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Optimal Resource Allocation for Video Streaming over Distributed Communication Networks

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Major Publications

- Y. He, I. Lee and L. Guan, “"Distributed throughput optimization in P2P VoD systems,” to appear in *IEEE Transactions on Multimedia*.
- Y. He, I. Lee and L. Guan, “Distributed algorithms for network lifetime maximization in wireless visual sensor networks,” *IEEE Transactions on Circuits and Systems for Video Technology* (subject to minor revision).
- Y. He, I. Lee and L. Guan, “Optimized video multicast in wireless ad hoc network using network coding,” to appear in *IEEE Transactions on Circuits and Systems for Video Technology.*
- Y. He, G. Shen, Y. Xiong and L. Guan, “Optimal prefetching scheme in P2P VoD applications with guided seeks,” accepted by *IEEE Transactions on Multimedia*
- Y. He and L. Guan, “Optimal resource allocation in distributed visual communications,” in *Intelligent Multimedia Communication: Techniques and Applications*, C.W. Chen, Z. Li and S. Lian, eds, Springer-Verlag, to be published in 2009.

Outline

- Motivation and contributions
- Principles of convex optimization
- Resource allocation in distributed video communication systems
  - Throughput maximization in P2P VoD applications
  - Network lifetime maximization in wireless visual sensor networks
  - Optimization for video streaming over wireless ad hoc networks
- Conclusions

Motivation

- Many multimedia applications involve real-time video transmissions over distributed networks. Some examples:
  - P2P VoD applications
  - Video streaming over wireless ad hoc networks
  - Wireless visual sensor networks
- Distributed algorithms to optimize resource allocations in distributed networks
  - Each node has local knowledge
  - No centralized controller
  - Scalability

Challenges

- P2P VoD applications
  - Limited bandwidth
  - Unreliable and dynamic peers
  - Random seeks
- Video streaming over wireless ad hoc networks
  - High transmission error rate
  - Source rate allocation
  - Optimized routing scheme
- Wireless visual sensor networks
  - Video compression, consuming a large amount of power
  - Trade-off between network life time and video quality

Contributions

- Formulate resource allocation problems in distributed networks based on convex optimization, and
- Solve them using distributed algorithms
  - Throughput maximization in P2P VoD applications
  - Optimized video streaming over wireless ad hoc networks
  - Network lifetime maximization in wireless visual sensor networks

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Convex optimization problem

- Convexity is often viewed as the “watershed” between easy and hard optimization problems.
- Convex optimization: the primal problem [Boyd2004]

$$\begin{aligned} &\text{minimize}: \ w_0(\mathbf{x}) \\ &\text{Subject to}: w_i(\mathbf{x}) \le 0, \quad i = 1,\dots,m \\ &\qquad\qquad\quad q_i(\mathbf{x}) = 0, \quad i = 1,\dots,p \end{aligned}$$

where $\mathbf{x} \in \mathbf{R}^n$ is optimization variable, $w_0(\mathbf{x}), w_i(\mathbf{x})$ are convex functions, $q_i(\mathbf{x})$ is affine function.

- Solution:

Distributed algorithm: Lagrange duality properties →construct a dual problem →dual decomposition →solve dual problem with subgradient method → obtain primal optimization variable from dual variables

Convex function and affine function

Convex function:

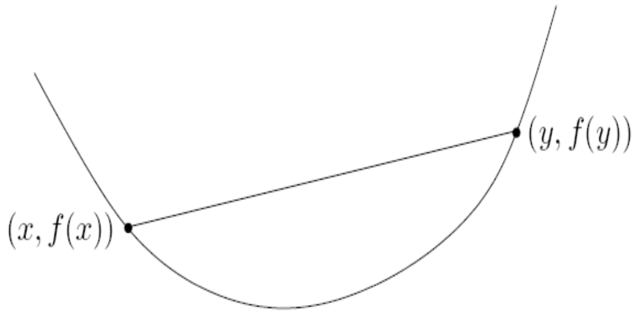


Figure 3.1 Graph of a convex function. The chord (*i.e.*, line segment) between any two points on the graph lies above the graph.

[Boyd2004]

What is affine function? $q_i(\mathbf{x})$

Definition:

$$\begin{aligned}
&\text{Let } q_i(x_1) = 0, \text{ and } q_i(x_2) = 0 \\
&y = \alpha x_1 + (1-\alpha)x_2, \quad \alpha \in \mathbf{R} \\
&\text{if we have } q_i(y) = 0, \\
&\text{Then } q_i(x) \text{ is affine function.} \\
&\text{Linear function is always affine.}
\end{aligned}$$

Dual solution

- Construct a dual problem [Boyd2004]

The Lagrangian:

$$L(\mathbf{x},\boldsymbol{\lambda},\mathbf{v}) = w_0(\mathbf{x}) + \sum_{i=1}^{m}\lambda_i w_i(\mathbf{x}) + \sum_{i=1}^{p} v_i q_i(\mathbf{x})$$

wher $\boldsymbol{\lambda}, \mathbf{v}$ are dual variables.

The dual function: $g(\boldsymbol{\lambda},\mathbf{v}) = \min_{\mathbf{x}}\{L(\mathbf{x},\boldsymbol{\lambda},\mathbf{v})\} = \min_{\mathbf{x}}\left\{w_0(\mathbf{x}) + \sum_{i=1}^{m}\lambda_i w_i(\mathbf{x}) + \sum_{i=1}^{p} v_i q_i(\mathbf{x})\right\}$

The minimum of several linear functions is always concave

The dual function is always concave.

The dual problem:

$$\begin{aligned}&\text{maximize}: \ g(\boldsymbol{\lambda},\mathbf{v})\\ &\text{Subject to}: \ \boldsymbol{\lambda} \geq 0\end{aligned}$$

Dual objective function

$$g(\boldsymbol{\lambda},\mathbf{v}) = \min_{\mathbf{x}}\left\{w_0(\mathbf{x}) + \sum_{i=1}^{m}\lambda_i w_i(\mathbf{x}) + \sum_{i=1}^{p} v_i q_i(\mathbf{x})\right\} \leq w_0(\mathbf{x}) + \sum_{i=1}^{m}\lambda_i w_i(\mathbf{x}) + \sum_{i=1}^{p} v_i q_i(\mathbf{x}) \leq w_0(\mathbf{x})$$

Dual objective value is no larger than primal objective value.

Dual solution

- Duality gap: $d = w_0^* - g^* \geq 0$

$$g^* \text{ is the maximal dual objective value, } g(u,v) \leq g^*$$

$$w_0^* \text{ is the minimal primal objective value, } \mathrm{w}(\mathbf{x}) \geq w_0^*$$

Strong duality: under Slater's condition,

$$\text{duality gap } d = 0, \text{ that is : } w_0^* = g^*$$

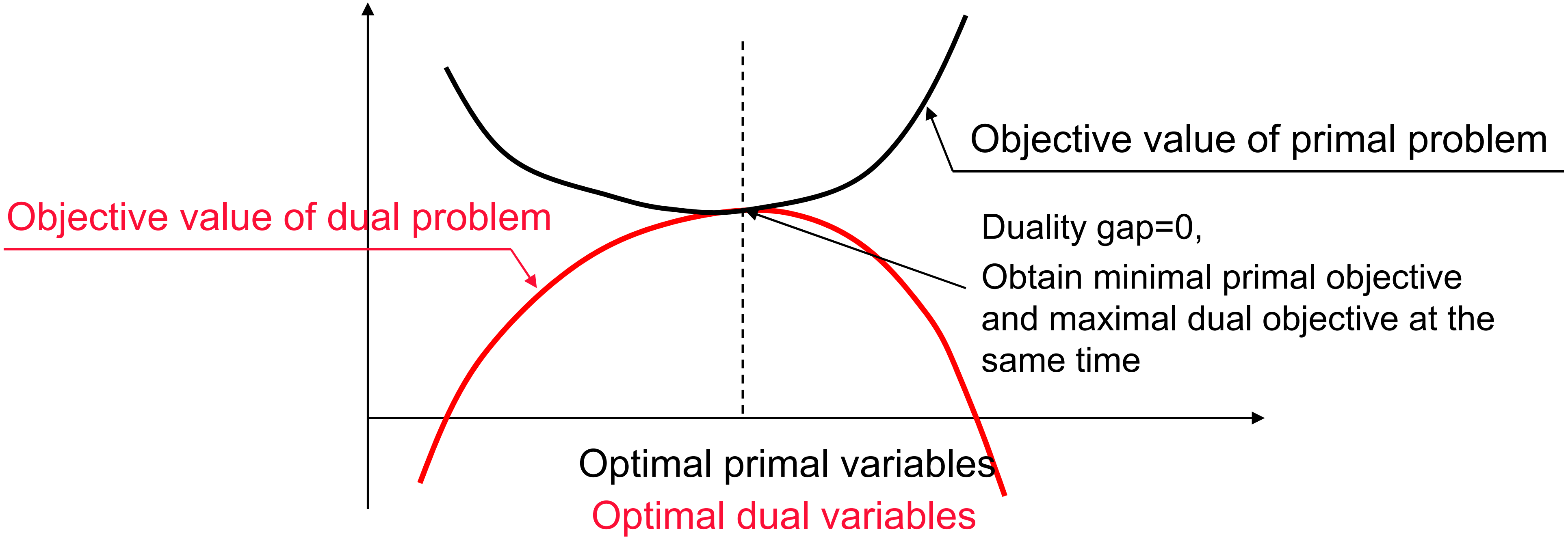
Slater’s condition: There exists a **x** that satisfies:

$$w_i(\mathbf{x}) < 0, \quad i = 1,\ldots, m \quad \text{and} \quad q_i(\mathbf{x}) = 0, \quad i = 1,\ldots, p$$

In other word, there exist a strictly feasible point

Weak duality: $d > 0$

Optimality



Objective value of primal problem

Objective value of dual problem

Duality gap=0,
Obtain minimal primal objective and maximal dual objective at the same time

Optimal primal variables
Optimal dual variables

Subgradient

- A subgradient of function *f* at point *x* is any vector *g*, that satisfies the inequality: $f(z) >= f(x) + g^T(z-x)$ for all *z*, *f* is a convex function

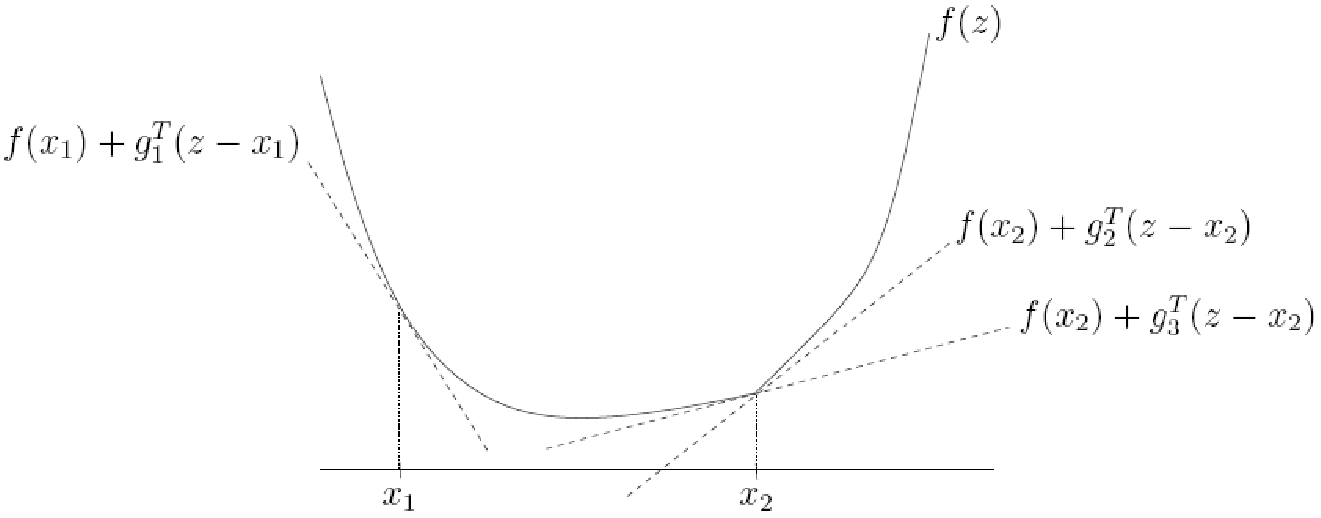


Figure 1: At x_1, the convex function f is differentiable, and g_1 (which is the derivative of f at x_1) is the unique subgradient at x_1. At the point x_2, f is not differentiable. At this point, f has many subgradients: two subgradients, g_2 and g_3, are shown. [Boyd2004]

Subgradient

- Subgradient method to update dual variables [Bertsekas2003]

$$\lambda_i^{(k+1)} = \max\left\{0, \lambda_i^{(k)} - \alpha^{(k)} h_i^{(k)}\right\} \quad \forall i = 1, \ldots, m$$

$$v_i^{(k+1)} = v_i^{(k)} - \theta^{(k)} f_i^{(k)} \quad \forall i = 1, \ldots, p$$

where $h_i^{(k)}, f_i^{(k)}$ is the subgradient of $-g$ at $\lambda_i^{(k)}, v_i^{(k)}$ respectively

$$h_i^{(k)} = -w_i\left(\mathbf{x}^*\left(\boldsymbol{\lambda}^{(k)}, \mathbf{v}^{(k)}\right)\right) \quad \forall i = 1, \ldots, m$$

$$f_i^{(k)} = -q_i\left(\mathbf{x}^*\left(\boldsymbol{\lambda}^{(k)}, \mathbf{v}^{(k)}\right)\right) \quad \forall i = 1, \ldots, p$$

Non-summable diminishing Step size for convergence:

$$\theta^{(k)} > 0, \quad \lim_{k \to \infty} \theta^{(k)} = 0, \quad \sum_{k=1}^{\infty} \theta^{(k)} = \infty$$

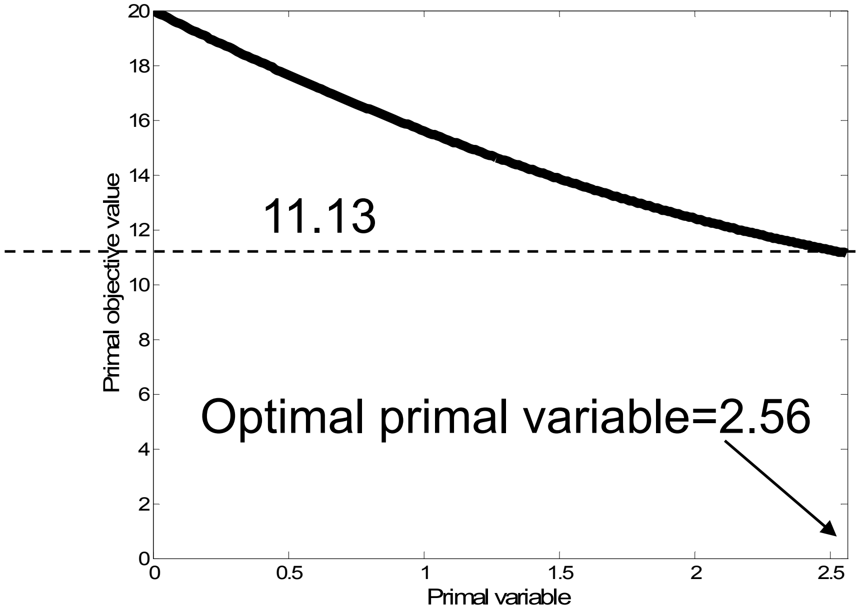
- Find optimal primal variables from dual variables: $\mathbf{x}^*(\boldsymbol{\lambda}, \mathbf{v}) = \arg\inf L(\mathbf{x}, \boldsymbol{\lambda}, \mathbf{v})$

Example: convex optimization

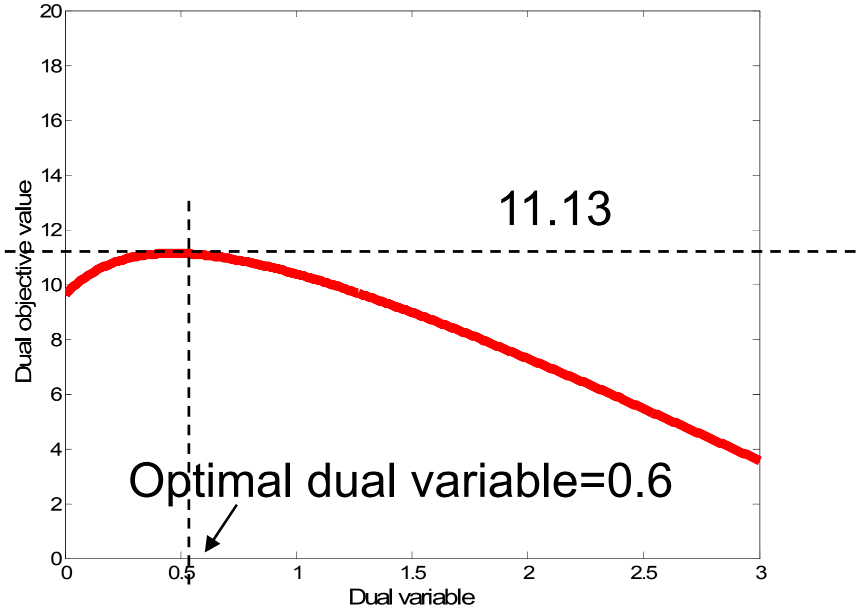
$$\text{minimize}: \; w_0(x) = 0.6x^2 - 5x + 20$$

$$\text{Subject to}: w_1(x) = x^2 - x - 4 \le 0,$$

$$x \in [0 \;\; 5].$$



Primal Objective Value



Dual Objective Value

Regularization term makes dual function differentiable

$$\text{minimize}: \; 2x$$

$$\text{Subject to}: 1\text{-}x \le 0.$$

Lagrange dual function:

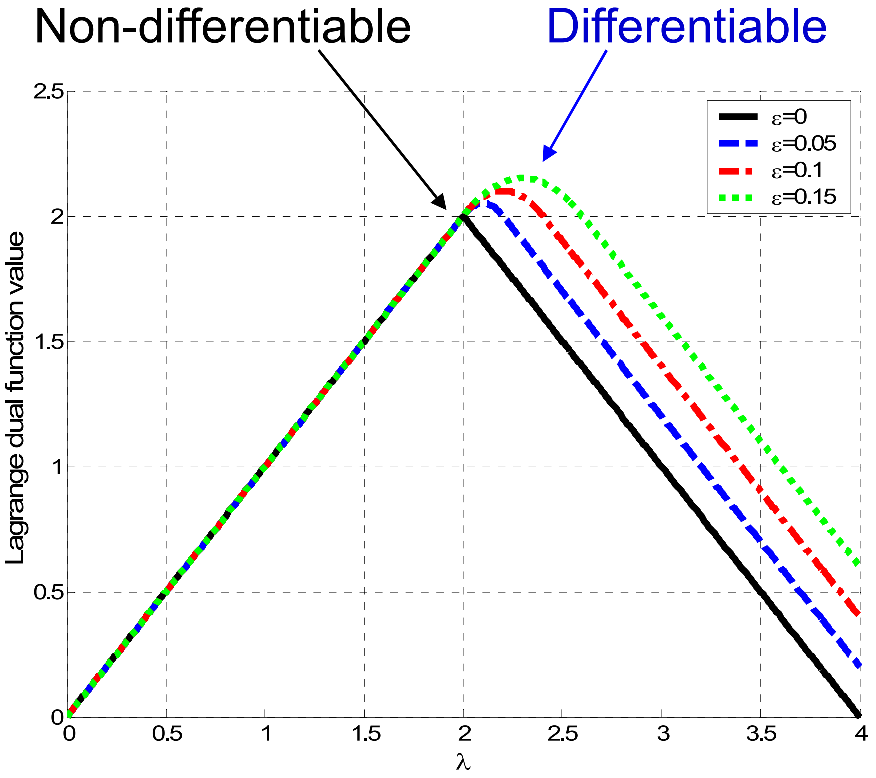
$$g(\lambda) = 2x + \lambda(1\text{-}x)$$

$$\text{minimize}: \; 2x + \varepsilon x^2$$

$$\text{Subject to}: 1\text{-}x \le 0.$$

Lagrange dual function:

$$g(\lambda) = 2x + \varepsilon \mathrm{x}^2 + \lambda(1\text{-}x)$$



Dual decomposition

- Why solve the primal problem by first solving the dual problem?
  1. Dual problem is always convex, can be efficiently solved.
  2. Dual problem can be decomposed easily, leading to distributed algorithm
- Dual decomposition: (to obtain distributed algorithm)

Primal problem:

$$\text{minimize}: \ f(x_1) + f(x_2)$$
$$\text{Subject to}: \ x_1 + x_2 \le c$$

Dual problem:

$$\begin{aligned}\text{maximize}: \ & \inf\left(f(x_1) + f(x_2) + \lambda(x_1 + x_2 - c)\right) \\ & = \inf\left(f(x_1) + \lambda x_1\right) + \inf\left(f(x_2) + \lambda x_2\right) - \lambda c\end{aligned}$$
$$\text{Subject to}: \ \boldsymbol{\lambda} \ge 0$$

Dual variables update:

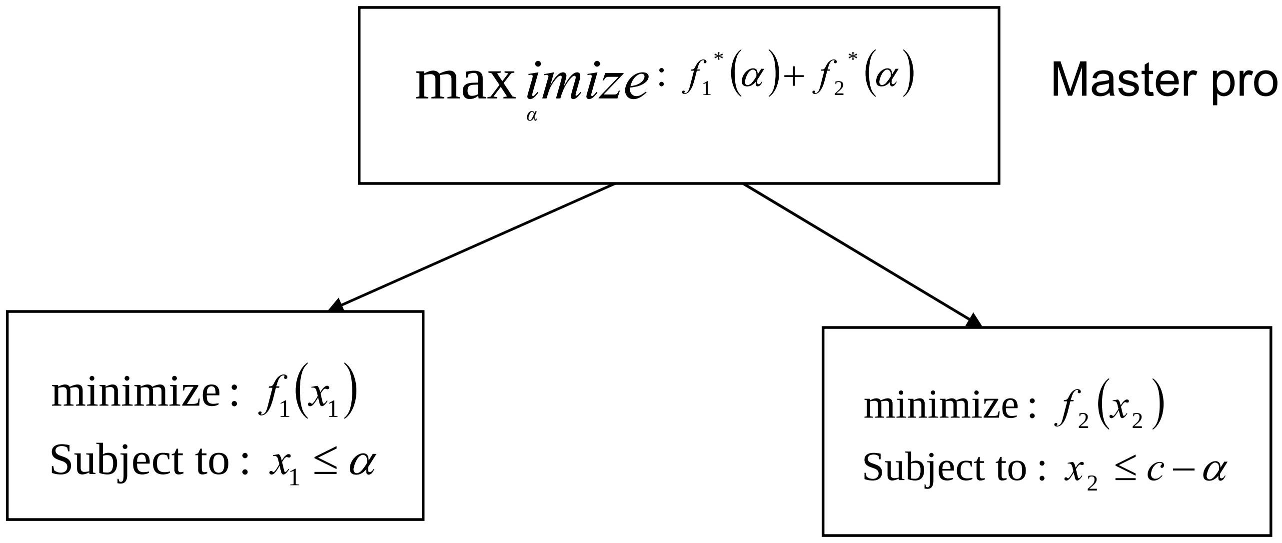
$$\lambda^{(k+1)} = \max\left\{0, \lambda^{(k)} - \theta^{(k)}\left(c - (x_1 + x_2)\right)\right\}$$

Primal decomposition

Primal problem:

$$\text{minimize}: \; f_1(x_1) + f_2(x_2)$$

$$\text{Subject to}: \; x_1 + x_2 \le c$$



$$\max \underset{\alpha}{imize}: \; f_1^*(\alpha) + f_2^*(\alpha)$$

Master problem

$$\text{minimize}: \; f_1(x_1)$$

$$\text{Subject to}: \; x_1 \le \alpha$$

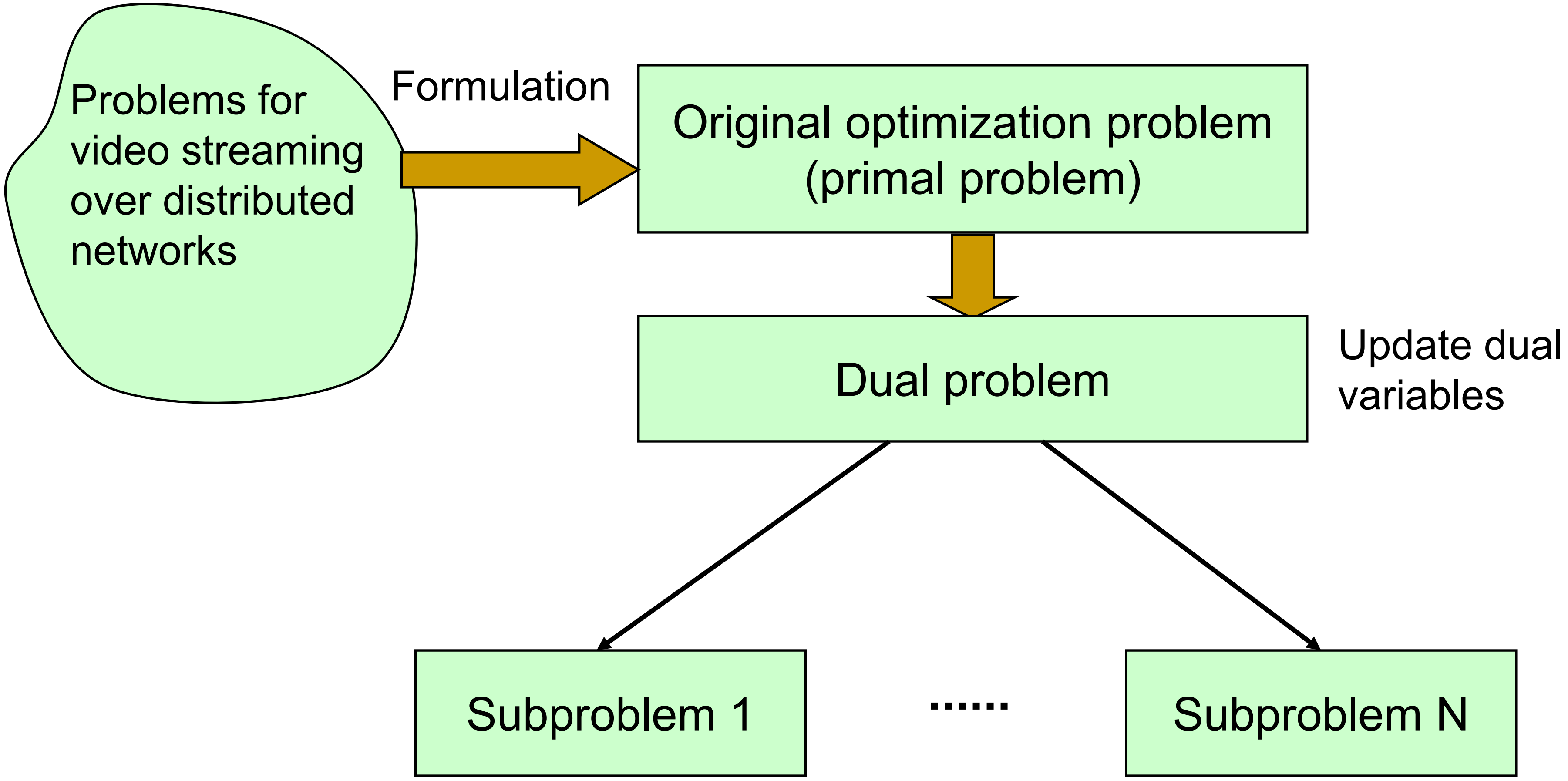
Subproblem 1

$$\text{minimize}: \; f_2(x_2)$$

$$\text{Subject to}: \; x_2 \le c - \alpha$$

Subproblem 2

Distributed solution



Problems for video streaming over distributed networks

Formulation

Original optimization problem (primal problem)

Dual problem

Update dual variables

Subproblem 1

……

Subproblem N

Compute primal variable x_1 at node 1

Compute primal variable x_N at node N

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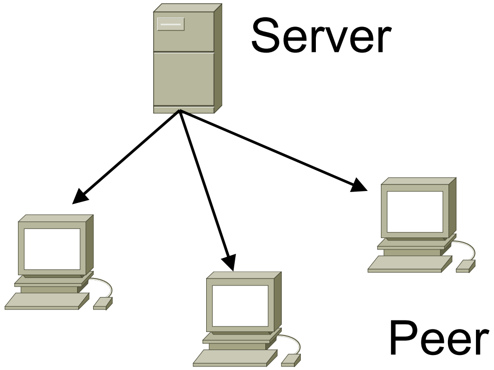
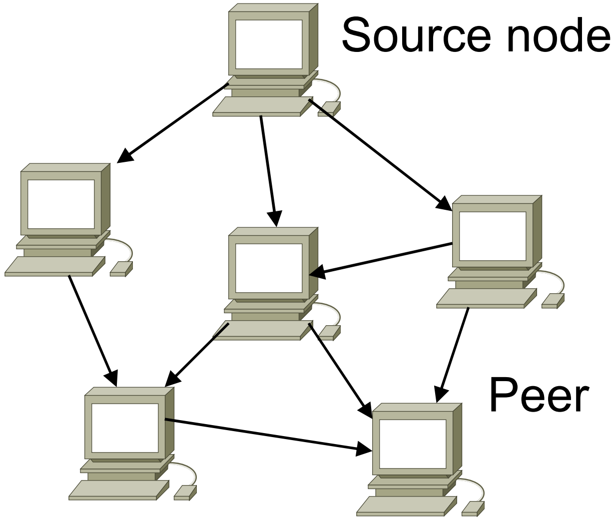
Client/server VoD vs. P2P VoD

- Client/server VoD
  - Server bandwidth bottleneck
- P2P applications
  - P2P VoD, P2P live TV
- Single-layer coded P2P VoD
  - Each user receives the same quality
- **Scalable P2P VoD**
  - Lower bandwidth→ lower quality
  - High bandwidth→ higher quality



Client/server



P2P

Related work

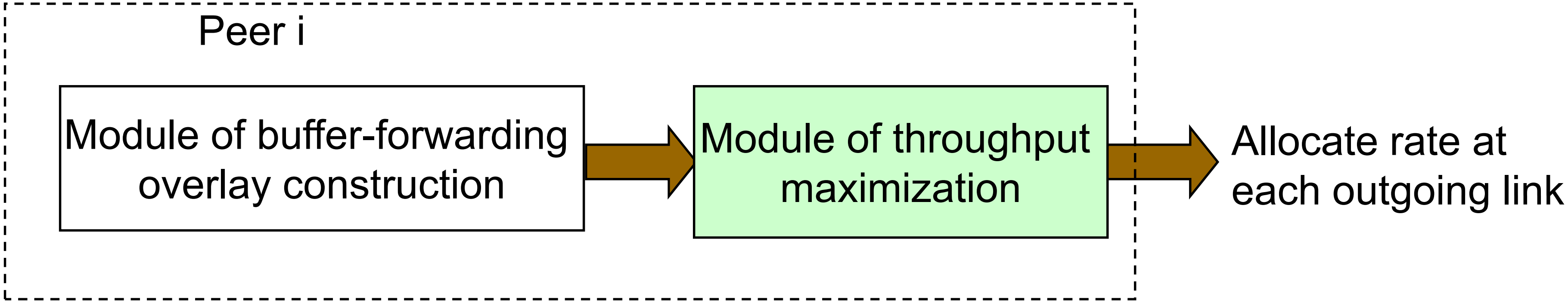
- P2P VoD applications
  - Existing P2P architectures
    - Buffer-forwarding architectures:
      - Tree-based: P2VoD [Do2004]
      - Mesh-based [Li2006]
    - Storage-forwarding architecture: VMesh [Yiu2007]
    - Hybrid-forwarding architecture [[YHe-ICASSP08,YHe-TMM08a]
  - Existing optimizations in P2P
    - Minimum-Delay for constant-bit-rate (CBR) P2P media session [Wu2005]
    - Distributed auction algorithm for rate allocation [Li2006]
    - Maximization of throughput in scalable P2P VoD systems taking into account packet loss due to excessive delay at each link [YHe-ICME07a]
  - Prefetching in P2P [YHe-TMM08b]

Scalable VoD: prioritized coding scheme

- Prioritized coding scheme
  - Originally proposed in [Chou2003], useful for video broadcast
  - Layered coding + prioritized packetization + network coding (at source and intermediate nodes)
  - Advantages:
    - Scalable
    - Resilient to packet loss
    - Duplicate-free
      - A larger throughput at a receiver leads to a higher quality

Buffer-forwarding overlay for P2P VoD

- Existing approaches to construct buffer-forwarding overlay
  - Tree-based
  - Mesh-based
- Our work is on the module of throughput maximization



Graph model

- A network can be modeled as a directed graph **G=(N,L)**
  - **N** is the set of nodes
  - **L** is the set of links
- Matrix to represent the node-link relationship

A: the relationship between the node and its connected links

$$\mathbf{A} = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 \\ -1 & 0 & 1 & 1 & 0 \\ 0 & -1 & -1 & 0 & 1 \\ 0 & 0 & 0 & -1 & -1 \end{bmatrix} \begin{matrix} \\ \Leftarrow \text{Node 2} \\ \\ \\ \end{matrix}$$

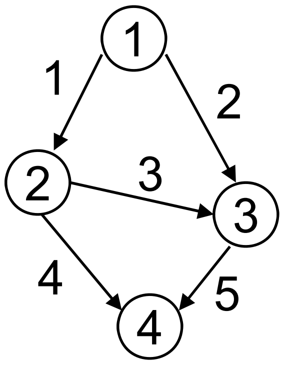
A⁺ : the relationship between the node and its outgoing links

$$\mathbf{A}^{+} = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

A⁻ : the relationship between the node and its incoming links

$$\mathbf{A}^{-} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 \end{bmatrix}$$

$A = A^{+} - A^{-}$



A network

Graph model

- Network graph
  - A P2P is modeled by a directed graph G = (N, L)

Matrix A:

$$a_{il} = \begin{cases} 1, & \text{if link } l \text{ is an outgoing link from node } i, \\ -1, & \text{if link } l \text{ is an incoming link into node } i, \\ 0, & \text{otherwise.} \end{cases}$$

Matrix A^+:

$$a_{il}^{+} = \begin{cases} 1, & \text{if link } l \text{ is an outgoing link from node } i, \\ 0, & \text{otherwise.} \end{cases}$$

Matrix A^-:

$$a_{il}^{-} = \begin{cases} 1, & \text{if link } l \text{ is an incoming link into node } i, \\ 0, & \text{otherwise.} \end{cases}$$

Throughput maximization in buffer-forwarding systems

- Problem formulation:

$$\text{minimize} \quad -\sum_{i\in N}\sum_{l\in L} a_{il}^{-}\left(x_l\left(1-p_l\right)\right)+\delta\sum_{l\in L} x_l^{2}$$

← Aggregate throughput

$$\text{subject to} \quad \sum_{l\in L} a_{il}^{-} x_l \le s_r, \qquad \forall i \in N,$$

← Source rate constraint

$$\sum_{l\in L} a_{il}^{-} x_l \le I_i, \qquad \forall i \in N,$$

← Download bandwidth constraint

$$\sum_{l\in L} a_{il}^{+} x_l \le O_i, \qquad \forall i \in N,$$

← Upload bandwidth constraint

$$x_l - \sum_{m\in L} c_{lm} x_m \le \sigma_l, \qquad \forall l \in L,$$

← Link-forwarding constraint

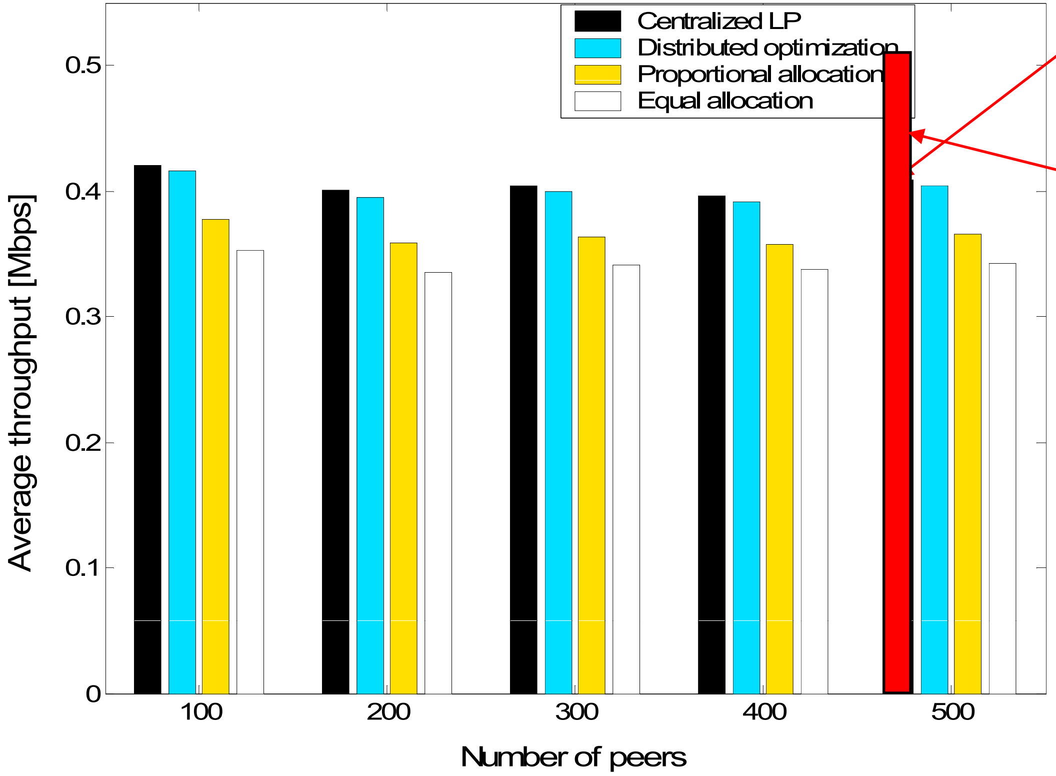
$$x_l \ge 0, \qquad \forall l \in L.$$

Converted to:

Strictly convex optimization problem, distributed algorithm to solve it

Throughput maximization in buffer-forwarding systems (cont.)

- Simulation results:

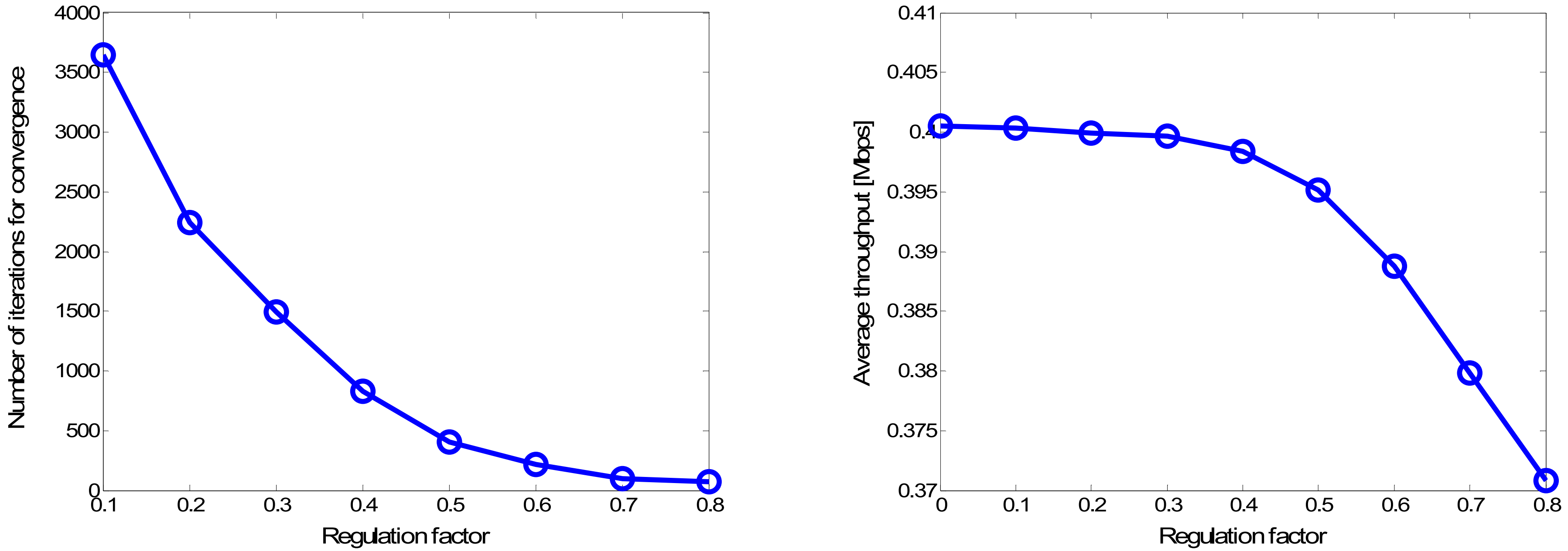


Comparison of average throughput

Achievable throughput in buffer-forwarding architecture

Any better architecture to improve the achievable throughput?

Impact of regularization factor



Complexity

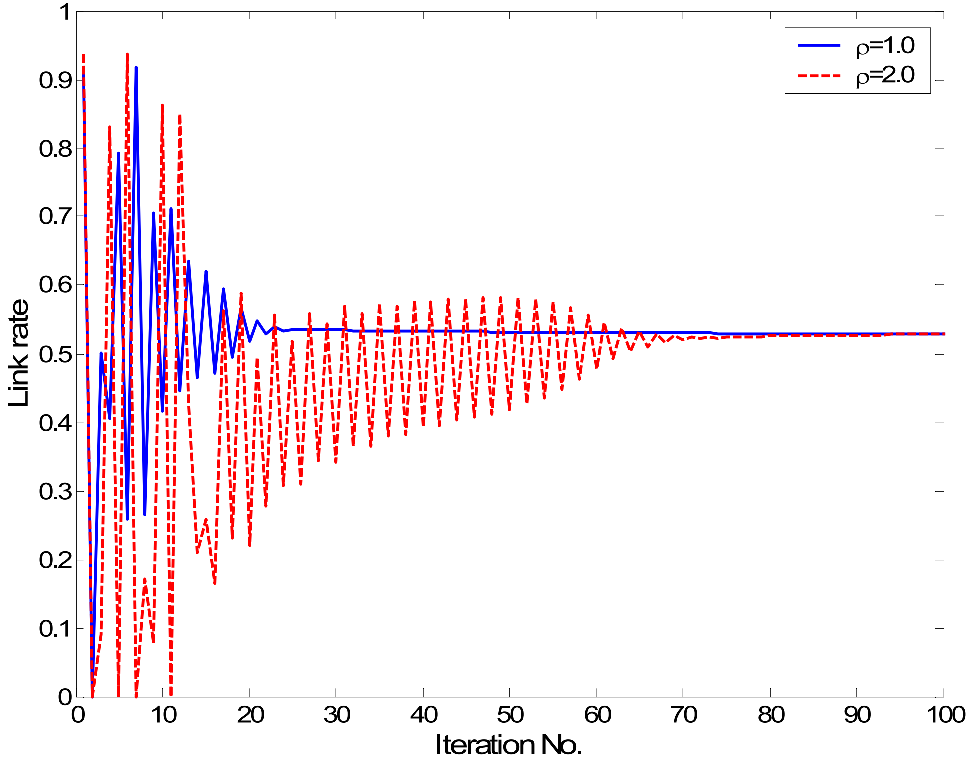
Sub-optimality

Throughput maximization in buffer-forwarding P2P VoD

Impact of step size to convergence speed

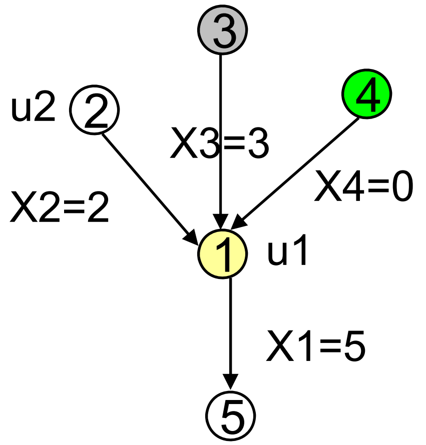
Non-summable diminishing step size sequence:

$$\theta^{(k)} = \frac{\rho}{\sqrt{k}}$$



Iteration of a link rate in a 100-peer P2P VoD buffer-forwarding system

Dynamics handling in P2P VoD



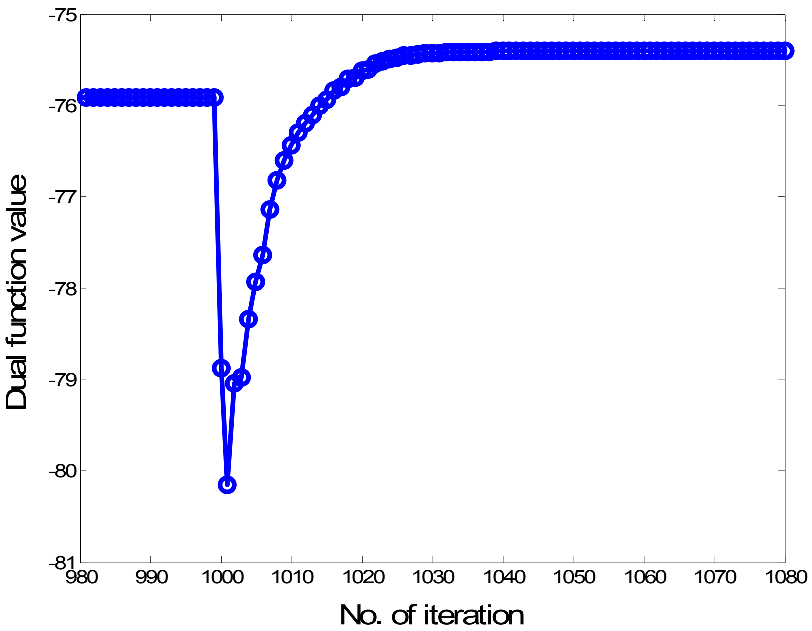
Steady state (flow conservation): x1=x2+x3
Dual variable: u1=0.4, u2=0.5, u3=0.3

Peer 3 left, peer 4 joined

Update dual variables: u1=0.6, u2=0.3, u4=0.1

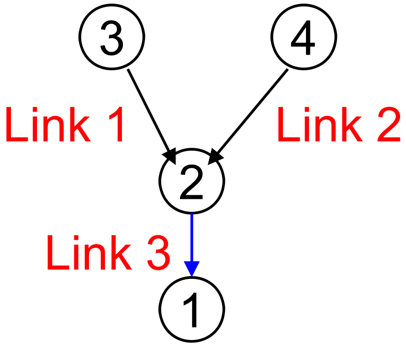
Update primal variables: x1=4, x2=3, x4=1
Reach new steady state: x1=x2+x4

Convergence speed during transition



Dynamic 200-peer and 4-parent/peer scenario, 10 peers left and 20 new peers joined in the previous time slot

Communication overhead for throughput maximization problem in buffer-forwarding systems



The dual variables at node *i*: $u_i,\ v_i$
The dual variables at link *l*: λ_l

The primal variable (link rate) at link *l*: x_l
Each node is responsible for updating the primal and dual variables at this node and at its outgoing links

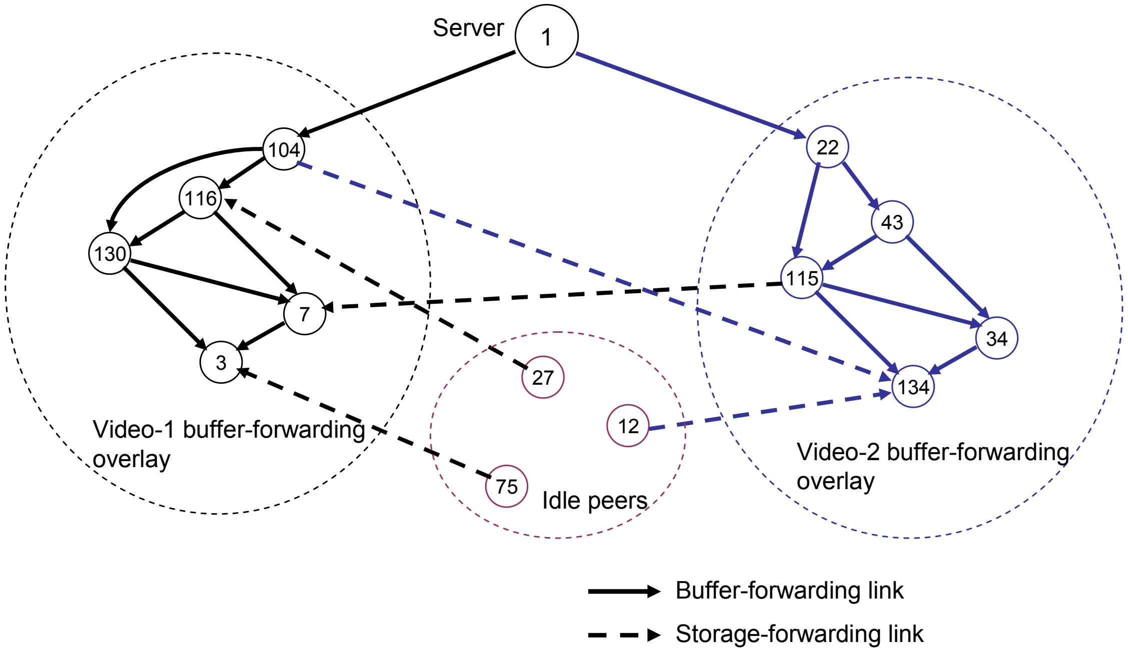
Node 2 computes the link rate at link 3: $x_3 = -(1 - p_3) + u_1 + v_2 + \lambda_3 - (\lambda_1 + \lambda_2)$

Communication overhead: node 2 needs to request u_1 from node 1, request λ_1 from node 3, and λ_2 from node 4

The update of dual variables requires the link rates of connected links, no communication overhead

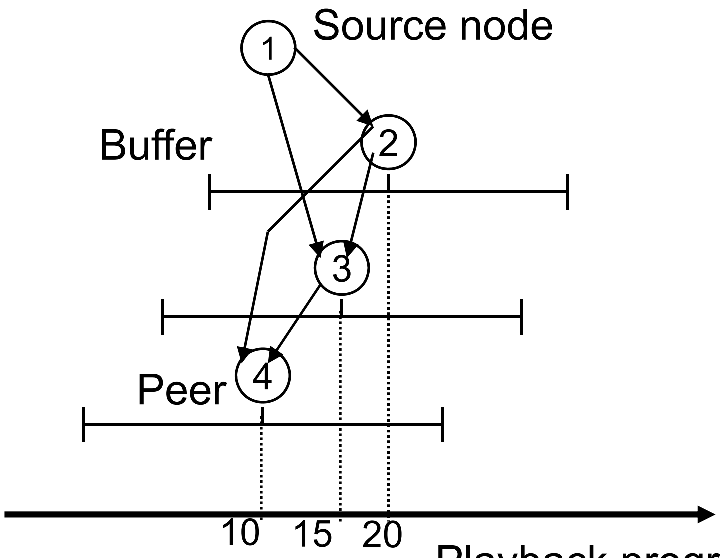
u_i: ← incoming link rates
v_i: ← outgoing link rates
λ_l: ← incoming link rates

A Hybrid-forwarding Architecture for P2P VoD



- Hybrid-forwarding architecture
  - Share both buffer and storage, to improve throughput
  - Peers contribute their stored segments to other peers
  - Implement service differentiation among videos
  - Stored segments are stable, robust to peer dynamics

Buffer-forwarding and storage-forwarding overlay construction



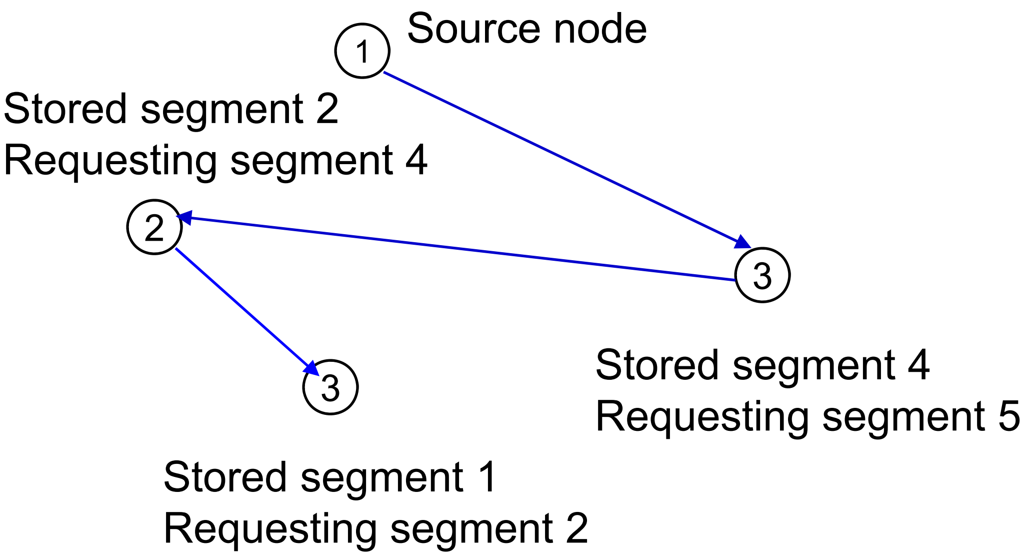
Source node

Buffer

Peer

Playback progress

Buffer-forwarding overlay



Source node

Stored segment 2
Requesting segment 4

Stored segment 4
Requesting segment 5

Stored segment 1
Requesting segment 2

Storage-forwarding overlay

Throughput maximization in hybrid-forwarding architecture

- Problem formulation:

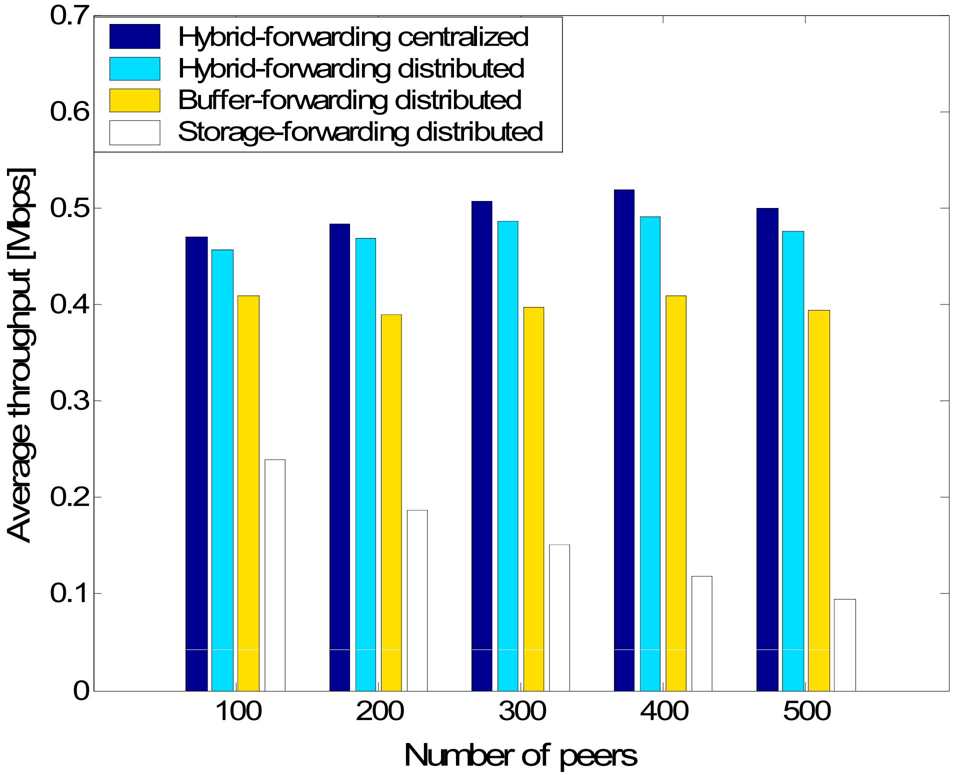
minimize	$-\sum_{i\in N}\beta_i\sum_{l\in L}a_{il}^{-}\left(x_l\left(1-p_l\right)\right)+\delta\sum_{l\in L}x_l^{2}$	← Aggregate weighted throughput
subject to	$\sum_{l\in L}a_{il}^{-}x_l\le s_r, \quad \forall i\in N,$	← Source rate constraint
	$\sum_{l\in L}a_{il}^{-}x_l\le I_i, \quad \forall i\in N,$	← Download bandwidth constraint
	$\sum_{l\in L}d_{il}x_l+\sum_{l\in L}h_{il}x_l\le O_i, \quad \forall i\in N,$	← Upload bandwidth constraint
	$x_l-\sum_{m\in L}c_{lm}x_m\le\sigma_l^{B}, \quad \forall l\in L,$	← Buffer-forwarding constraint
	$x_l-\sum_{i\in N}h_{il}F_i\le\sigma_l^{S}, \quad \forall l\in L,$	← Storage-forwarding constraint
	$x_l\ge 0, \quad \forall l\in L.$	

Converted to:

Strictly convex optimization problem, distributed algorithm to solve it

Throughput maximization in hybrid-forwarding architecture (cont.)

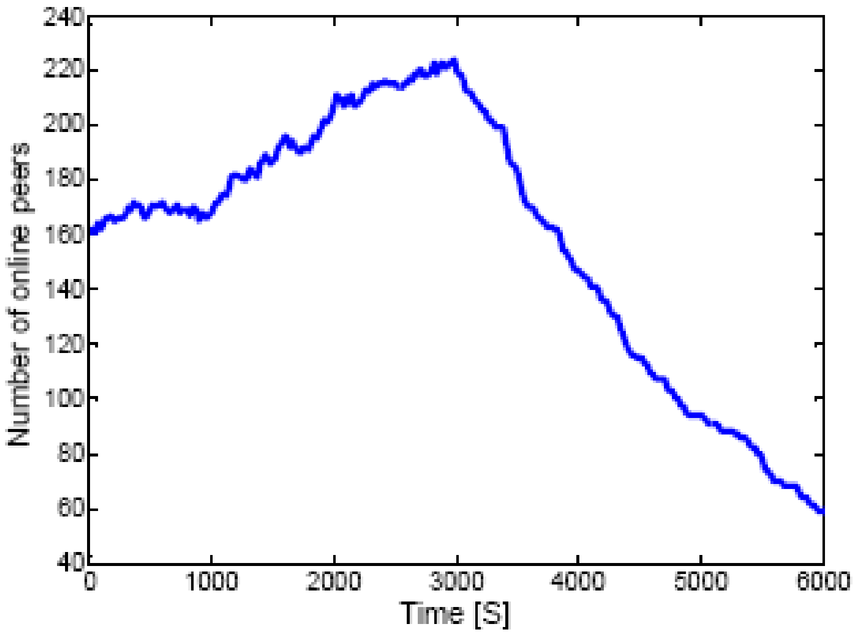
- Simulation results:



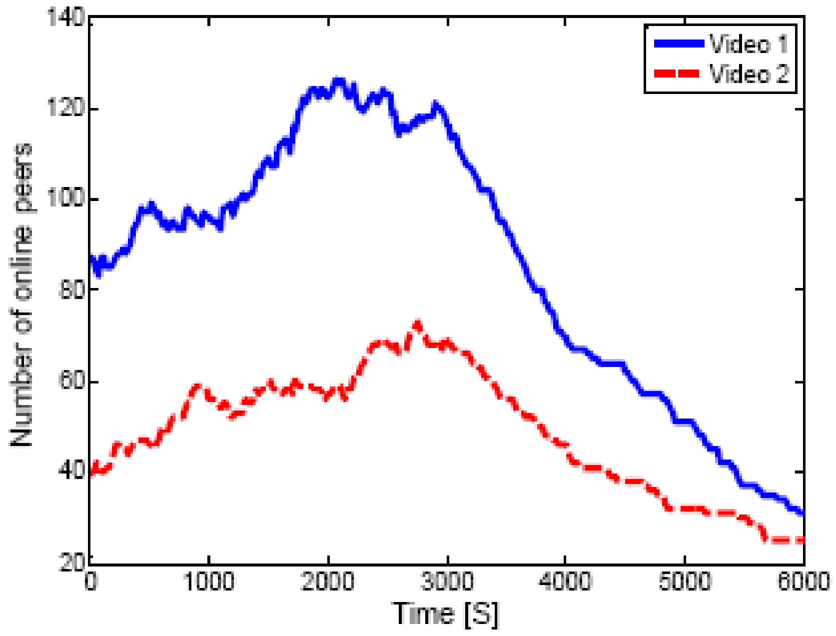
Comparison of average throughput

Other observation 1 – Number of Peers

- Simulation results (Poisson distribution):



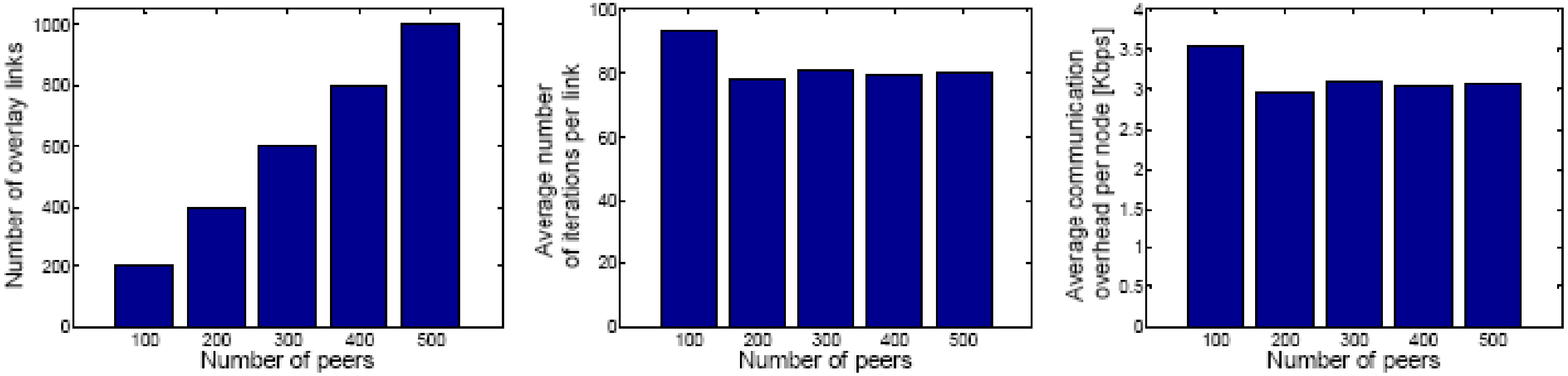
Buffer forwarding



Hybrid forwarding

Other observation 2 – Scalability

- Simulation results:



(a) (b) (c)

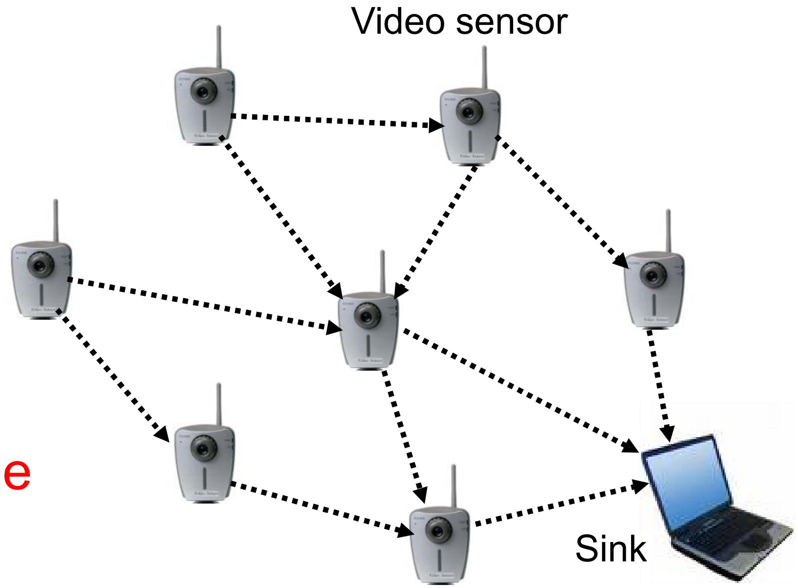
Comparison of the cost introduced by the proposed distributed algorithm in buffer-forwarding P2P VoD systems with different network sizes: (a) the number of the overlay links, (b) the average number of iterations per link, and (c) the average communication overhead per node

Outline

- Motivation and contributions
- Principles of convex optimization
- Resource allocation in distributed video communication systems
  - Throughput maximization in P2P VoD applications
  - Network lifetime maximization in wireless visual sensor networks
  - Optimization for video streaming over wireless ad hoc networks
- Conclusions

Wireless visual sensor networks

- Applications of WVSN
  - Video surveillance, environmental tracking
- The proposed distributed algorithm:
  - Maximize the network lifetime by jointly optimizing source rates, encoding powers, and routing scheme
- Total power consumption at a node
  - Encoding power + transmission power + reception power
- Network lifetime:
  - defined as minimum node lifetime



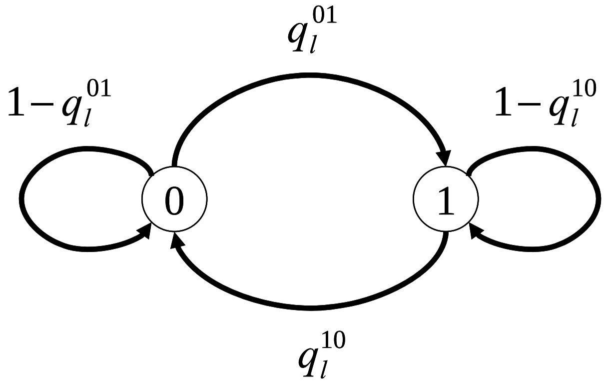
A wireless visual sensor network

Related work

- Network Lifetime maximization for Wireless visual sensor networks (WVSNs)
  - Conventional wireless sensor networks
    - Collect data (e.g., temperature), negligible power consumption on signal processing at sensor node
  - Existing distributed optimizations for conventional wireless sensor network
    - Tradeoff between the source rate allocation and the network lifetime [Nama2006]
    - Distributed algorithm to maximize lifetime [Madan2006]
    - These methods cannot be applied directly to WVSNs, since they omit the processing power consumption at the sensor nodes
- Maximization of network lifetime for WVSN by jointly optimizing source rates, encoding powers and routing scheme. [YHe-ICME07b, YHe-TCSVT2008a]

Markov model and encoding power

- Channel error model
  - Two-state Markov model



Average bit error probability: $p_l^b = \dfrac{q_l^{10}}{q_l^{10}+q_l^{01}}$,

packet loss rate (PLR): $p_l^p = 1-\left(1-p_l^b\right)^G$.

- Power consumption model
  - Encoding power consumption
    - Power-rate-distortion model [He2006]

$$d_{sh} = \sigma^2 e^{-\gamma \cdot s_h . P_{sh}^{2/3}}$$

- Under the same encoding power, increasing rate → reducing distortion
- Under the same rate, increasing encoding power → reducing distortion

Graph model

- Network graph
  - A WVSN is modeled by a directed graph G = (N, L)

Matrix A:

$$a_{il} = \begin{cases} 1, & \text{if link } l \text{ is an outgoing link from node } i, \\ -1, & \text{if link } l \text{ is an incoming link into node } i, \\ 0, & \text{otherwise.} \end{cases}$$

Matrix A⁺:

$$a_{il}^{+} = \begin{cases} 1, & \text{if link } l \text{ is an outgoing link from node } i, \\ 0, & \text{otherwise.} \end{cases}$$

Matrix A⁻:

$$a_{il}^{-} = \begin{cases} 1, & \text{if link } l \text{ is an incoming link into node } i, \\ 0, & \text{otherwise.} \end{cases}$$

  - Each session follows the law of flow conservation:

$$\sum_{l \in L} a_{il} x_{hl} = \eta_{hi}, \ \forall h \in V, \ \forall i \in N,$$

Achievable maximum network lifetime

- Without loss
- Problem formulation:

$$\text{maximize} \quad \left\{ T_{net} = \min\{T_i\} = \min\left\{ \frac{B_i}{P_{si} + \sum_{l \in L} a_{il}^{+} \left(c_l^{s} y_l\right) + c^{r} \sum_{l \in L} a_{il}^{-} y_l} \right\} \right\} \quad \Leftarrow \quad \boxed{\text{Network lifetime}}$$

$$\text{subject to:} \quad \sum_{l \in L} a_{il} x_{hl} = \eta_{hi}, \quad \forall h \in V,\ \forall i \in N, \quad \Leftarrow \quad \boxed{\text{Flow conservation}}$$

$$\sum_{h \in V} x_{hl} = y_l, \quad \forall l \in L, \quad \Leftarrow \quad \boxed{\text{Aggregate flow rate}}$$

$$\sigma^2 e^{-\gamma . s_h . P_{sh}{}^{2/3}} \le D_h, \quad \forall h \in V, \quad \Leftarrow \quad \boxed{\text{Video quality requirement}}$$

$$x_{hl} \ge 0, \quad \forall h \in V,\ \forall l \in L,$$

$$s_h \ge 0, \quad \forall h \in V, \qquad P_{sh} \ge 0, \quad \forall h \in V.$$

Original optimization problem

Achievable maximum network lifetime (cont.)

- Problem conversion:

$$
\begin{aligned}
&\text{minimize} && q \\
&\text{subject to:} && \sum_{l\in L} a_{il} x_{hl} = \eta_{hi}, \quad \forall h \in V,\ \forall i \in N, \\
& && \sum_{h\in V} x_{hl} = y_l, \quad \forall l \in L, \\
& && \log\left(\sigma^2 / D_h\right) / \left(\gamma P_{sh}{}^{2/3}\right) \le s_h,\ \forall h \in V, \\
& && P_{si} + \sum_{l\in L} a_{il}^{+}\left(c_l^s y_l\right) + c^r \sum_{l\in L} a_{il}^{-} y_l \le qB_i,\ \forall i \in N, \\
& && x_{hl} \ge 0, \quad \forall h \in V,\ \forall l \in L, \\
& && s_h \ge 0, \quad \forall h \in V, \quad P_{sh} \ge 0, \quad \forall h \in V.
\end{aligned}
$$

Flow conservation

Aggregate flow rate

Video quality requirement

Power constraint

First conversion:

change the variable: $q=1/T_{net}$

Problem conversion in wireless visual sensor networks (cont.)

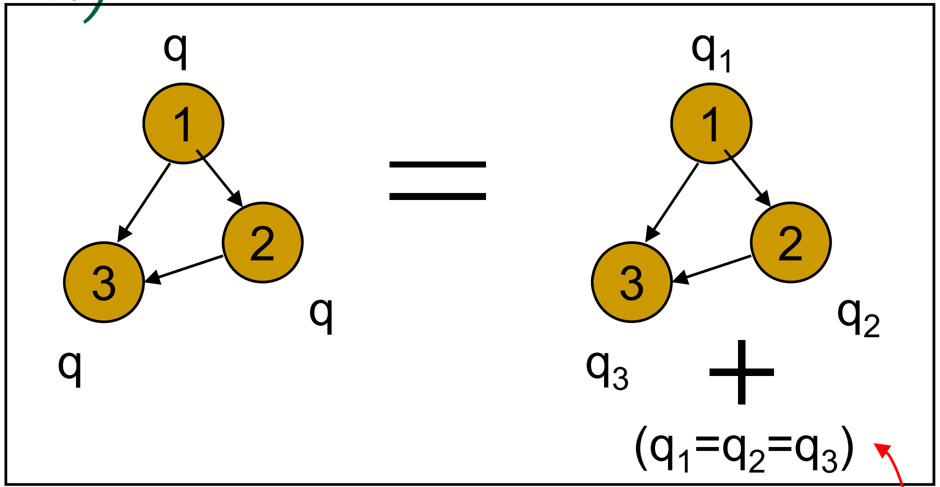
P2: $$\text{minimize} \quad q$$

$$\text{subject to}: \quad \text{constraints.}$$

$$q > 0$$

P3:

$$\begin{aligned}
&\text{minimize} \quad Nq^2 \\
&\text{subject to}: \sum_{l\in L} a_{il} x_{hl} = \eta_{hi}, \quad \forall h \in V,\ \forall i \in N, \\
&\sum_{h\in V} x_{hl} = y_l, \quad \forall l \in L, \\
&\log\left(\sigma^2 / D_h\right) / \left(\gamma P_{sh}{}^{2/3}\right) \le s_h, \ \forall h \in V, \\
&P_{si} + \sum_{l\in L} a_{il}^{+}\left(c_l^s y_l\right) + c^r \sum_{l\in L} a_{il}^{-} y_l \le qB_i, \ \forall i \in N, \\
&x_{hl} \ge 0, \quad \forall h \in V,\ \forall l \in L, \\
&s_h \ge 0, \quad \forall h \in V, \quad P_{sh} \ge 0, \quad \forall h \in V.
\end{aligned}$$



P4:

$$\begin{aligned}
&\text{minimize} \quad \sum_{i\in N} q_i^2 \ \boxed{+ \sum_{h\in V}\sum_{l\in L} \delta x_{hl}{}^2 + \sum_{h\in V} \delta s_h{}^2} \\
&\text{subject to}: \sum_{l\in L} a_{il} x_{hl} = \eta_{hi}, \quad \forall h \in V,\ \forall i \in N, \\
&\sum_{h\in V} x_{hl} = y_l, \quad \forall l \in L, \\
&\log\left(\sigma^2 / D_h\right) / \left(\gamma P_{sh}{}^{2/3}\right) \le s_h, \ \forall h \in V, \\
&P_{si} + \sum_{l\in L} a_{il}^{+}\left(c_l^s y_l\right) + c^r \sum_{l\in L} a_{il}^{-} y_l \le q_i B_i, \ \forall i \in N, \\
&\boxed{\sum_{i\in N} a_{il} q_i = 0, \quad \forall l \in L,} \\
&x_{hl} \ge 0, \quad \forall h \in V,\ \forall l \in L, \\
&s_h \ge 0, \quad \forall h \in V, \quad P_{sh} \ge 0, \quad \forall h \in V.
\end{aligned}$$

Achievable maximum network lifetime (cont.)

- Problem conversion:

$$\text{minimize} \quad \sum_{i\in N} q_i^2 + \sum_{h\in V}\sum_{l\in L} \delta x_{hl}^2 + \sum_{h\in V} \delta s_h^2$$

$$\text{subject to: } \sum_{l\in L} a_{il} x_{hl} = \eta_{hi}, \quad \forall h \in V, \ \forall i \in N,$$

Flow conservation

$$\log\left(\sigma^2 / D_h\right) / \left(\gamma P_{sh}^{2/3}\right) \le s_h, \ \forall h \in V,$$

Video quality requirement

$$P_{si} + \sum_{l\in L} a_{il}^{+}\left(c_l^s \sum_{h\in V} x_{hl}\right) + c^r \sum_{l\in L}\left(a_{il}^{-} \sum_{h\in V} x_{hl}\right) \le q_i B_i, \ \forall i \in N,$$

Power constraint

$$\sum_{i\in N} a_{il} q_i = 0, \quad \forall l \in L,$$

Auxiliary variables are equal

$$x_{hl} \ge 0, \ \forall h \in V, \ \forall l \in L, \quad q_i > 0, \ \forall i \in N,$$

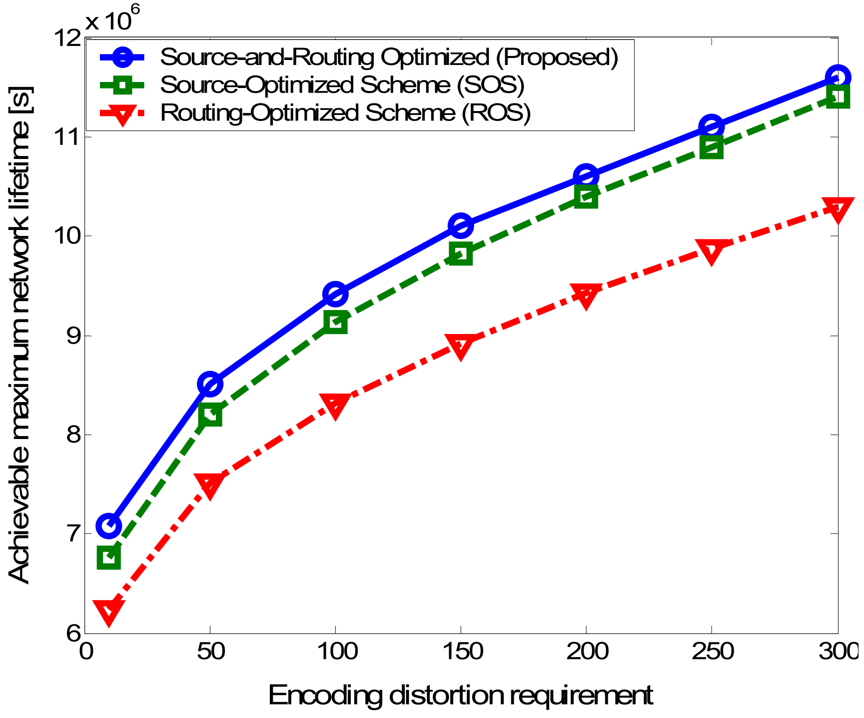
$$s_h \ge 0, \ \forall h \in V, \quad P_{sh} \ge 0, \ \forall h \in V.$$

Second conversion:

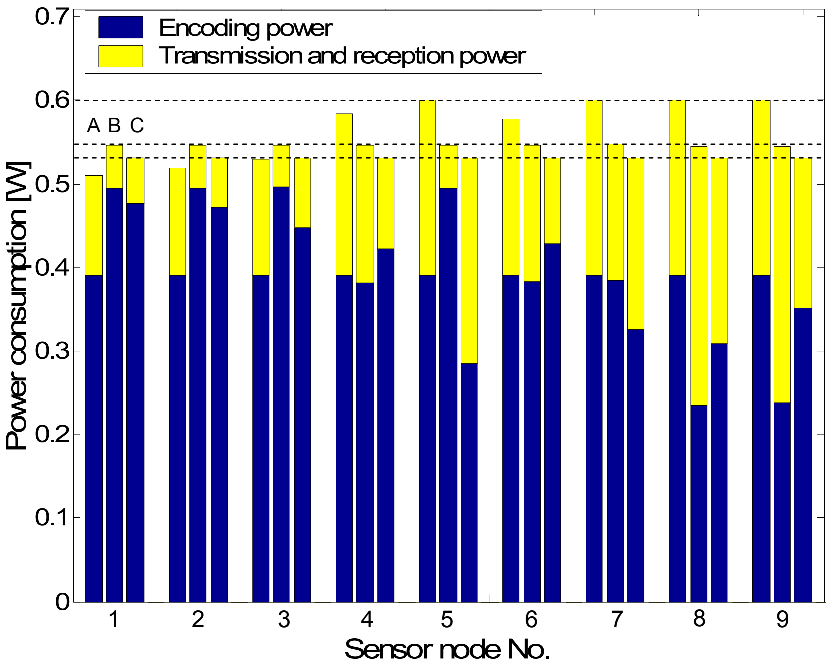
introduce auxiliary variables: q_i

Achievable maximum network lifetime (cont.)

- Simulation results



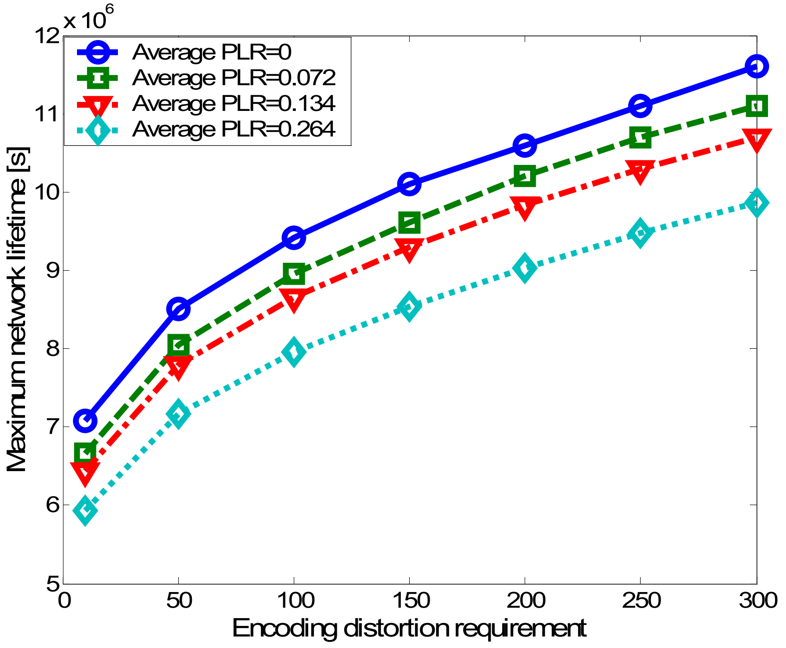
Network lifetime comparison



Power consumption at each node

Network lifetime for large-delay applications

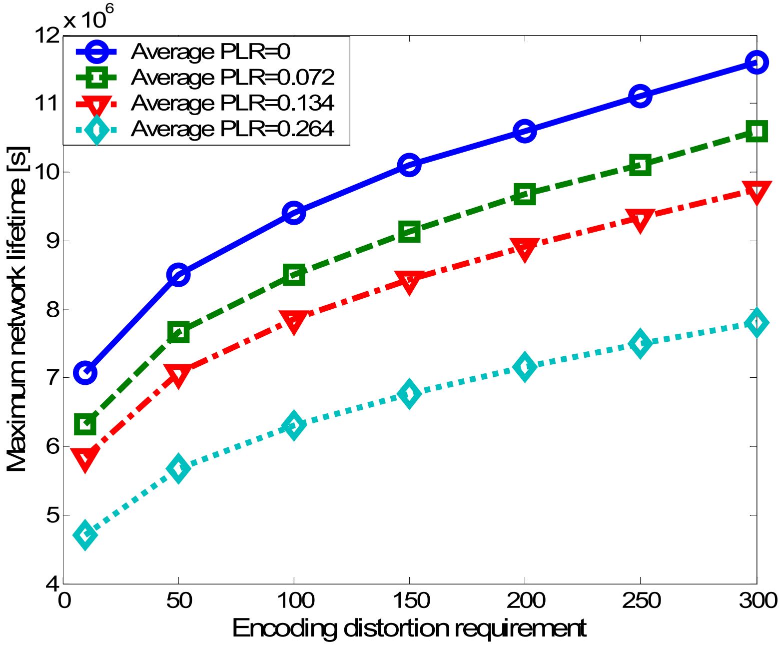
- Large-delay applications:
  - Example: visual data collection
  - Retransmissions to recover the corrupted packets
  - Retransmission consumes extra power, reduce network lifetime



Network lifetime with retransmissions

Network lifetime for small-delay applications

- Small-delay applications:
  - Example: real-time traffic monitoring
  - FEC to recover the corrupted packets
  - Introduce extra encoding and decoding power consumption, reduce network lifetime



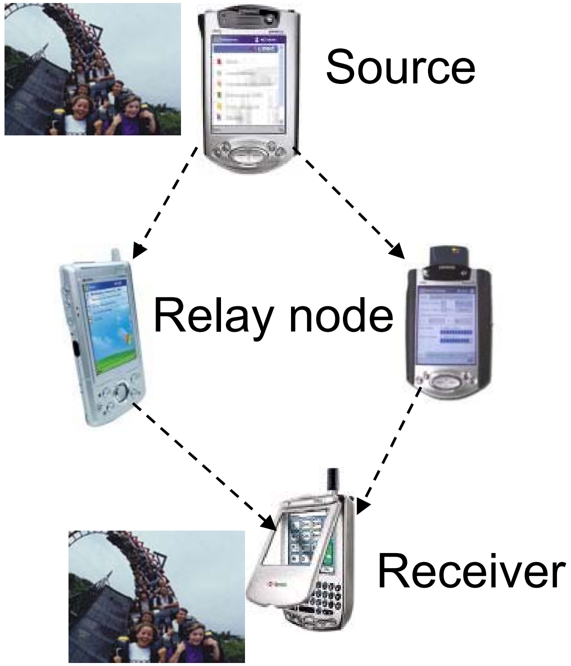
Network lifetime with FEC

Outline

- Motivation and contributions
- Principles of convex optimization
- Resource allocation in distributed video communication systems
  - Throughput maximization in P2P VoD applications
  - Network lifetime maximization in wireless visual sensor networks
  - Optimization for video streaming over wireless ad hoc networks
- Conclusions

Optimized video unicasting over wireless ad hoc networks

- Video unicasting
  - From a source to a receiver
  - Example: A group of visitors in a park, person A receives video streaming from person B via relays.
- The proposed optimized video unicasting scheme
  - Prioritized coding + network coding
  - Minimize the distortion by jointly optimizing the **source rate allocation** and the **routing scheme**



Video unicasting

Related work

- Video streaming over wireless ad hoc networks
  - Distributed optimization for data communications over wireless ad hoc networks [Xiao2004, Chen2006]
  - The optimizations for data communications cannot be applied directly to real-time streaming applications
  - Existing optimizations for video streaming over wireless ad hoc networks
    - Maximize the expected video quality using genetic algorithm [Mao2004] (centralized thus high complexity)
    - Optimization of resource competition among *multiple unicast* video sessions [Zhu2006] (distributed and low complexity at each node)
  - Optimal resource allocation for both video unicast streaming [and video multicast streaming [YHe-ISCAS06, YHe-PCM07, YHe-TCSVT08b] over wireless ad hoc networks.

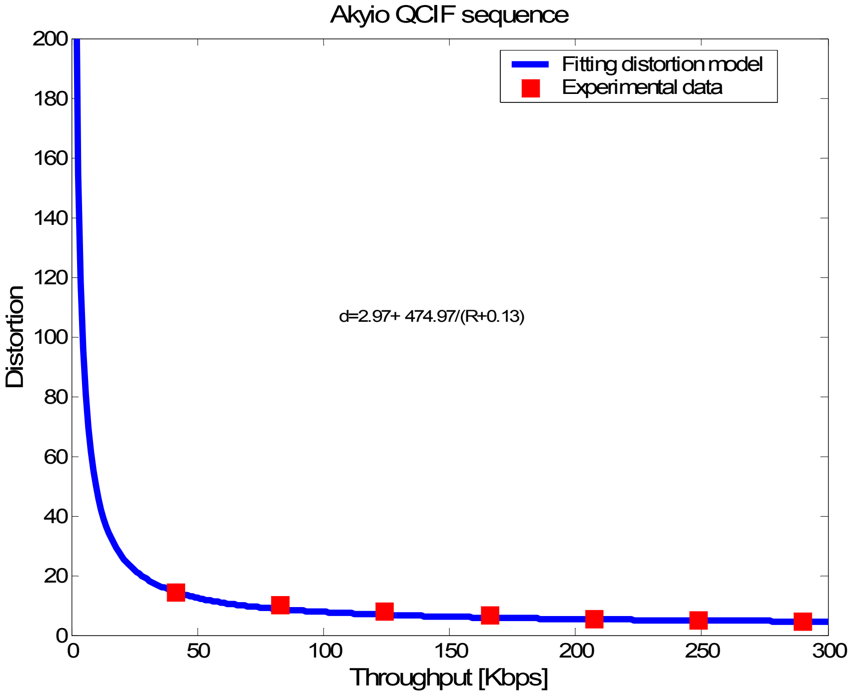
Video distortion model

- Video distortion model
  - Distortion vs. received throughput
  - Modeled as:

$$d = D_0 + \frac{\theta_0}{R + \phi_0},$$

  - Convex function
  - Data fitting technique to find

Parameters: D_0, θ_0, ϕ_0



D_0 : Parameter related to encoding distortion

θ_0, ϕ_0 : Parameters for transmission distortion

Optimized video unicasting over wireless ad hoc networks (cont.)

- Problem formulation:

$$\begin{array}{lll} \text{minimize} & -s_r + \sum_{l\in\mathbf{L}} x_l p_l + \delta s_r^2 + \delta \sum_{l\in\mathbf{L}} x_l^2 & \\ \text{subject to} & \sum_{l\in\mathbf{L}} a_{il} x_l = \eta_i, & \forall i \in \mathbf{N}, \\ & o \leq x_l \leq c_l, & \forall l \in \mathbf{L}, \\ & s_r \geq 0, & \end{array}$$

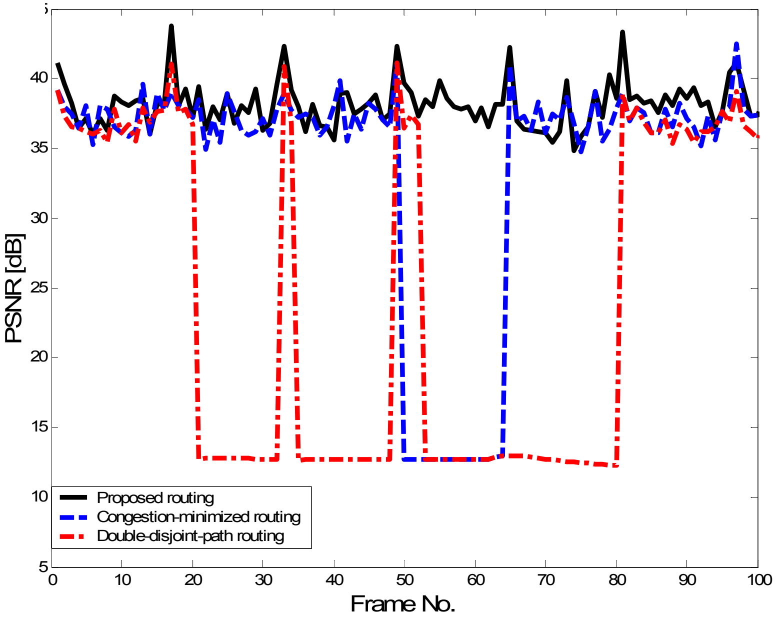
Video distortion

Flow conservation

Link capacity constraint

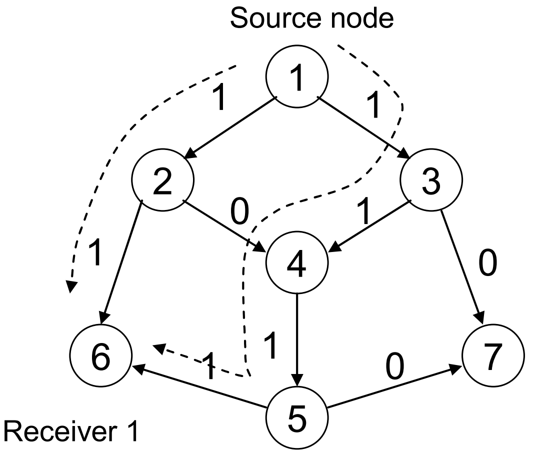
Converted to:
strictly convex optimization problem,
develop distributed algorithm to solve it

- Simulation results:
  - Comparison of frame PSNR

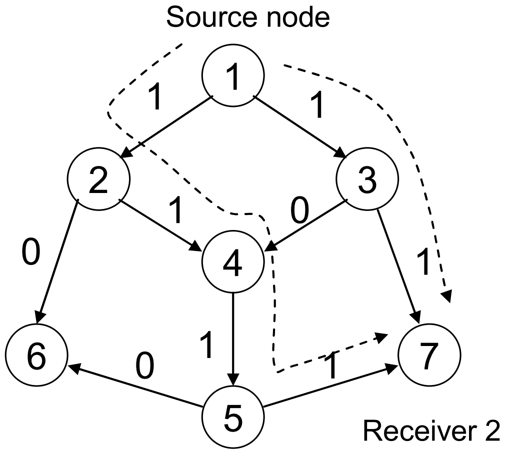


Optimized video multicasting over wireless ad hoc networks

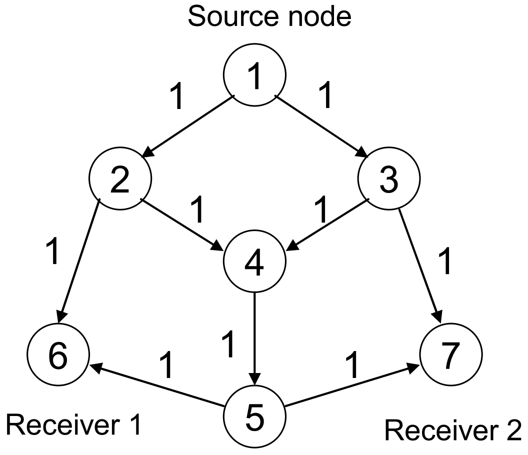
- Video multicasting:
  - Streaming from a source node to *H* receivers simultaneously
- With network coding, a multicast flow = H conceptual unicast sessions [Ahlswede2000]
- The proposed optimized multicasting scheme
  - Minimize the distortion by jointly optimizing the source rate allocation, the routing scheme and the power



Conceptual unicast session 1



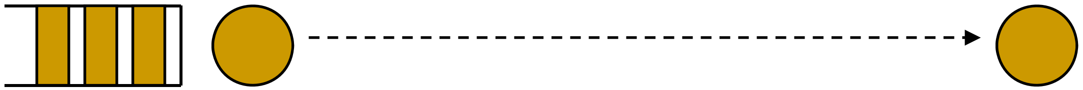
Conceptual unicast session 2



Multicast flow

Optimized video multicasting over wireless ad hoc networks

- Packet loss rate (PLR) in wireless ad hoc networks



Loss due to transmission error (p_{i2})

Loss due to congestion (p_{i1})

•PLR at link *i*: $p_i = 1-(1-p_{i1})(1-p_{i2})$

where $p_{i1} = \Pr ob(delay > T) = \exp(-\lambda T) = \exp\left(-\left(\frac{C-R}{L}\right)T\right)$

$$p_{i2} = 1 - \prod_{k \neq i} \frac{1}{1 + \frac{SIR_{th} G_{ik} P_k}{G_{ii} P_i}}$$

Optimized video multicasting over wireless ad hoc networks (cont.)

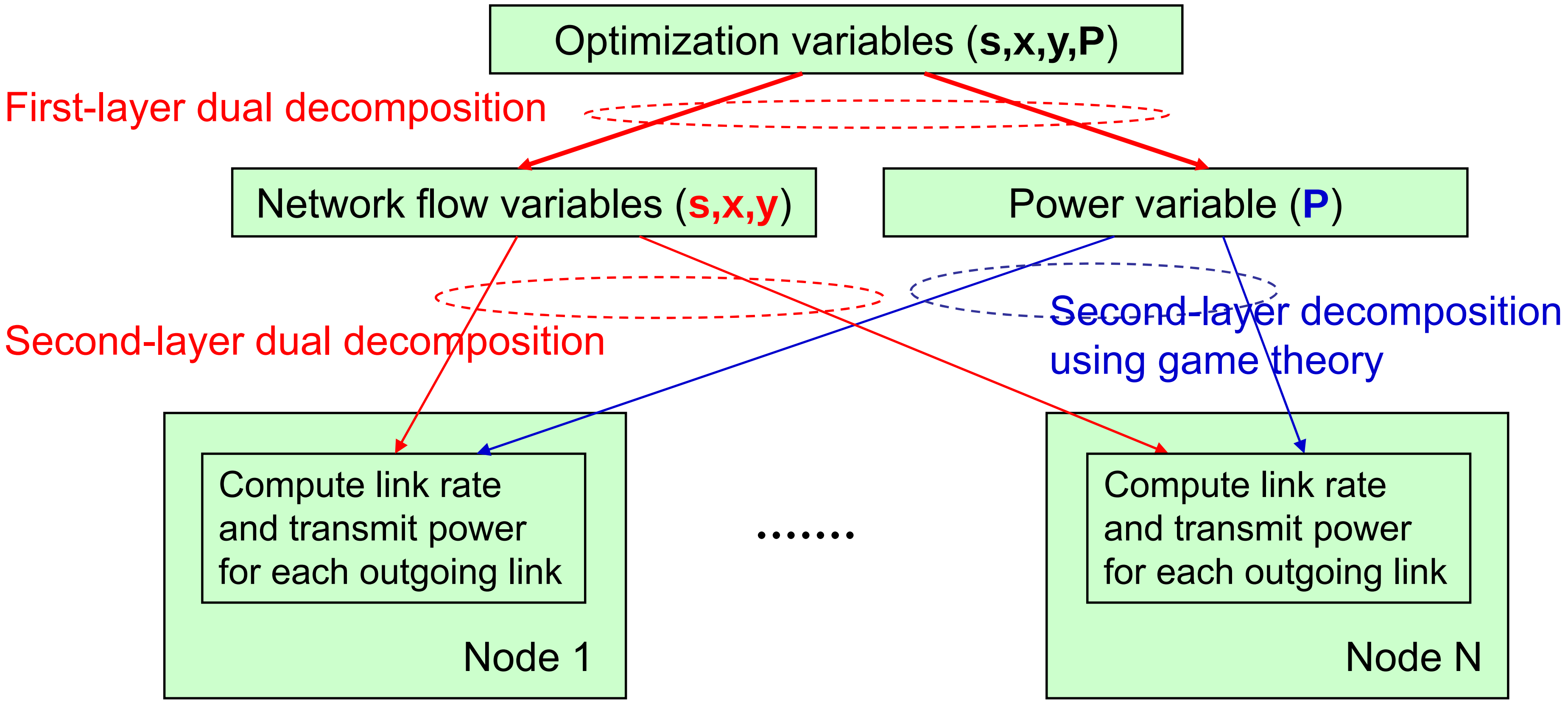
- Problem formulation:

maximize $\sum_{h\in \mathbf{V}}(s_h - \sum_{l\in \mathbf{L}} p_l x_{hl})$		Aggregate throughput
subject to $\sum_{l\in \mathbf{L}} a_{il} x_{hl} = \eta_{hi},$	$\forall h \in \mathbf{V}, \forall i \in \mathbf{N},$	Flow conservation
$x_{hl} \le y_l,$	$\forall h \in \mathbf{V}, \forall l \in \mathbf{L},$	Multicast flow rate y_l
$y_l \le c_l,$	$\forall l \in \mathbf{L},$	Capacity constraint
$c_l = \frac{1}{T}\log_2\left(1+\frac{G_{ll}P_l}{\sum_{k\in \mathbf{L},k\neq l} G_{lk}P_k + n_l}\right),$	$\forall l \in \mathbf{L},$	Link capacity under CDMA
$x_{hl} \ge 0,$	$\forall h \in \mathbf{V}, \forall l \in \mathbf{L},$	
$s_h \ge 0,$	$\forall h \in \mathbf{V},$	
$0 \le P_l \le P_m,$	$\forall l \in \mathbf{L},$	Transmit power constraint

Network coding eliminates duplicate packets, change the objective function to maximize the aggregate throughput

Optimized video multicasting over wireless ad hoc networks (cont.)

- Distributed solution using hierarchical dual decompositions



Optimization variables (**s,x,y,P**)

First-layer dual decomposition

Network flow variables (**s,x,y**)

Power variable (**P**)

Second-layer dual decomposition

Second-layer decomposition using game theory

Compute link rate and transmit power for each outgoing link

Node 1

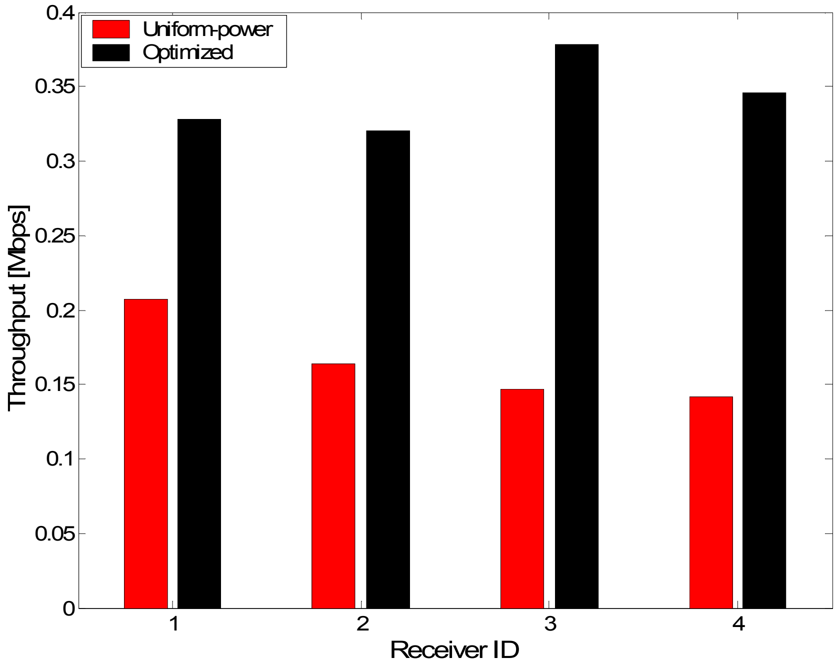
…….

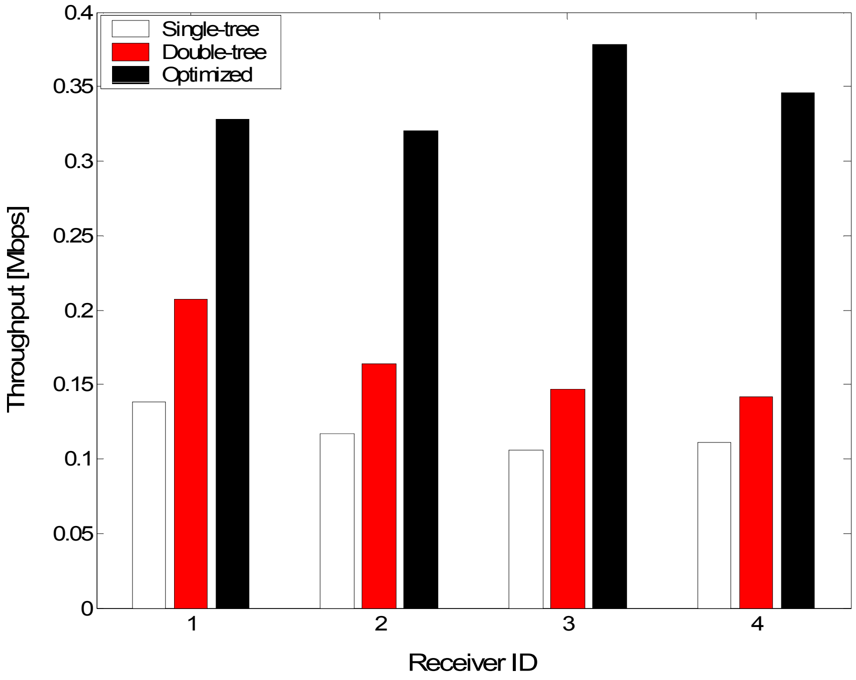
Compute link rate and transmit power for each outgoing link

Node N

Optimized video multicasting over wireless ad hoc networks (cont.)

- Simulation results:

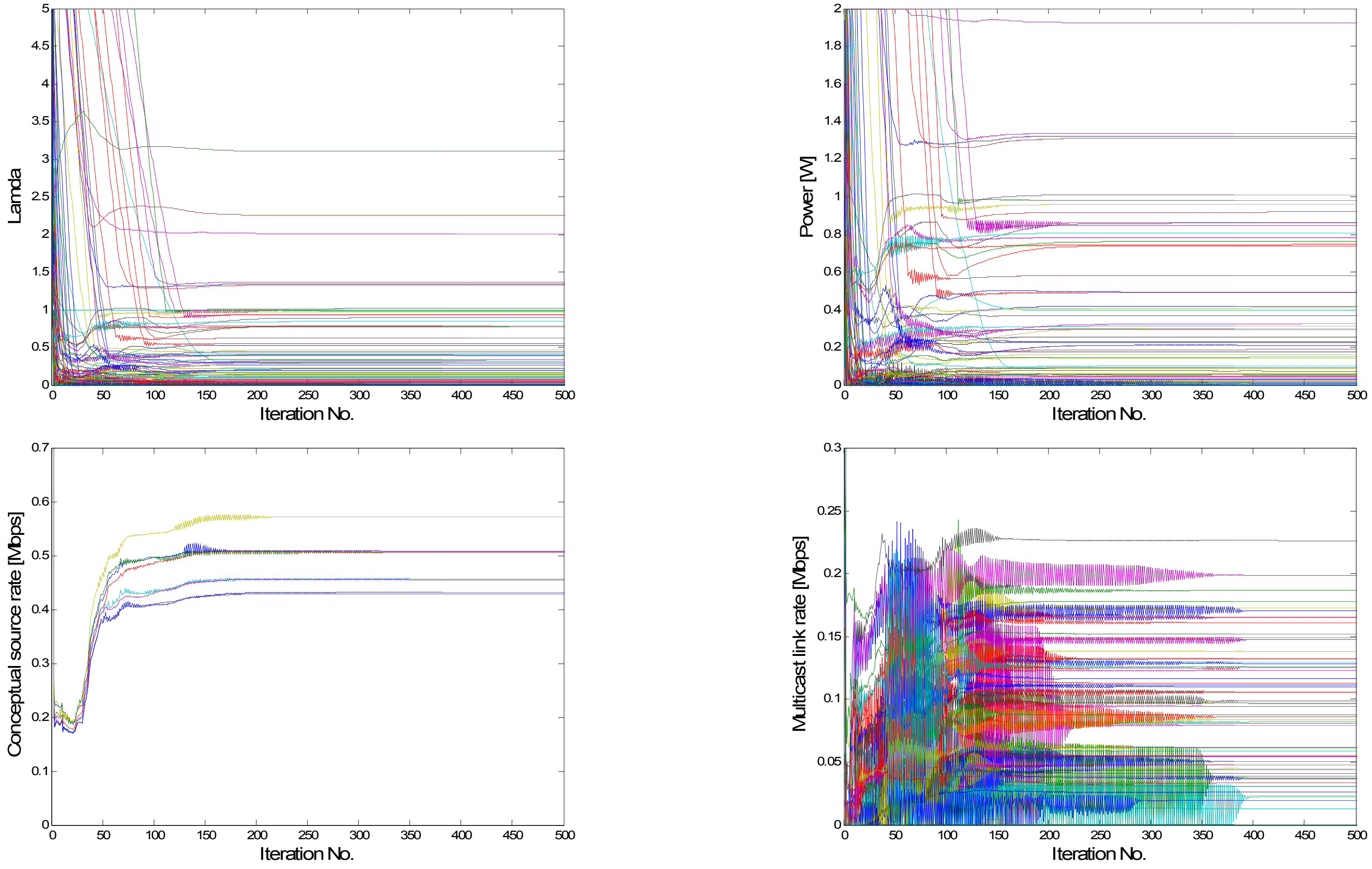




<u>Compare to uniform-power scheme</u>

<u>Compare to tree-based schemes</u>

Optimized video multicasting over wireless ad hoc networks



<u>Optimization results for a 50-node wireless ad hoc network</u>

A multicast flow for a source to 8 receivers

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Thank You!