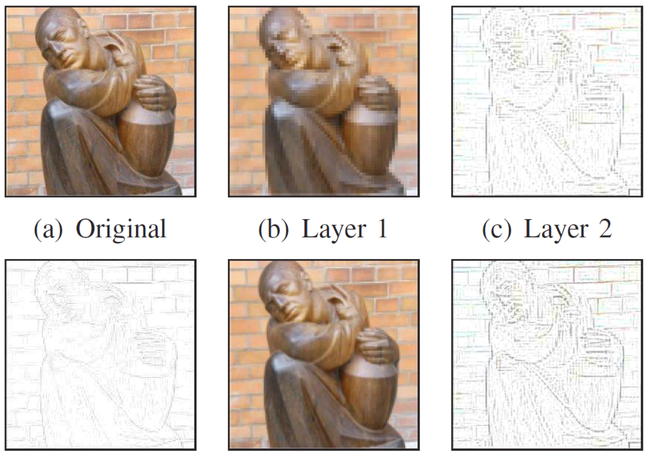
Layered Video Streaming

Video Streaming

- Delivering video stream using different resolutions to satisfy different client needs/constraints

Multi-Layer Coding (Multi-resolution)

- Base layer
- Enhancement layers

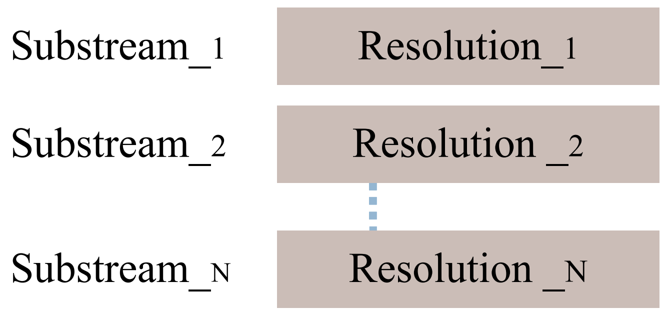


(a) Original (b) Layer 1 (c) Layer 2

(d) Layer 3 (e) Layers 1 & 2 (f) Layers 2 & 3

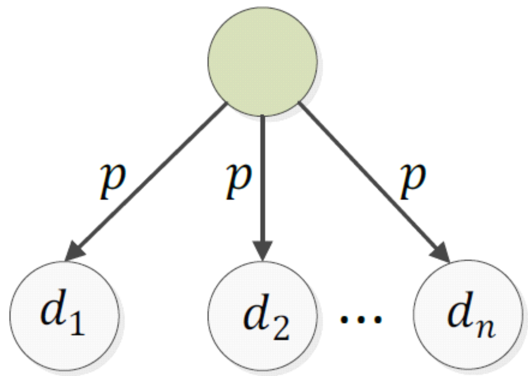
Multiple Description Coding (MDC)

- Multiple independent video substreams
- Receiving more substreams increases the video quality



Setting and Objective

- One-hop WiFi networks
- Video stream: sequence of packets
- Packet deadline: X transmissions
- Layered streams : L layers
- Objective: maximizing throughput in terms of the total number of received layers by the users
- Intra-layer coding: linear coding
- Inter-layer coding: triangular coding



Lossy Bernoulli channel

Inter-Layer Coding Strategies

- Random linear network coding (RLNC)

$$\alpha_1 L_1 + \beta_1 L_2 + \gamma_1 L_3$$
$$\alpha_2 L_1 + \beta_2 L_2 + \gamma_2 L_3$$
$$\alpha_3 L_1 + \beta_3 L_2 + \gamma_3 L_3$$

Triangular coding

Prefix coding

$$\alpha_1 L_1$$
$$\alpha_2 L_1 + \beta_2 L_2$$
$$\alpha_3 L_1 + \beta_3 L_2 + \gamma_3 L_3$$

Packets in lower layers are more important

Included in more coded packets

More chance to be decoded

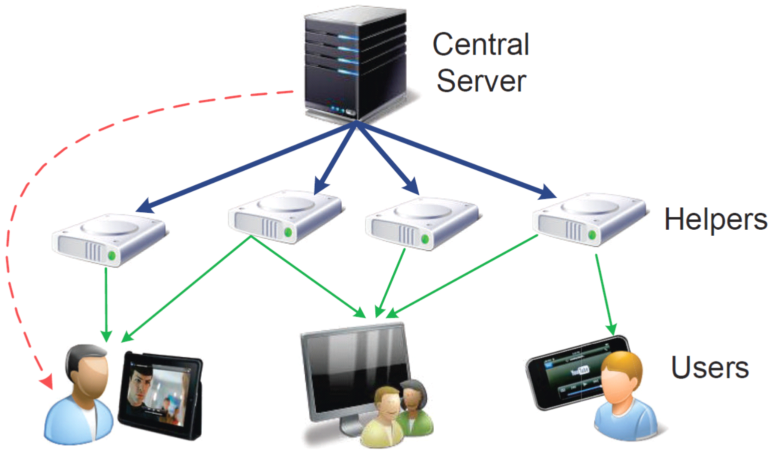
Advantage of Triangular Coding

- Coefficients are not shown for simplicity
- 6 transmissions in round-robin pattern
  - Blue cells are received

No coding	L1	L2	L3	L1	L2	L3	Unable to decode
Triangular coding	L1	L1 + L2	L1 + L2+ L3	L1	L1 + L2	L1 + L2+ L3	Decodes 2 layers
Random linear coding	L1 + L2+ L3	L1 + L2+ L3	L1 + L2+ L3	L1 + L2+ L3	L1 + L2+ L3	L1 + L2+ L3	Unable to decode

Multi-Layer Video Streaming with Helpers

- Links
  - Cost: direct download from the server
  - Reliable links
- Link capacity
  - High capacity links: server to helpers
  - Low capacity links: helpers to users
- Use of helpers
  - System scalability for more users
  - Helpers: limited capacity and bandwidth

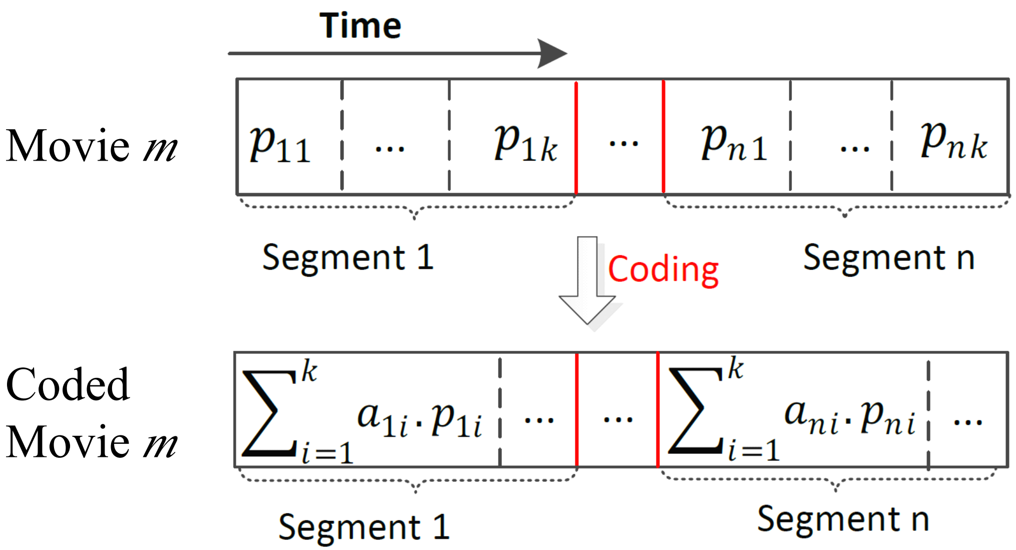


Resource Management

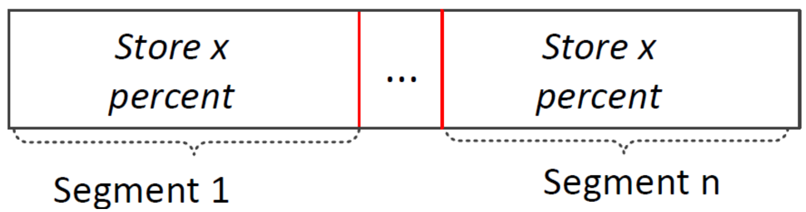
- Optimal resource management
- Questions:
  - **Content placement**: Which packets of each video should a helper node store?
  - **Bandwidth allocation**: Which packets, and to which users, should each helper serve?
- NP-complete

Resource Management (Network Coding)

- Network coding changes the problem to a linear programming



- Storing x percent of each segment

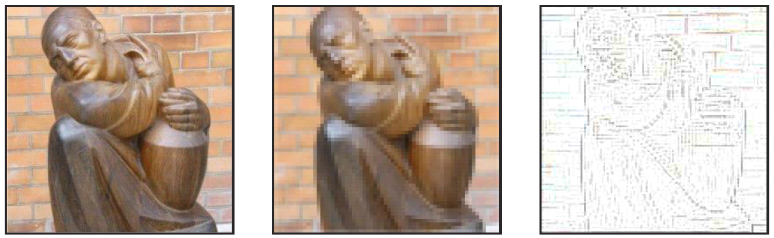


No longer NP-complete

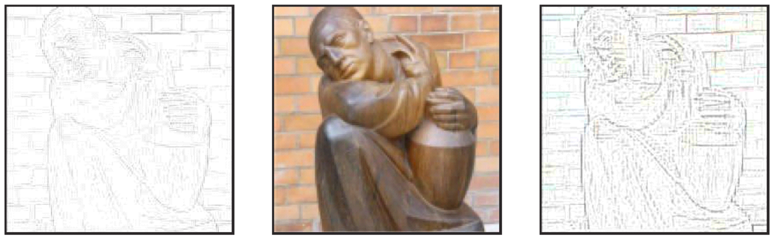
Flow-based model using network coding

Multi-Layer Video

- Benefits of multi-layer
  - Provides smooth playback for the users
  - Reduces the load on the server with a fixed number of users
  - More layers increases system scalability



(a) Original (b) Layer 1 (c) Layer 2



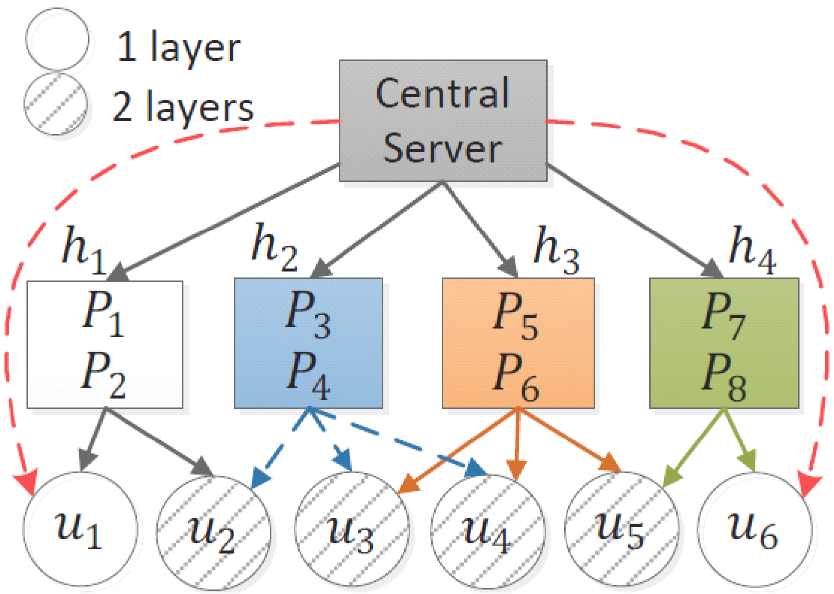
(d) Layer 3 (e) Layers 1 & 2 (f) Layers 2 & 3

Motivation

- Single video with 4 packets
- No-layer approach

  (Hao et al. 2011)
  - 4 packets in the same layer
  - Load on the server: 4

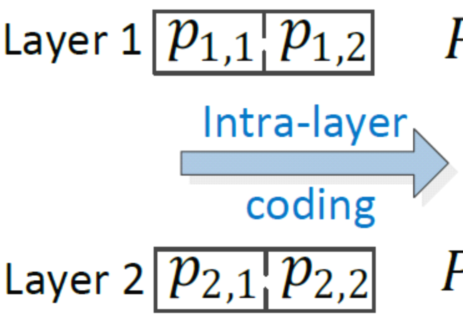
$$p_1 \,|\, p_2 \,|\, p_3 \,|\, p_4 \Rightarrow P_i = \sum_{j=1}^{4} \alpha_{i,j} p_j$$



Motivation

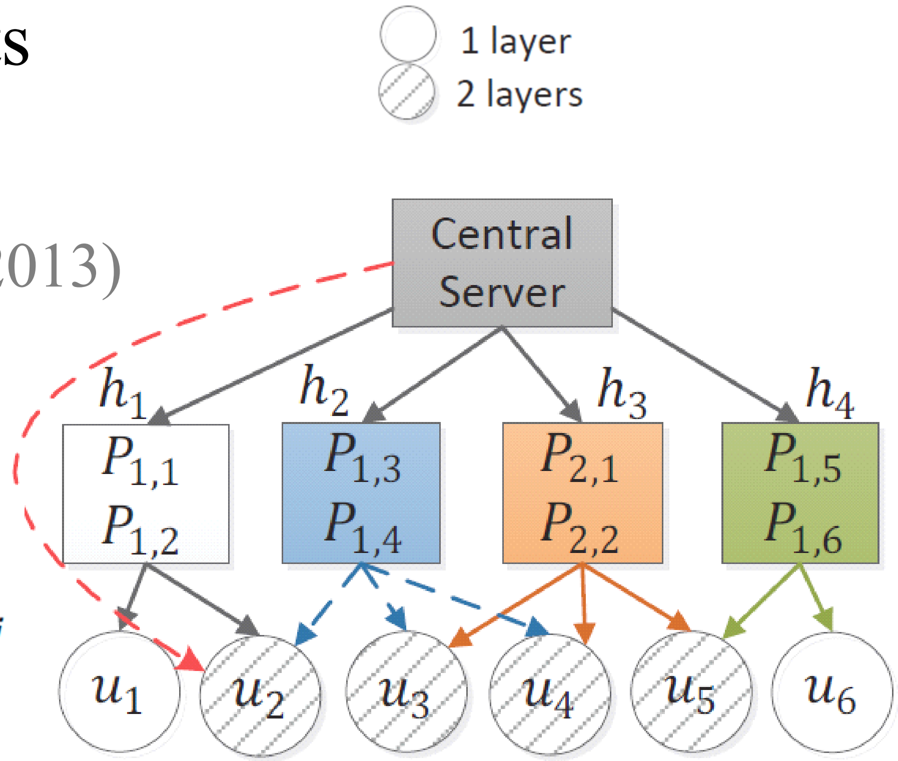
- Single video with 4 packets
- Intra-layer approach

  (Ostovari, Khreishah, and Wu 2013)
  - 2 packets per layer
  - Load on the server: 2



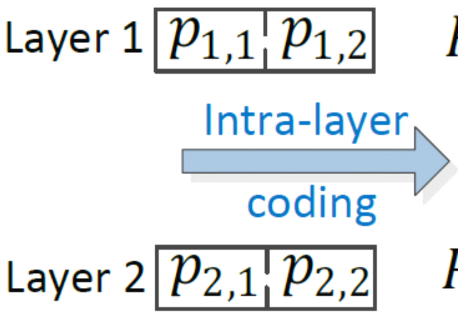
$$P_{1,i} = \sum_{j=1}^{2} \alpha_{i,j} p_{1,j}$$

$$P_{2,i} = \sum_{j=1}^{2} \alpha_{i,j} p_{2,j}$$



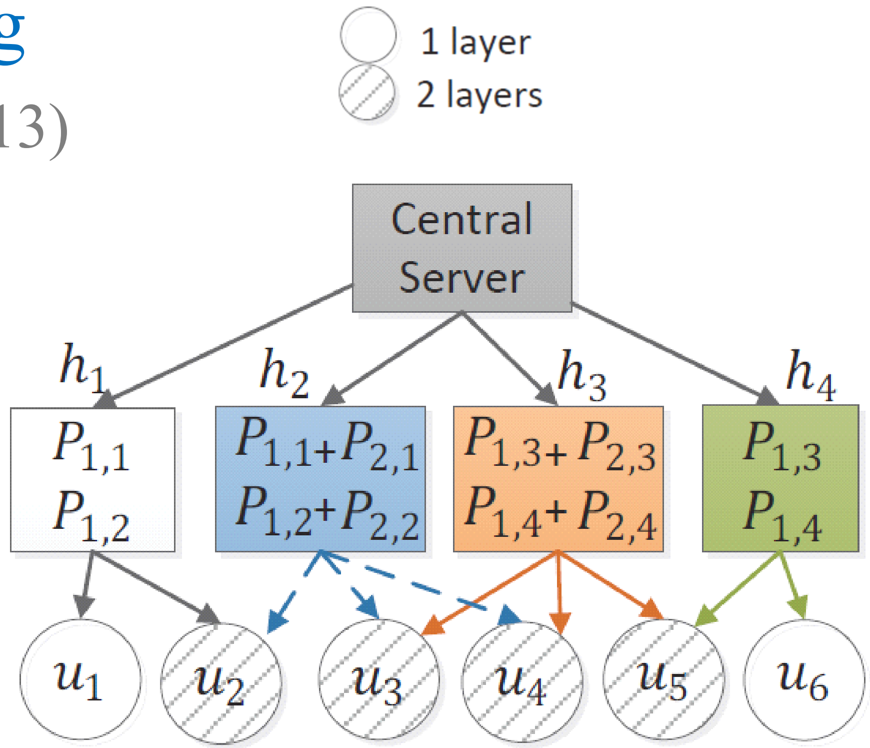
Motivation

- Single video with 4 packets
- Inter- and intra-layer coding
  (Ostovari, Khreishah, and Wu 2013)
  - Prefix coding
  - 2 packets per layer
  - Load on the server: 0



$$P_{1,i} = \sum_{j=1}^{2} \alpha_{i,j} p_{1,j}$$

$$P_{2,i} = \sum_{j=1}^{2} \alpha_{i,j} p_{2,j}$$



Triangular coding

VoD with Inter- and Intra-Layer NC

$$\max \sum_{\substack{i,k: \\ m_k = q_i}} \sum_{\substack{j,l: h_j \in N(u_i) \\ l \le c_i}} x_{ji}^{kl}$$

Objective function (maximize upload rate from helpers to users)

$s.t$

$$x_{ji}^{kl} \le f_j^{kl} \times \frac{r_k}{L}, \quad \forall j, i, l : u_i \in N(h_j), l \le L$$

The upload rate of a cache cannot exceed the rate of the stored videos

- x_{ji}^{kl} : Upload rate from helper h_j to user u_i over layer l of video m_k
- f_j^{kl} : Fraction of the layer l of video m_k that is stored on helper h_j
- r_k : Rate of video m_k
- L : Number of layers of a video
- $N(u_i)$: Adjacent helpers to user u_i
- u_i 's request: (c_i , q_i) = (quality level, video)

VoD with Inter- and Intra-Layer NC

$$\sum_{\substack{i,k:u_i \in N(h_j) \\ m_k = q_i}} \sum_{l \leq c_i} x_{ji}^{kl} \leq B_j, \quad \forall j : h_j \in H$$

Bandwidth constraints

$$\sum_{k:m_k \in M} \sum_{l:l \leq L} f_j^{kl} \times \frac{v_k}{L} \leq S_j, \quad \forall j : h_j \in H$$

Storage constraints

$$\sum_{l=1}^{l'} \sum_{j:h_j \in N(u_i)} x_{ji}^{kl} \leq \frac{r_k}{L} \times l', \quad \forall i, l' : 1 \leq l' \leq c_i$$

Limits the total download of a user to the rate of the video

- B_j : The bandwidth limit of helper h_j
- S_j : The capacity limit of helper h_j

VoD with Intra-Layer NC

- The difference is in the last constraint

$$\sum_{j:h_j \in N(u_i)} x_{ji}^{kl} \leq \frac{r_k}{L}, \quad \forall i, l : u_i \in U, l \leq c_i$$

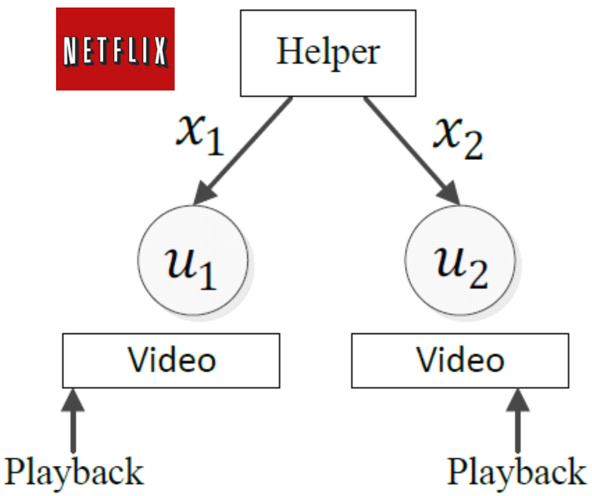
Limits the total download of a user to the rate of the video

U: the set of users

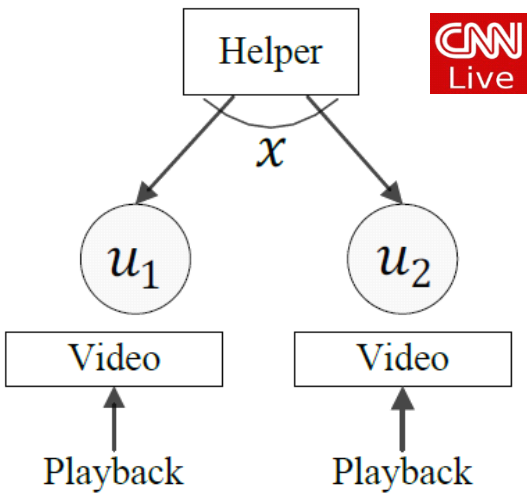
- The objective function and other constraints are the same

Live Streaming (TV)

- Videos are broadcast to the users
- Synchronous playback
  - Helpers do not need to allocate separate bandwidths to adjacent users that watch the same video



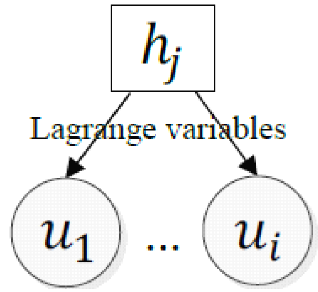
Total bandwidth: x_1+x_2



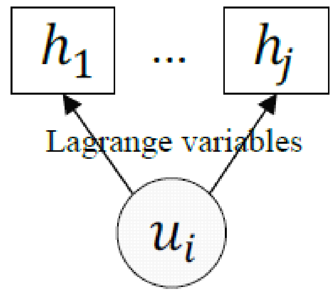
Total bandwidth: x

Distributed Algorithm

- Dual optimization
  - Solving Lagrangian dual using gradient method
- Helper h_j
  - Start from empty storage and dynamically adjust the amount of stored videos
  - Update and transmit Lagrange variables to adjacent users



- User u_i
  - Update and transmit Lagrange variables to adjacent helpers



- Step control
  - Slope of changes: fast convergence vs. oscillation

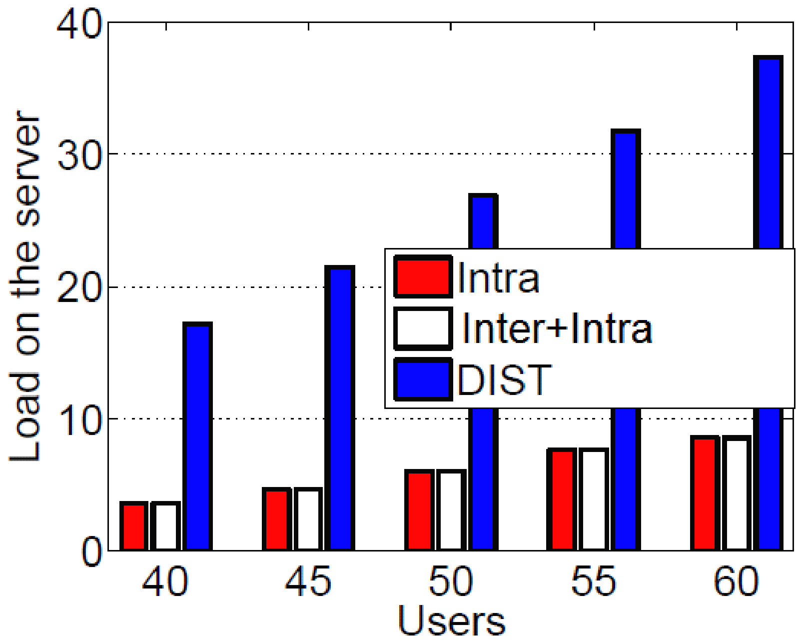
Simulations Setting

- MATLAB environment
- 100 random topologies
  - Random connections of helpers and users
  - Helpers: random bandwidth and capacity limit
  - Users: random requests
- Comparing with optimal non-layer approach
- Measuring
  - Load on the server
  - Convergence to optimal solution in dynamic environments

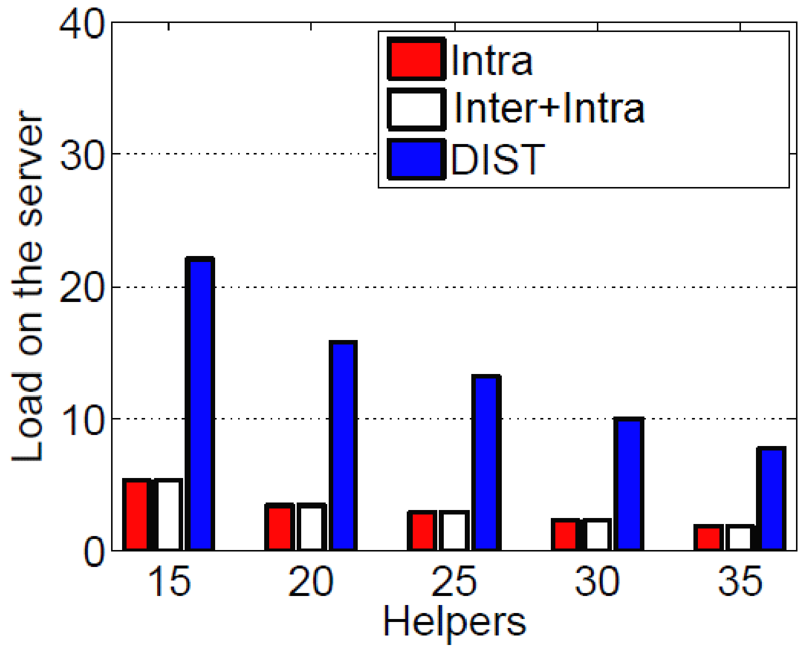
Video's rate	Video's size	Bandwidth capacity	Storage capacity	Num. of adjacent helpers to a user
[1,2] kbps	[0.5,2] MB	[2,4] kbps	[0.5,2] MB	[1,3]

Simulation Results (Load)

- VoD
- Number of videos: 5
- Number of layers: 5
- DIST: a non-layer approach with intra-layer coding (Hao et al. 2011)



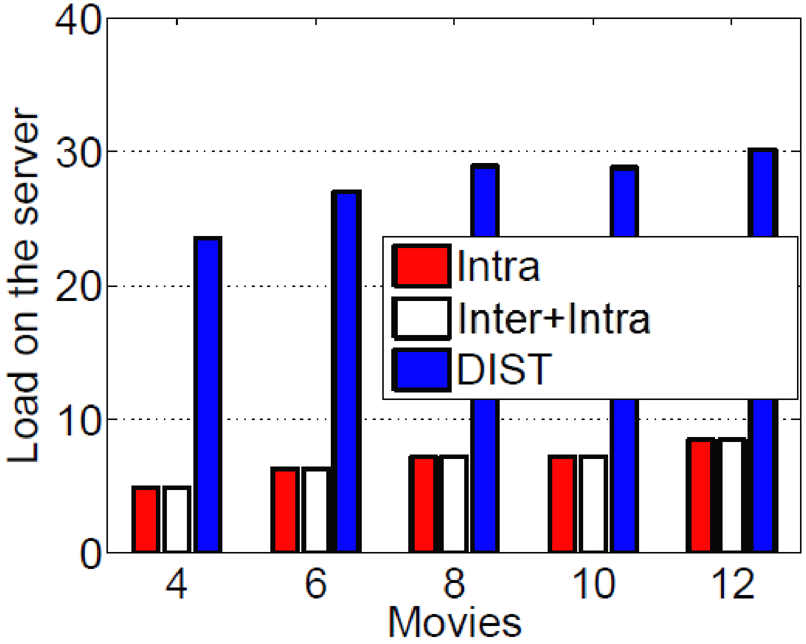
Number of helpers: 20



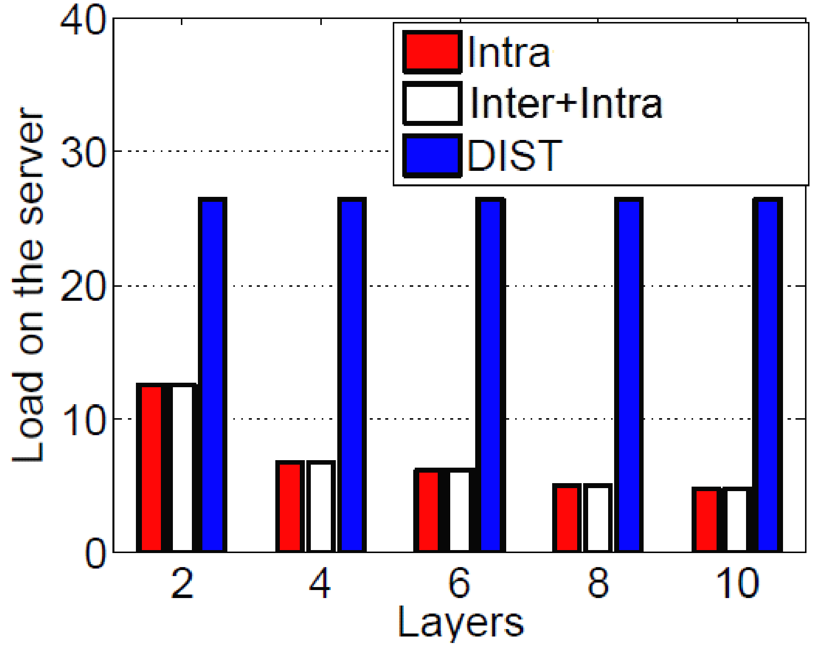
Number of users: 40

Simulation Results (Load)

- VoD
- Number of users: 50
- Number of helpers: 20



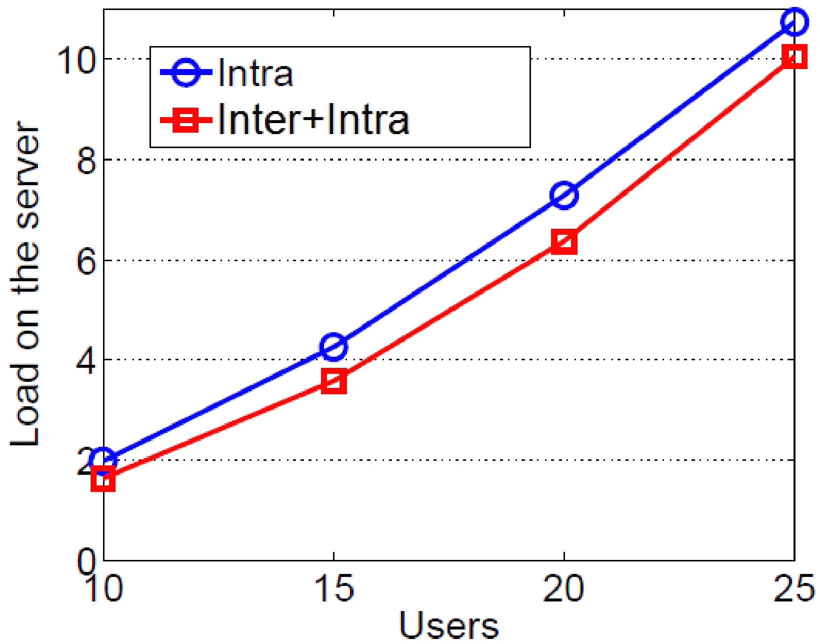
Number of layers: 5



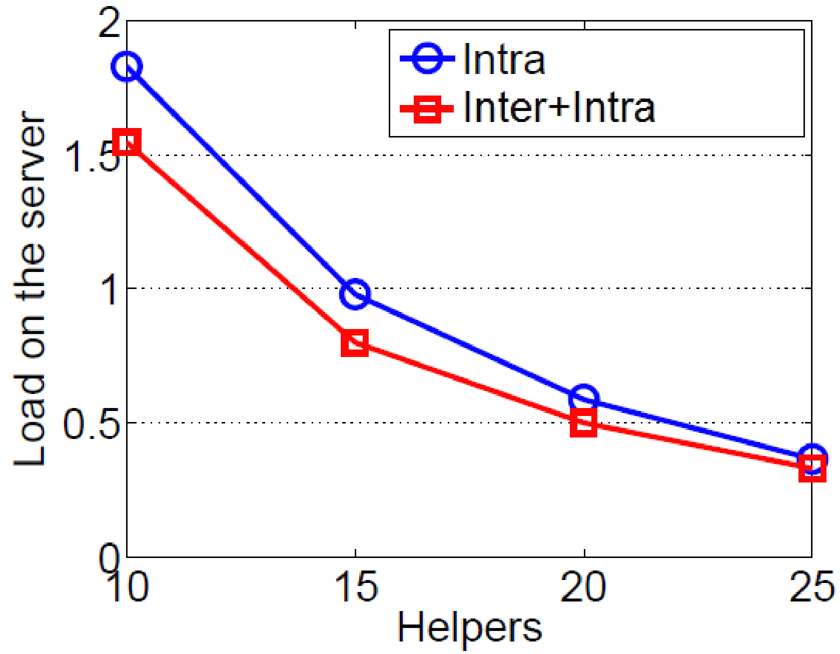
Number of videos: 5

Simulation Results (Load)

- VoD
- Number of layers: 4
- Single video



Number of helpers: 10

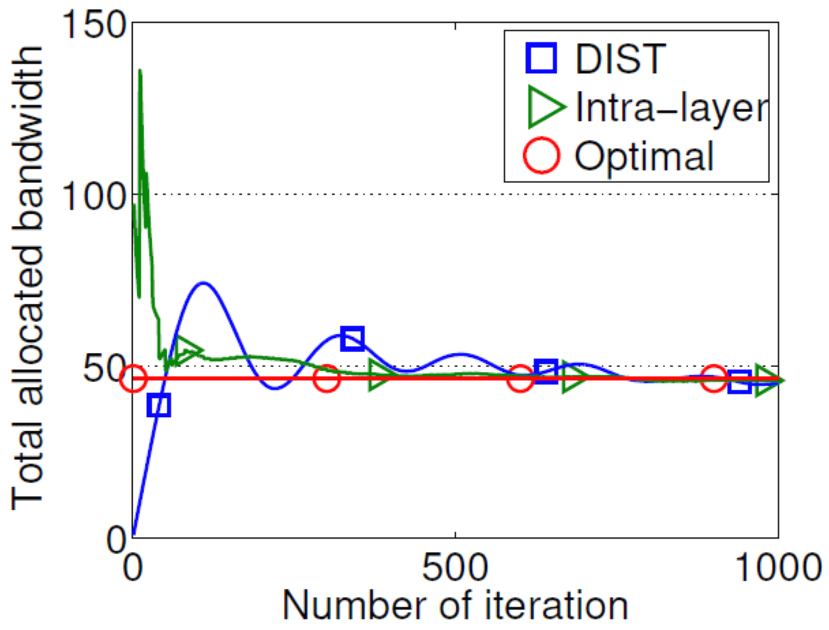


Number of users: 10

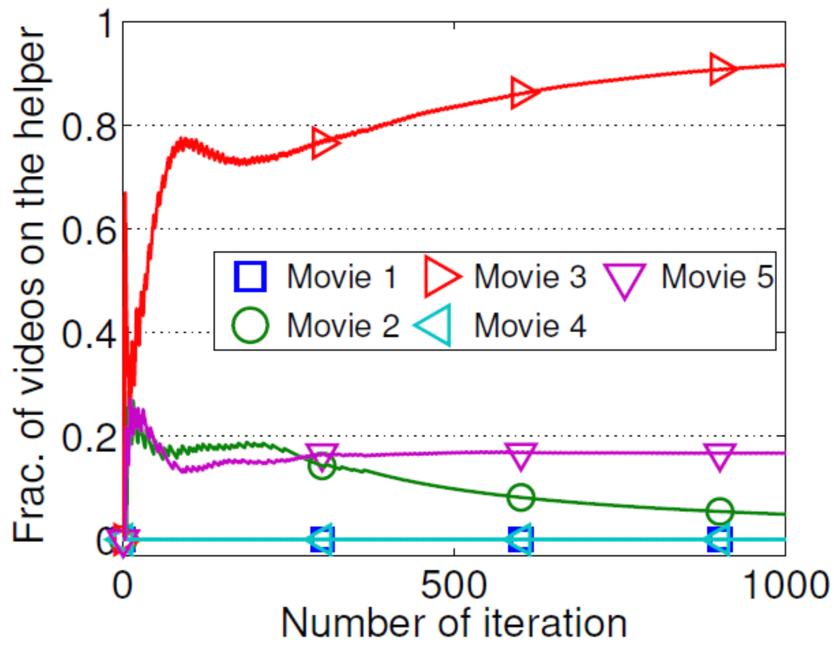
Simulation Results (Convergence)

- VoD
- Layers: 4
- Videos: 5

Users: 50
Helpers: 20



Convergence to the optimal solution (LP)

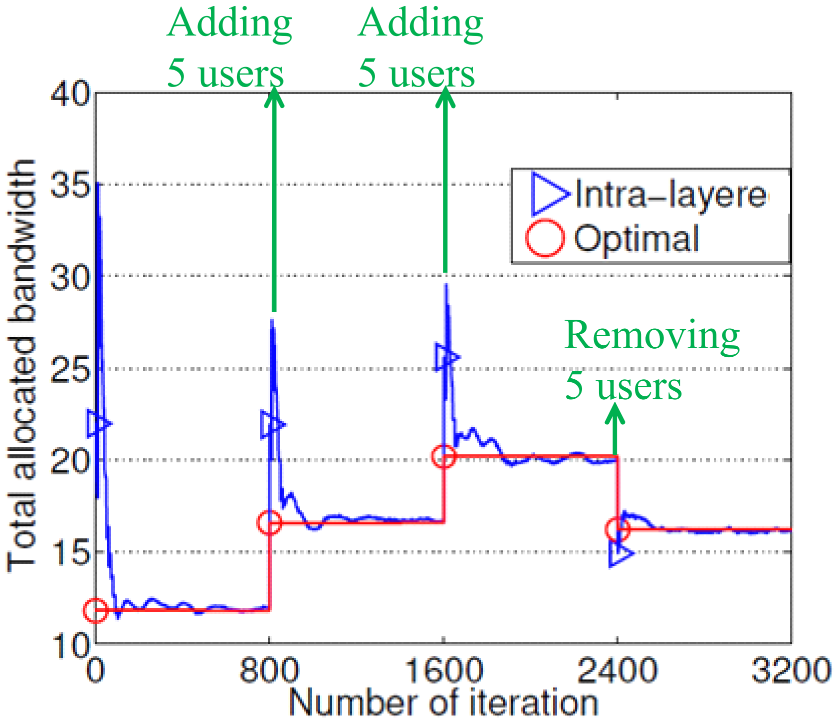


The fraction of each video on helper h5

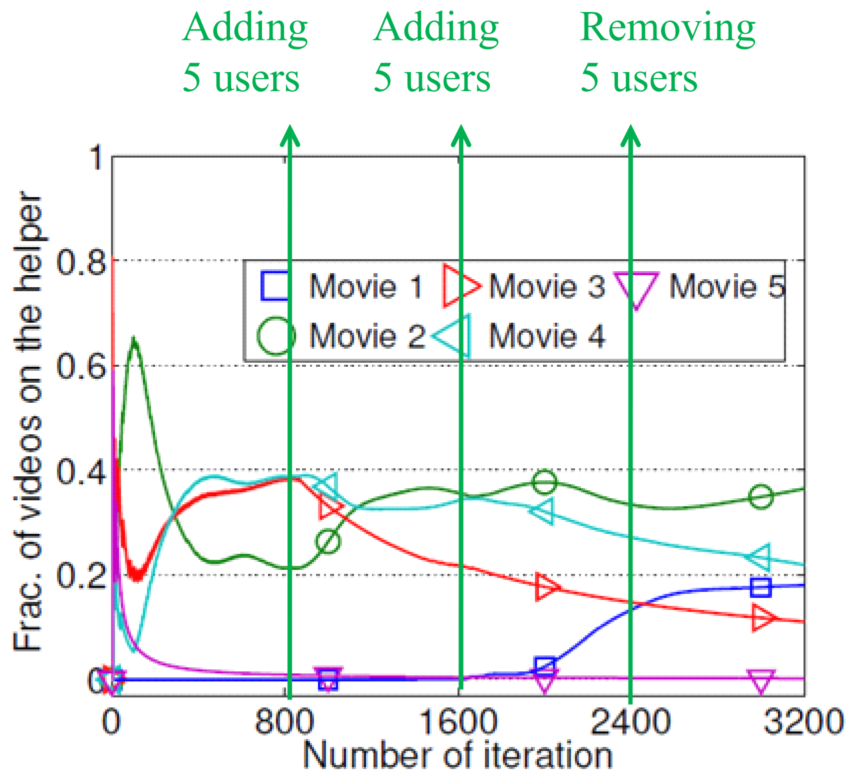
Simulation Results (Dynamic Users)

- VoD
- Layers: 4
- Videos: 5

Initial Users: 10
Helpers: 10



Convergence to the optimal solution (LP)

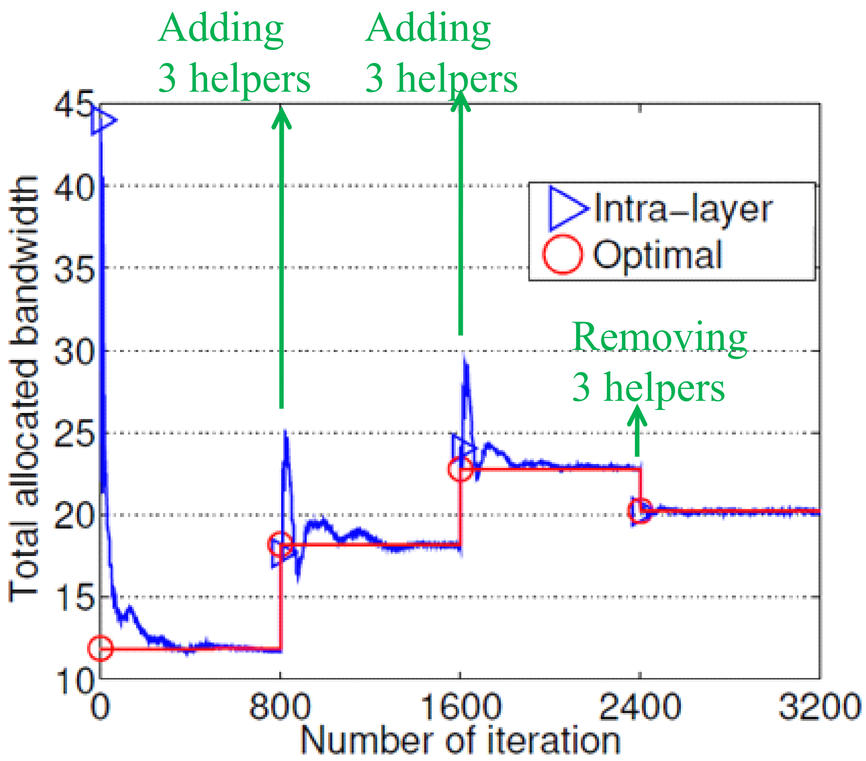


The fraction of each video on helper h8

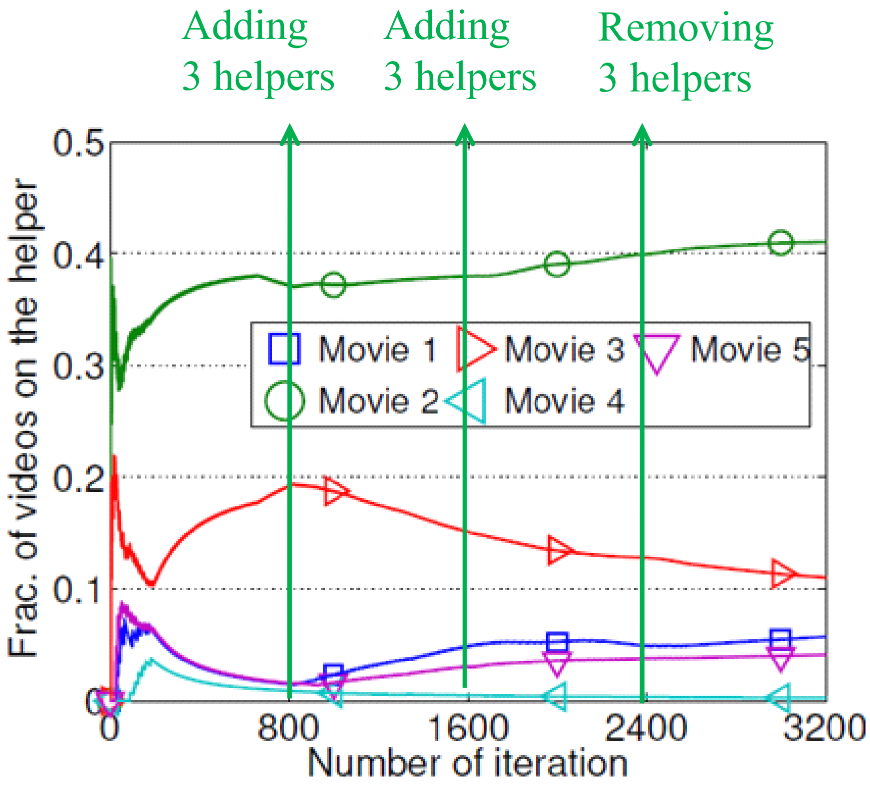
Simulation Results (Dynamic Helpers)

- VoD
- Layers: 4
- Videos: 5

Users: 20
Initial helpers: 6



Convergence to the optimal solution (LP)



The fraction of each video on helper h3

Future Work and Challenges

- Other objectives
  - Fairness, layers with different weights, …
- Extension of layered VoD with unreliable links
  - Using symbol-level transmission work in layered VoD
- Cost-efficient helper provisioning
  - Based on user demands and resource availability
- Real implementation

Conclusions

Conclusions

Priority-Based Network Coding

- Data transmission
  - Transmitting the more important data with more redundancy
- Triangular coding in multi-layer video streaming
  - Increasing the number of received layers
- VoD and live streaming using helper nodes in multi-layer video streaming
  - Minimizing the load on the server

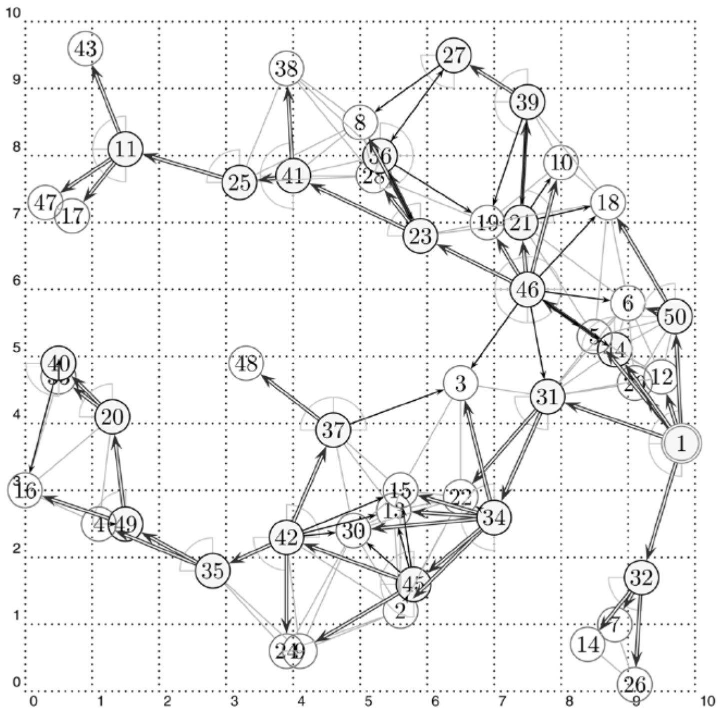
References

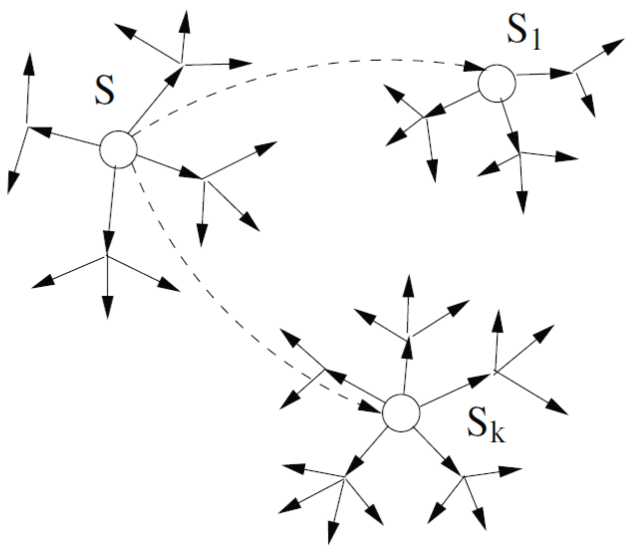
- P. Ostovari, J. Wu, and A. Khreishah, "Efficient Symbol-Level Transmission in Error-Prone Wireless Networks With Network Coding," *Proc. of IEEE WoWMoM*, 2013.
- P. Ostovari, A. Khreishah, and J. Wu, "Multi-Layer Video Streaming with Helper Nodes using Network Coding," *Proc. of IEEE MASS*, 2013.
- H. Hao, M. Chen, A. Parekh, and K. Ramchandran, "A Distributed Multichannel Demand-Adaptive P2P VoD System with Optimized Caching and Neighbor-Selection," *Proc. of SPIE*, 2011.

Other Recent Works

Other Works

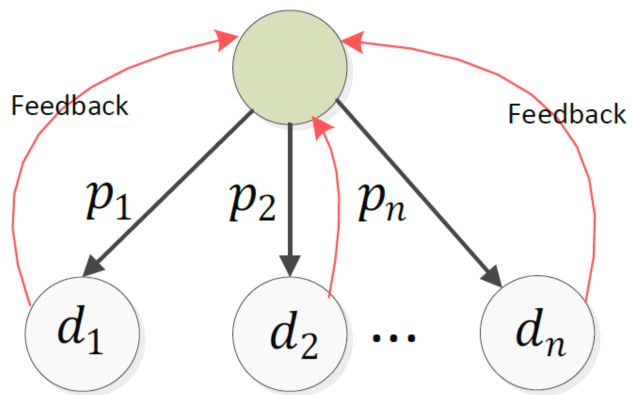
- S. Yang, J. Wu, and M. Cardei, "Efficient Broadcast in MANETs Using Network Coding and Directional Antennas," *Proc. of IEEE INFOCOM*, 2008.
  - Network coding in multiple broadcast in a wireless network.
  - Using dominating set as relays and for inter-session coding. (combine routing and coding)
  - Using both dominating set and directional antennas to reduce contention.





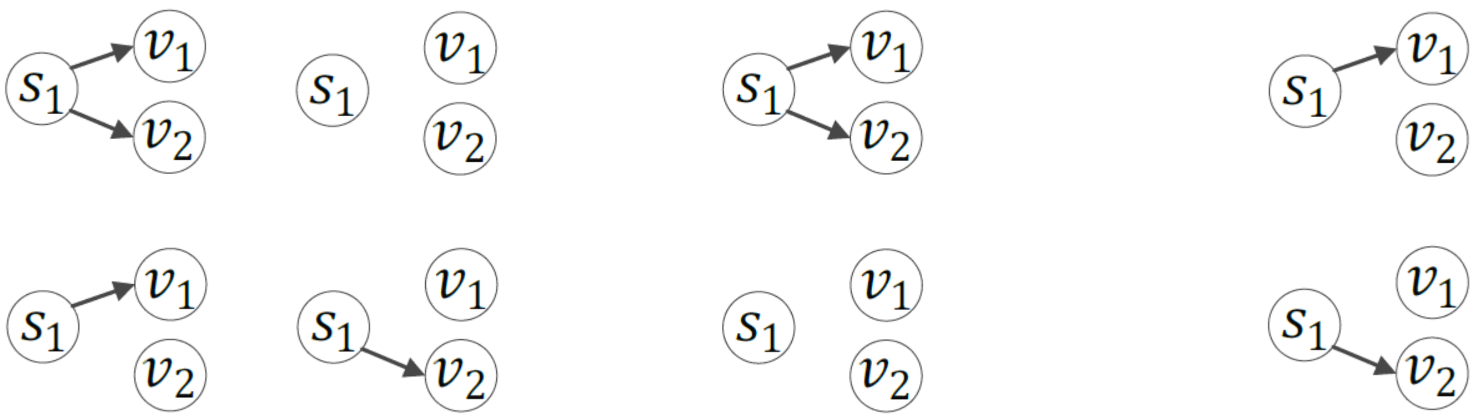
Other Works

- P. Ostovari, A. Khreishah, J.Wu, and W. –S. Yang, "Trade-off between Redundancy and Feedbacks in Wireless Network Communication," accepted to appear in *Ad-Hoc & Sensor Wireless Networks*, 2013.
  - One-hop broadcasting using XOR coding
  - Minimum-cost reliable broadcast considering the cost of feedback messages
  - Multiple retransmissions before receiving feedback
  - How many retransmissions are required?



Other Works

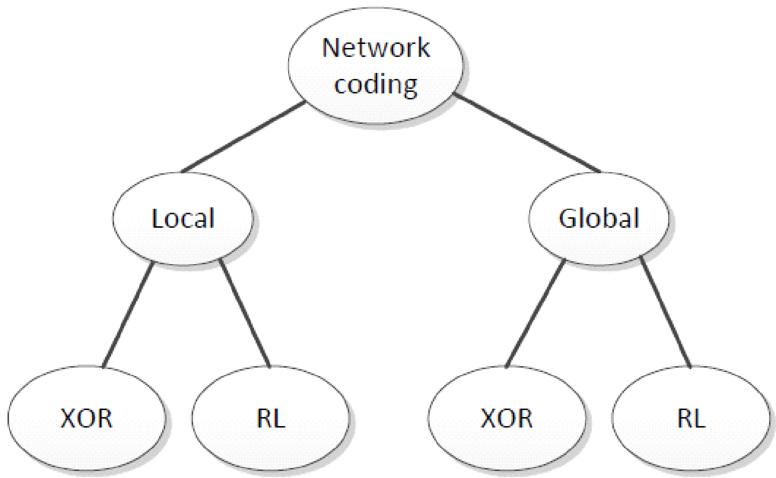
- A. Khreishah, I. M. Khalil, and J. Wu, "Universal Opportunistic Routing Scheme using Network Coding," *Proc. of IEEE SECON*, 2012.
  - Distributed opportunistic routing algorithm
  - The correlation of the links through network tomography
  - Coded feedback (for source to determine the type of link failure)
  - Unicast (and multicast in *ACM MobiHoc 2012*)

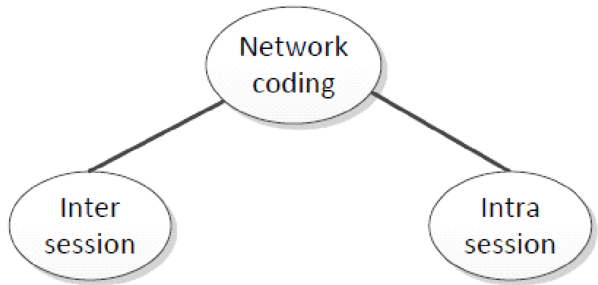


Independent   Correlated   Negatively correlated

Other Works

- P. Ostovari, J. Wu, and A. Khreishah, " Network Coding Techniques for Wireless and Sensor Networks," accepted to appear in *The Art of Wireless Sensor Networks*, H. M. Ammari (ed), Springer.
  - Unicast
  - Multicast
  - Broadcast





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CCSS: An Architecture for Joint Integration of Inter and Intrasession Network Coding in Lossy Multihop Wireless Networks