QoS Amplification Research

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Overview

Goal Achieve QoS amplification over imperfect network service substrate

$\rightarrow$ end-to-end control & per-hop control

- End-to-end QoS amplification
  - Multiple time scale traffic control
  - Adaptive redundancy control
  - Adaptive label control
- Per-hop QoS amplification
  - Aggregate-flow label switching
  - Optimal classifiers
  - WAN experiments and collaborations

Outline

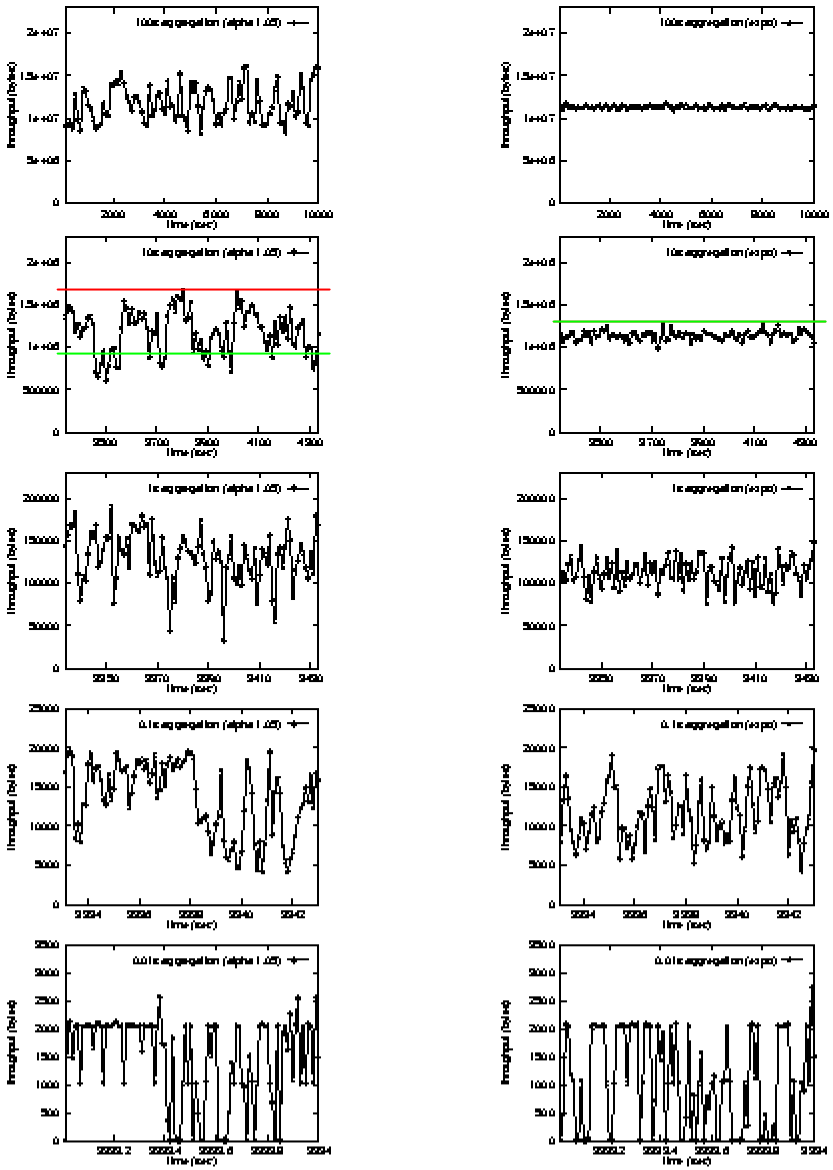
Multiple Time Scale Traffic Control

Self-similar Network Traffic

- Data traffic is fundamentally different from telephony traffic (Leland *et al.* '93)
  - → self-similar or long-range dependent

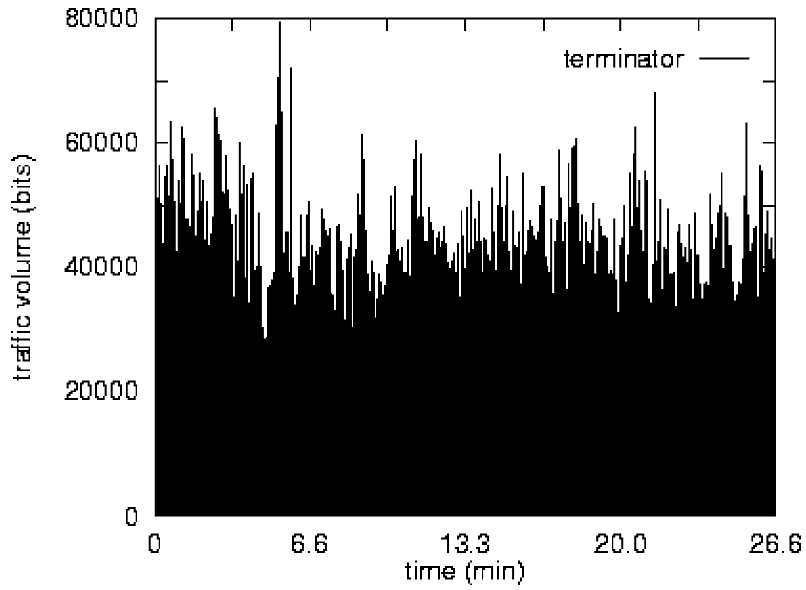
- Causality
- Performance Impact
- Control

Self-similar Network Traffic and Performance Evaluation, Park and Willinger (eds.), Wiley-Interscience, 2000



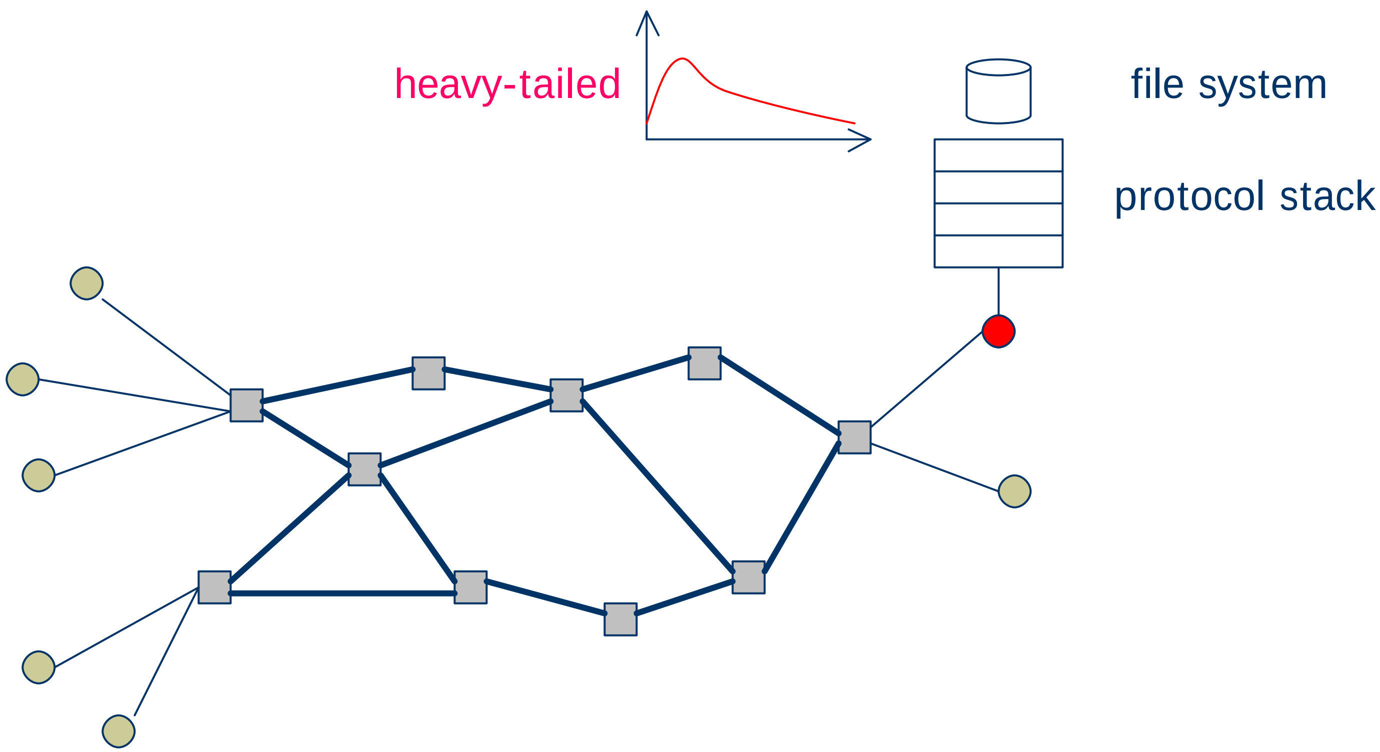
Multiple Time Scale (cont.)

- Causality
  - Single-source causality (e.g., MPEG video)



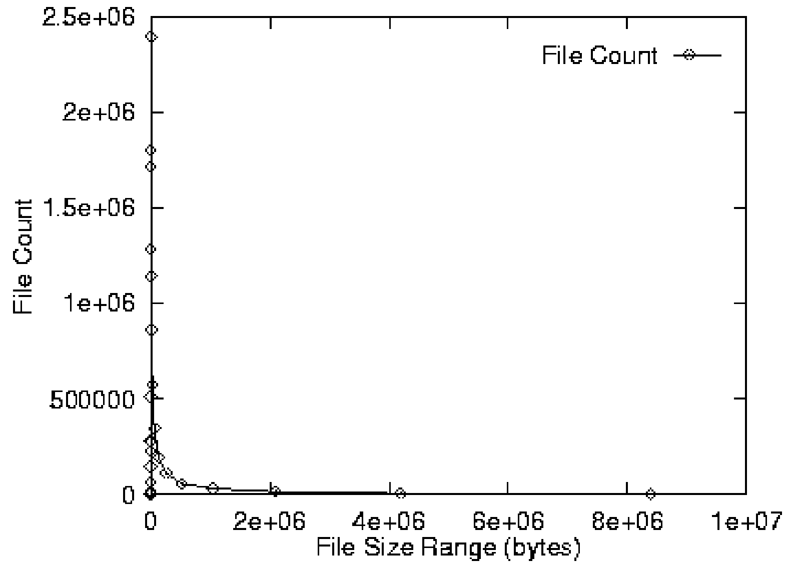
Multiple Time Scale (cont.)

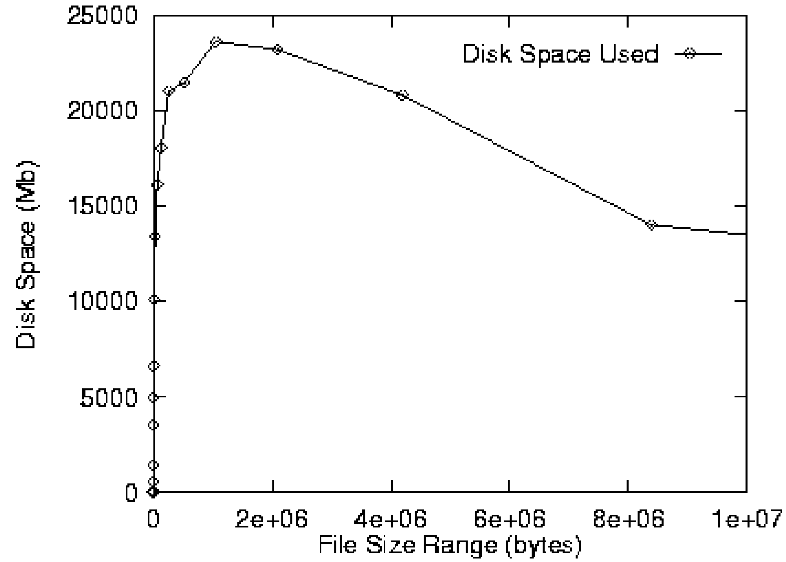
- Structural causality



Multiple Time Scale (cont.)

- Structual causality (cont.)

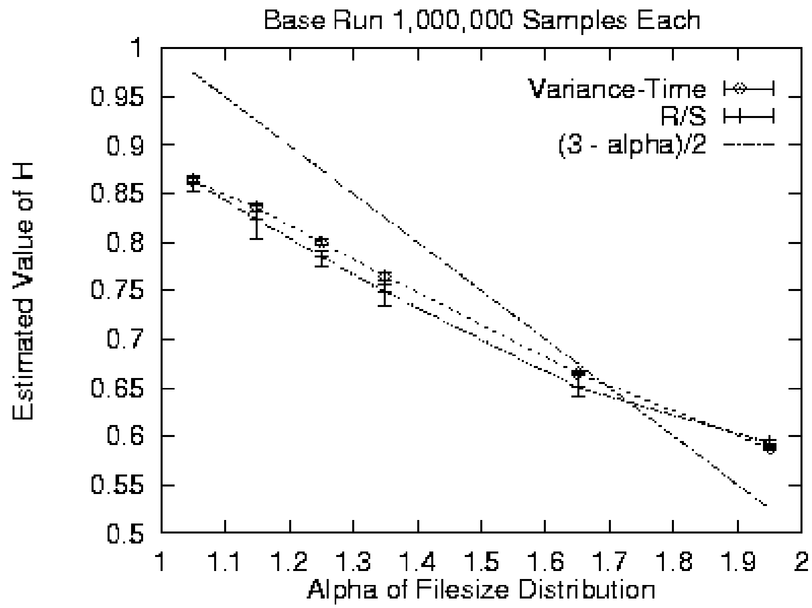




→ UNIX file system (G. Irlam)

Multiple Time Scale (cont.)

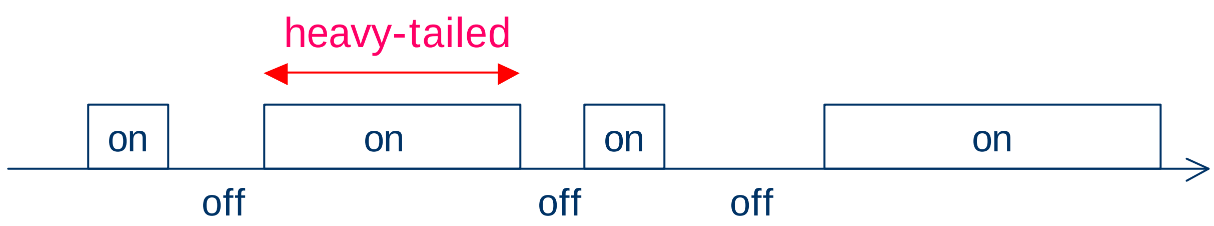
- Structural causality (cont.)



$\rightarrow$ impervious to “details”

Multiple Time Scale (cont.)

- Structural causality (cont.)

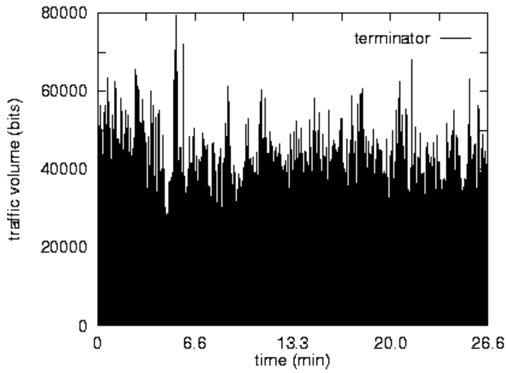


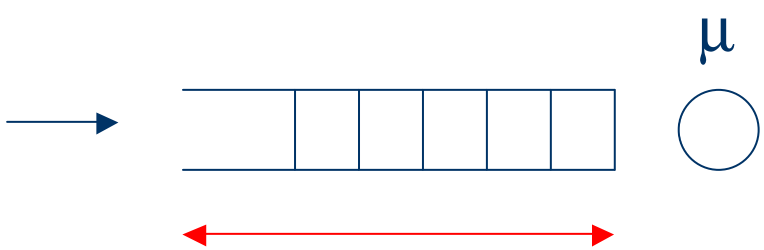
  - on/off traffic (0/1 reward renewal process)
  - asymptotic second-order self-similarity

- Two principal traits
  - Invariant correlation structure across multiple time scales
  - Correlation at a distance (long-range dependence)

Multiple Time Scale (cont.)

- Detrimental performance impact: queueing

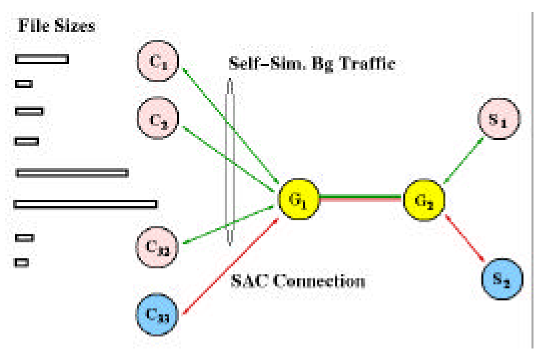




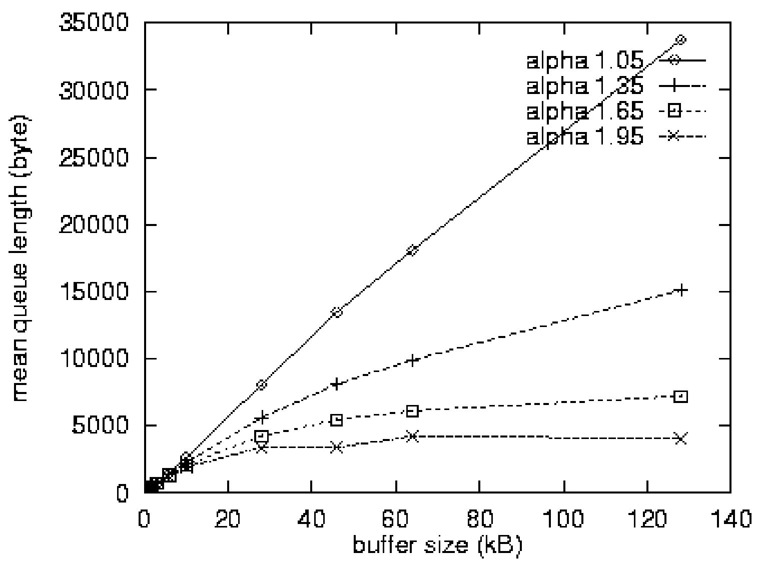
  - polynomial (vs. exponential) queue length distribution
  - infinite memory/asymptotic analysis

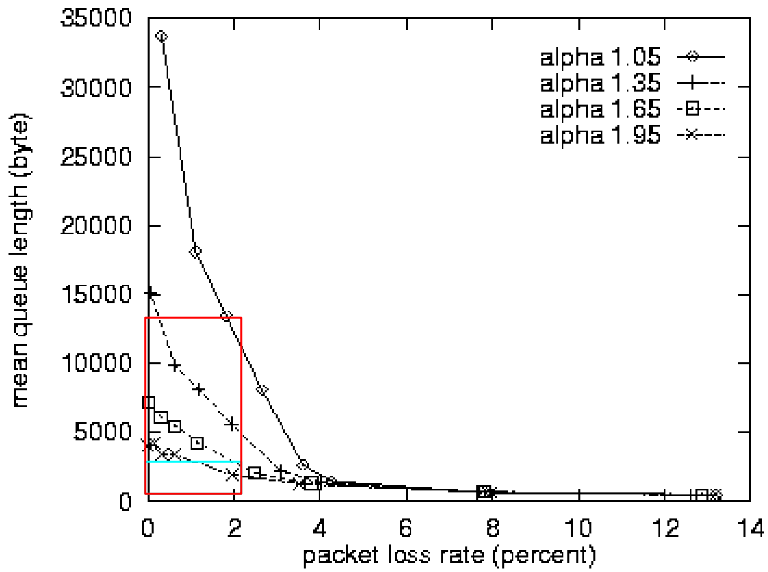
Multiple Time Scale (cont.)

- Empirical validation



with feedback control (e.g., TCP)



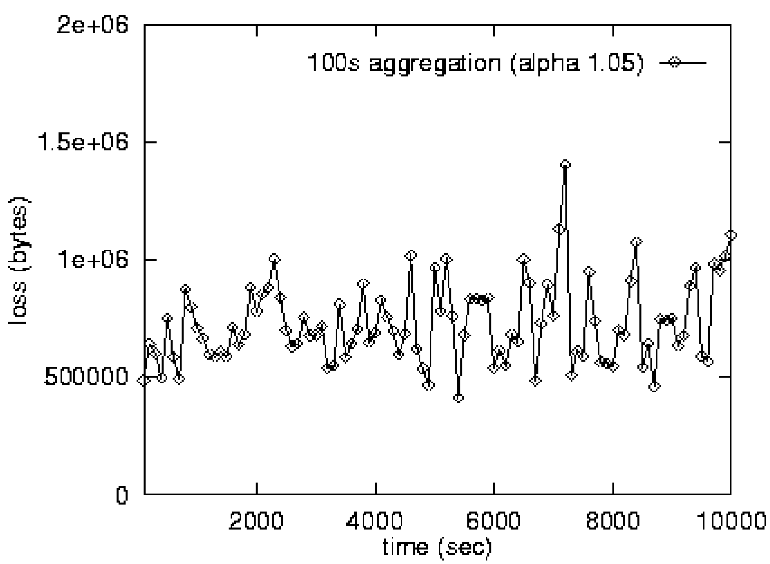


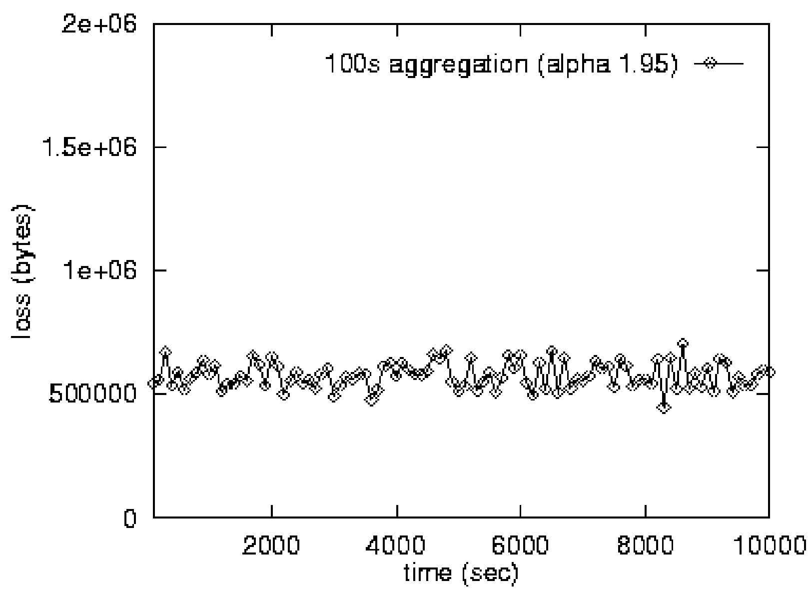
Multiple Time Scale (cont.)

- Impact of long-range structure can be curtailed
  - → extreme: bufferless queueing
  - → time horizon implied by finite memory
  - → short-range correlation can dominate
- Small buffer/large bandwidth resource provisioning policy
  - → statistical multiplexing
  - → central limit theorem

Multiple Time Scale (cont.)

- Importance of second-order performance measures
  - e.g., jitter



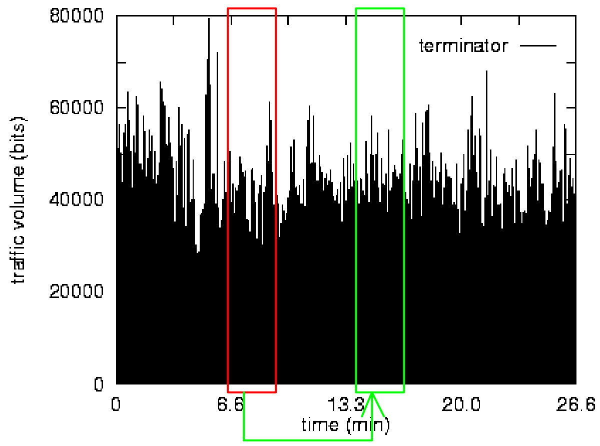


- concentrated periods of over- and under-utilization
- bufferless queueing does not help

Multiple Time Scale Traffic Control (cont.)

Traffic Control

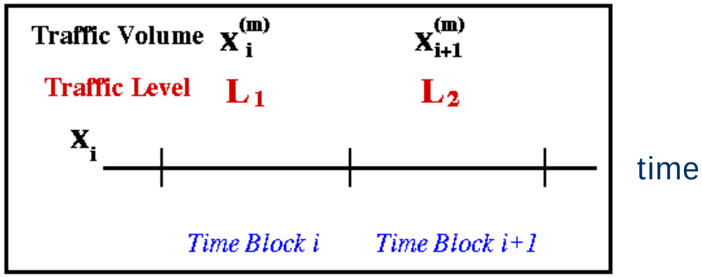
- Premise: exploit long-range correlation for traffic control
  - → correlation/predictability structure at large time scales

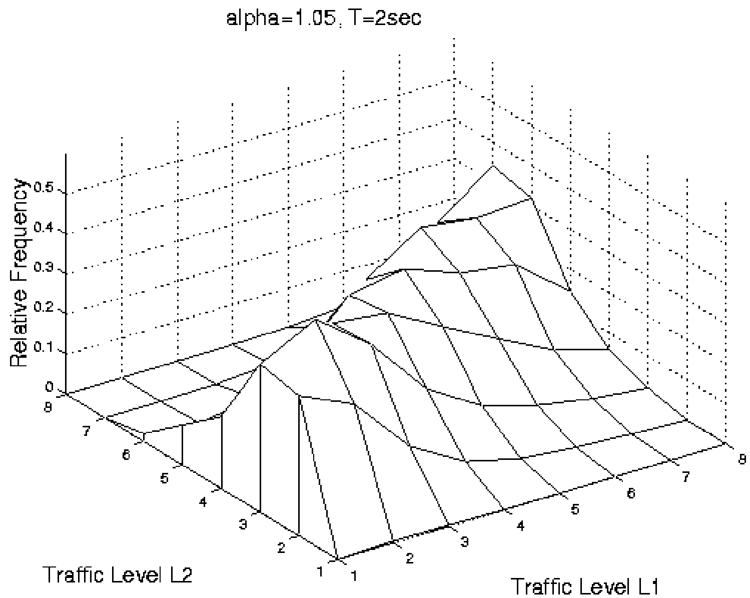


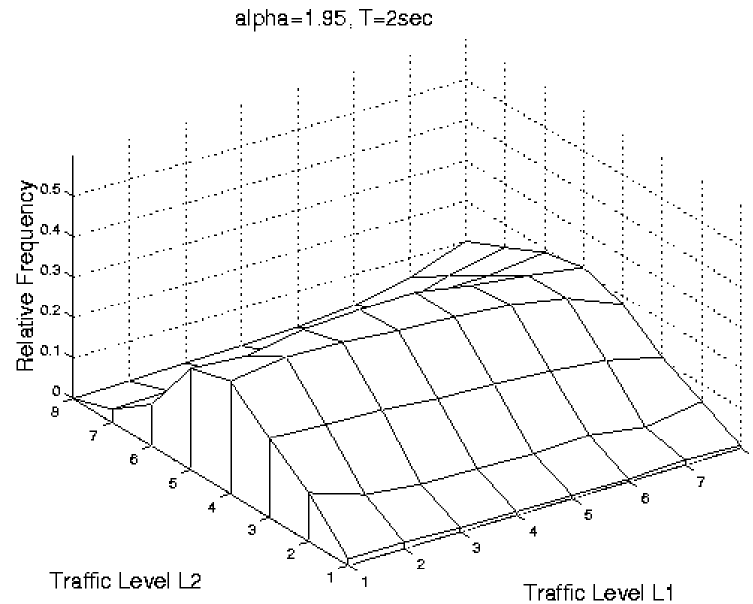
  - → relevant in broadband WANs with high delay-bandwidth product

Multiple Time ScaleTraffic Control (cont.)

Large time scale predictability:

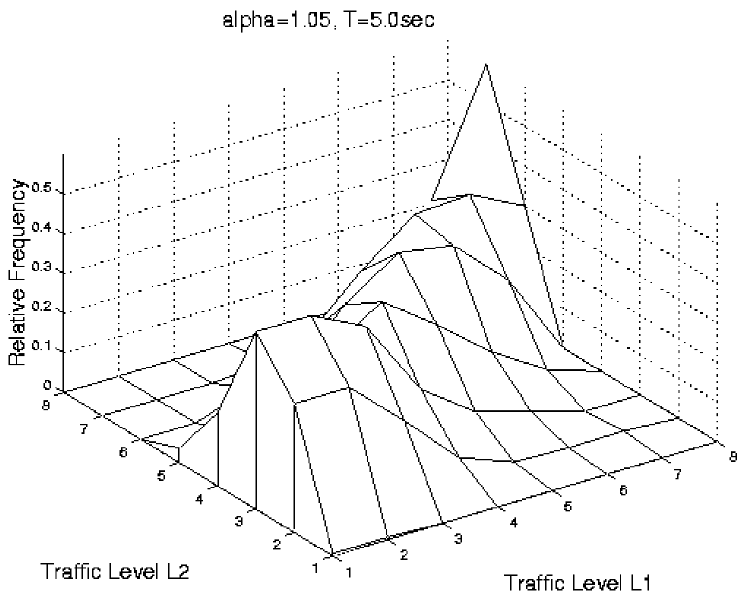


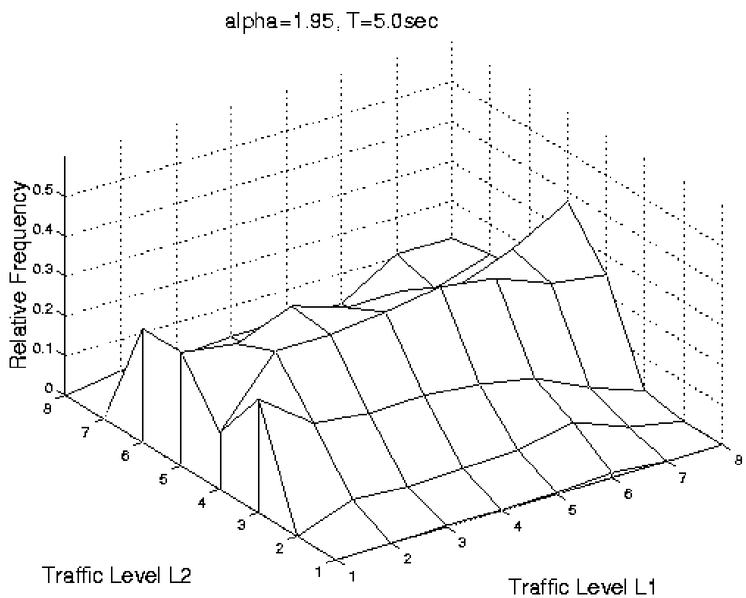




Multiple Time Scale Traffic Control (cont.)

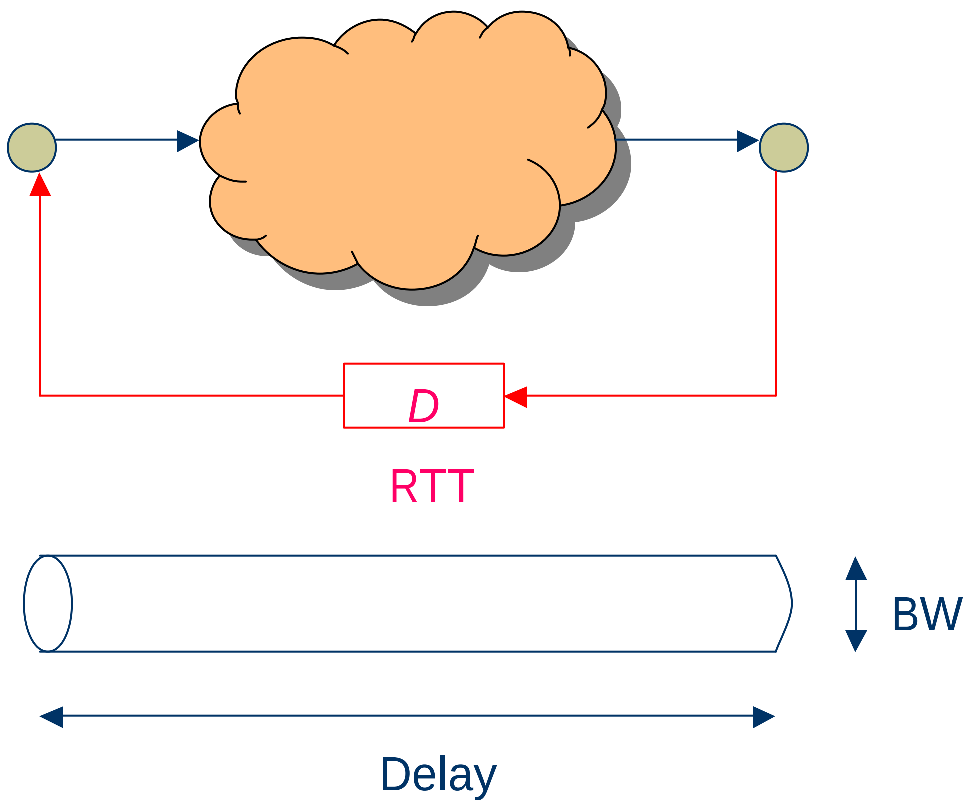
Large time scale predictability (5 sec):

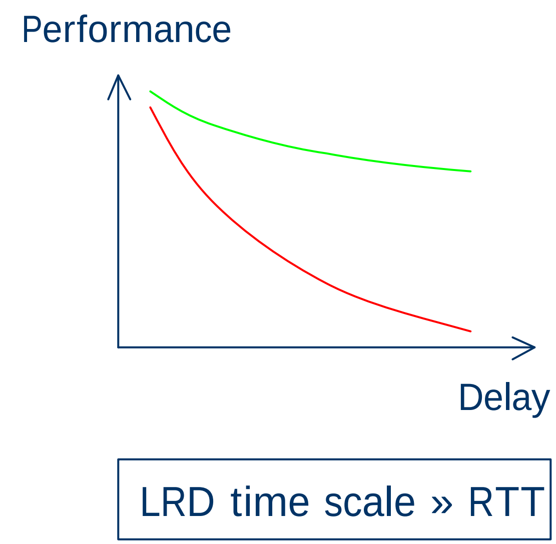




Multiple Time Scale Traffic Control (cont.)

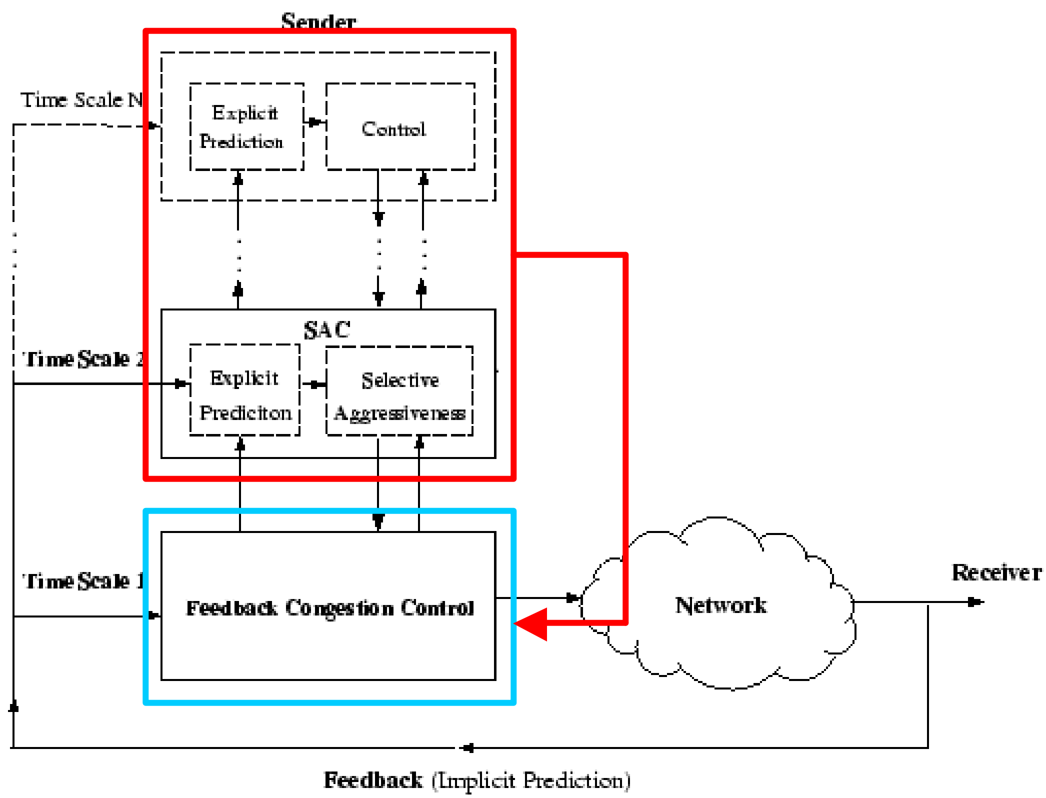
- Implications: mitigate reactive cost of feedback control





Multiple Time Scale Traffic Control (cont.)

Multiple time scale traffic control:



Multiple Time Scale Traffic Control (cont.)

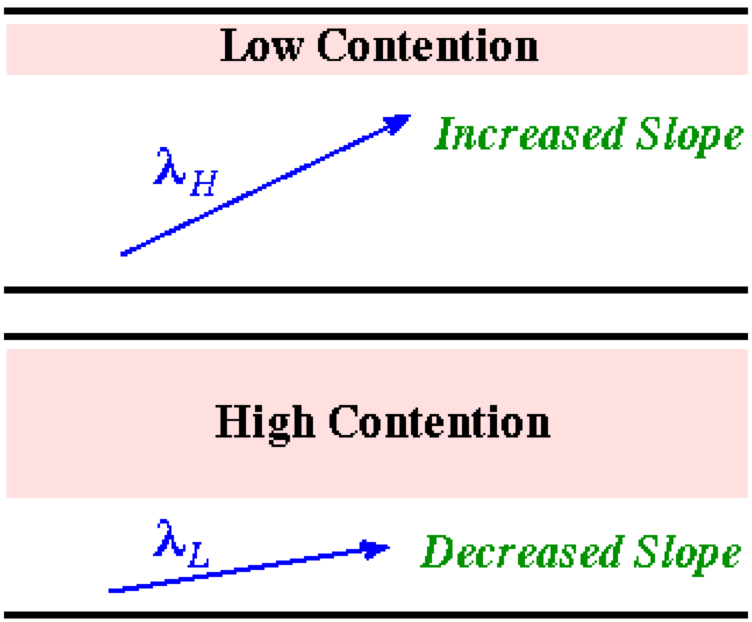
Application Domains:

- Bulk data transport – congestion control
  - → throughput maximization (TCP-MT)
- Real-time data transport – adaptive redundancy control
  - → end-to-end QoS (AFEC-MT)

Multiple Time Scale Traffic Control (cont.)

Congestion control: TCP and rate-based

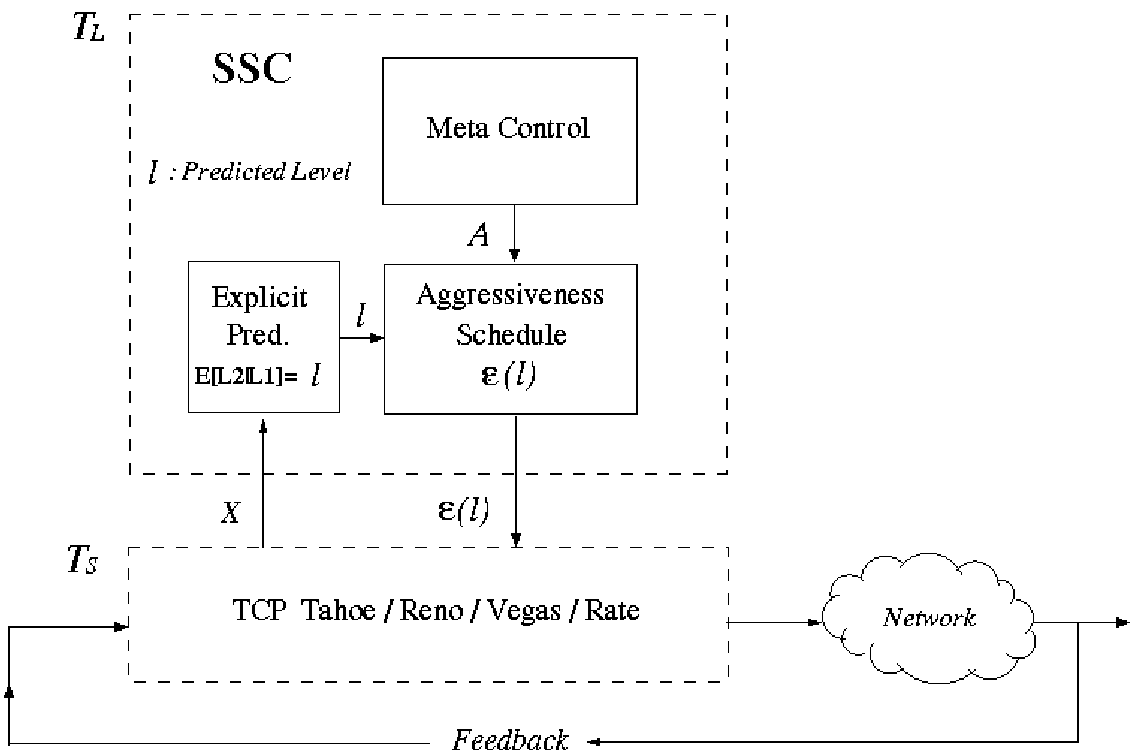
Idea:



$\rightarrow$ modulate slope of linear increase phase in AIMD

Multiple Time Scale Traffic Control (cont.)

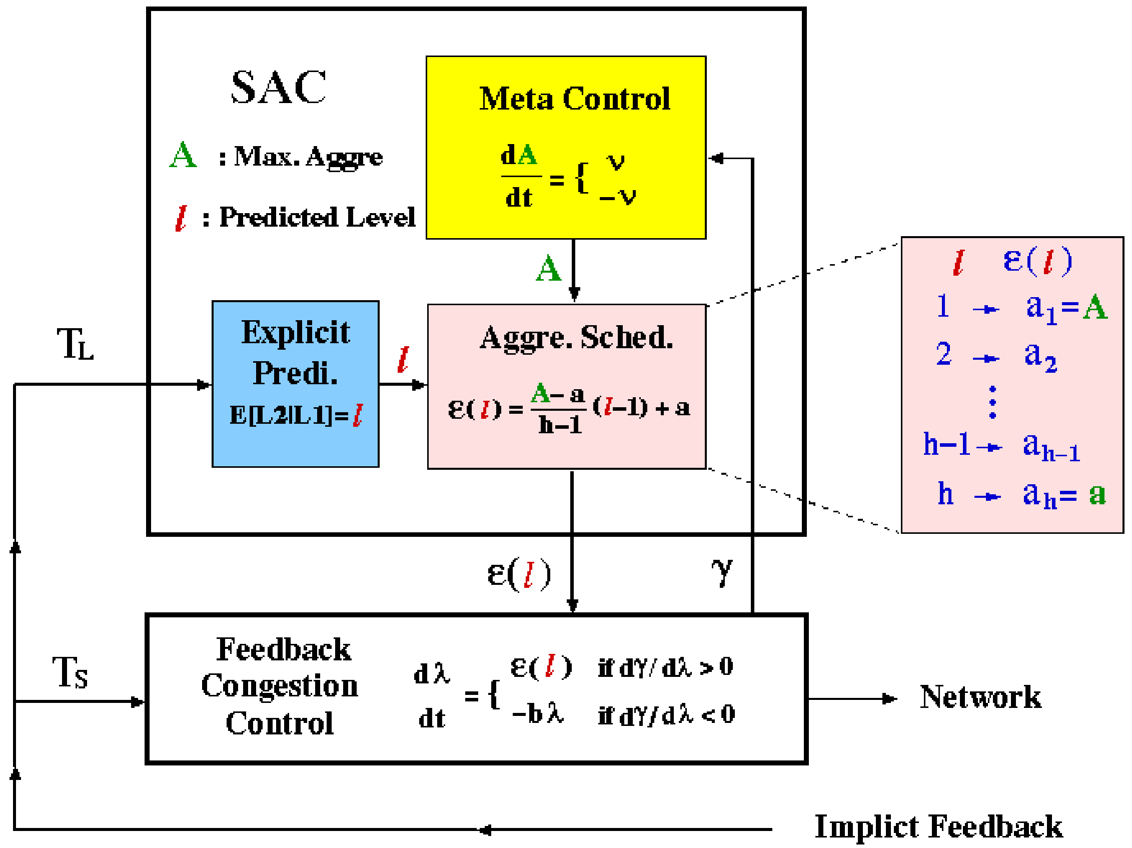
- Multiple time scale TCP (TCP-MT):



Multiple Time Scale Traffic Control (cont.)

- Multiple time scale rate-based congestion control:

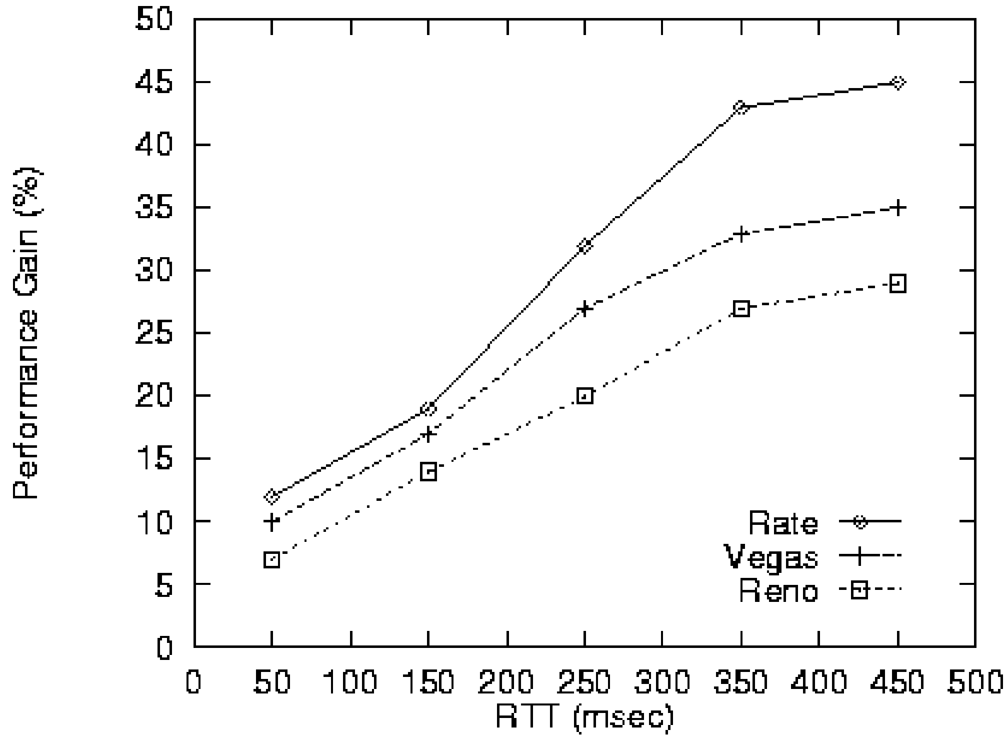
ATM:

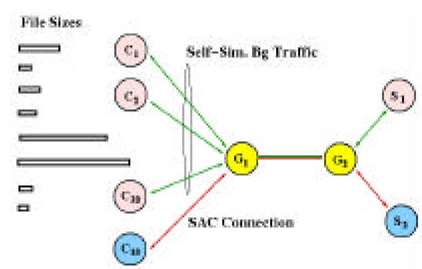


Multiple Time Scale Traffic Control (cont.)

- TCP-MT: performance gain as function of RTT

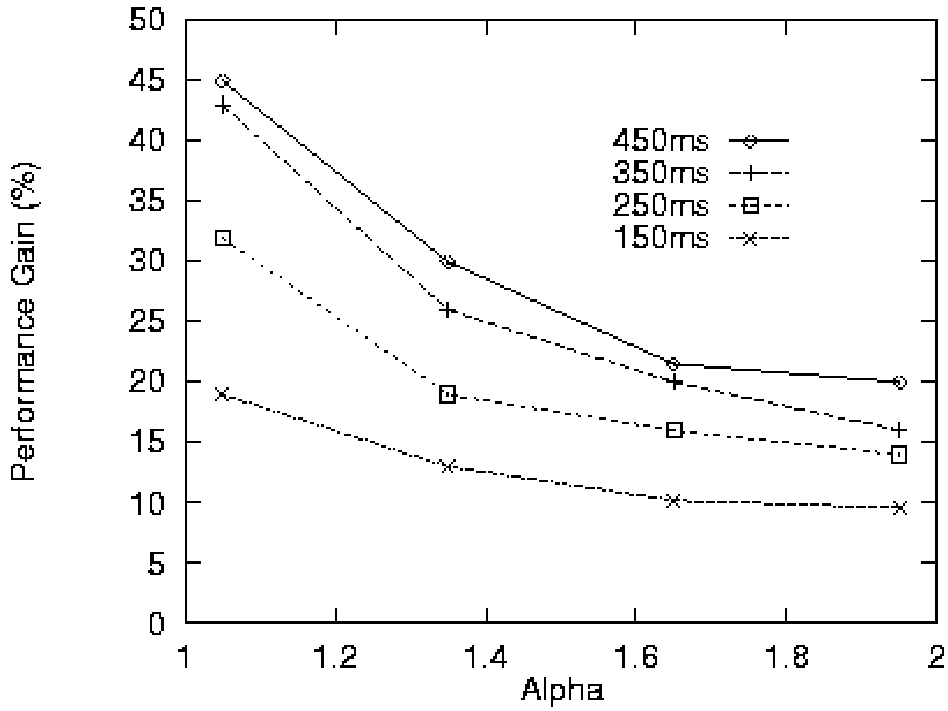
$\frac{\text{TCP-MT}}{\text{TCP}}$





Multiple Time Scale Traffic Control (cont.)

- TCP-MT: performance gain as function of self-similarity



Multiple Time Scale Traffic Control (cont.)

- Principal performance effect:
  - → impart proactivity above and beyond AFEC
  - → proactivity of reactive control in broadband WANs
  - → mitigate reactive cost

predictability at time scales exceeding RTT imparts timeliness

⇨ applications: broadband WAN, TCP-over-Satellite

Adaptive Redundancy Control

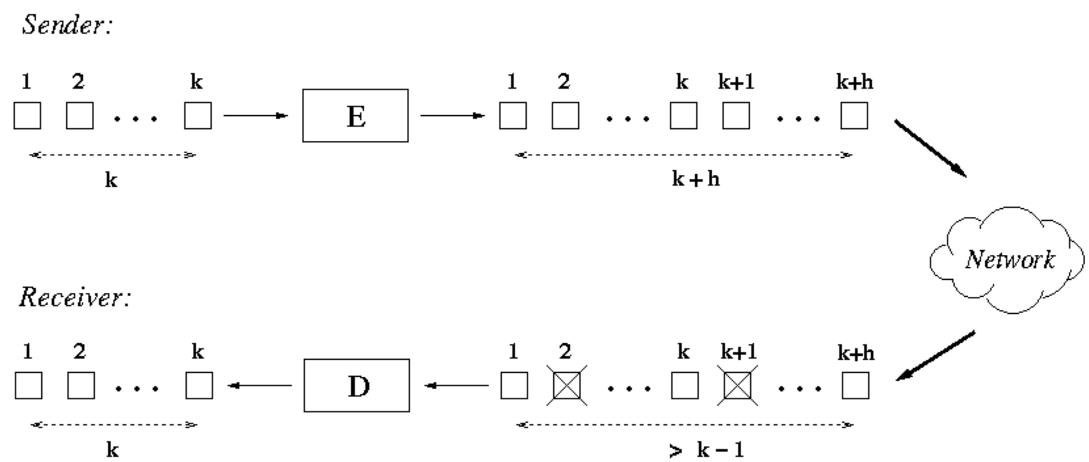
Real-time Traffic Transport

- Achieve invariant end-to-end QoS
- User-specified QoS
- ARQ infeasible (RTT & timeliness)
- Packet-level FEC
  - → proactive QoS protection
- Purely end-to-end (black box network)
- MPEG video/audio implementation (UDP)

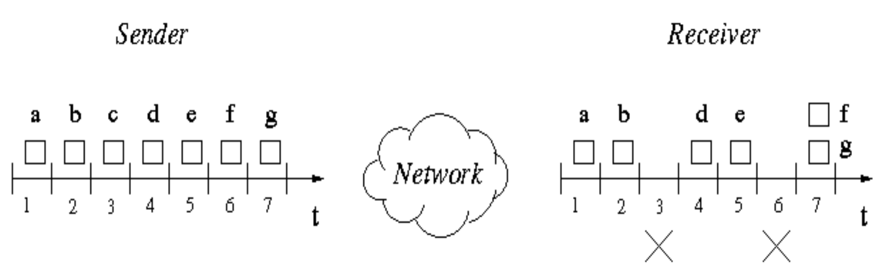
Adaptive Redundancy Control (cont.)

Adaptive redundancy control (AFEC):

FEC:



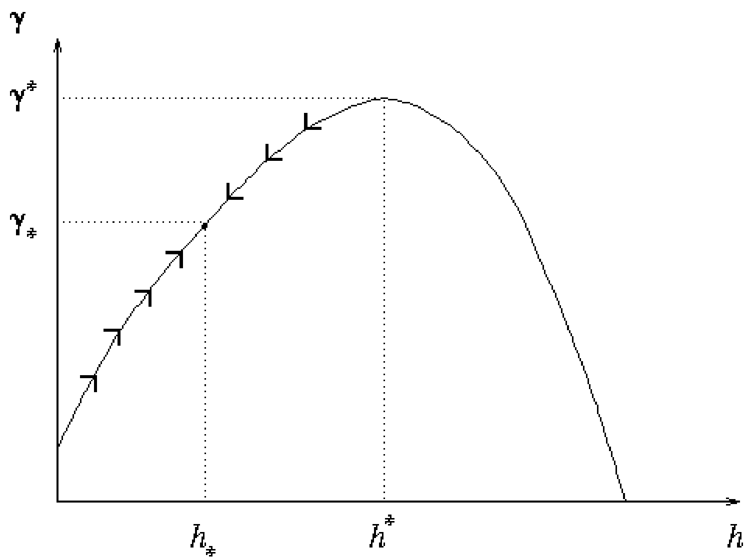
hit rate:

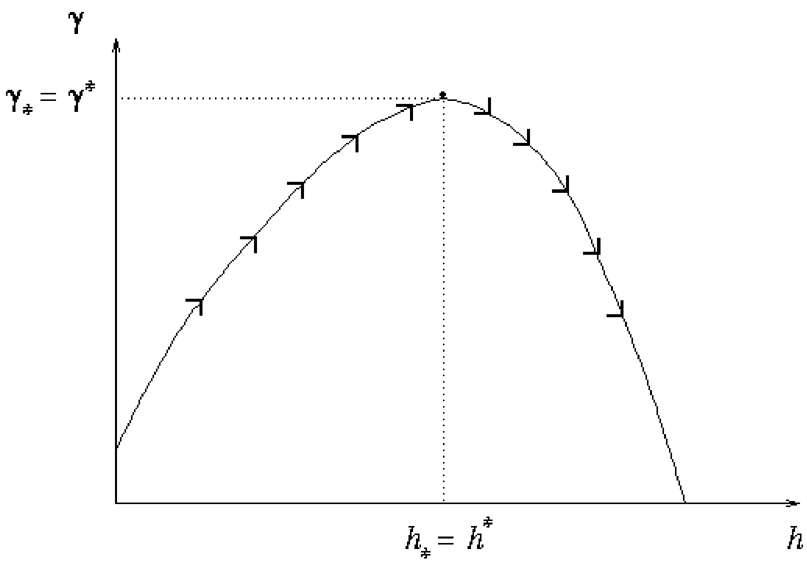


$0 \le \gamma \le 1$

Adaptive Redundancy Control (cont.)

- Redundancy-recovery relation:

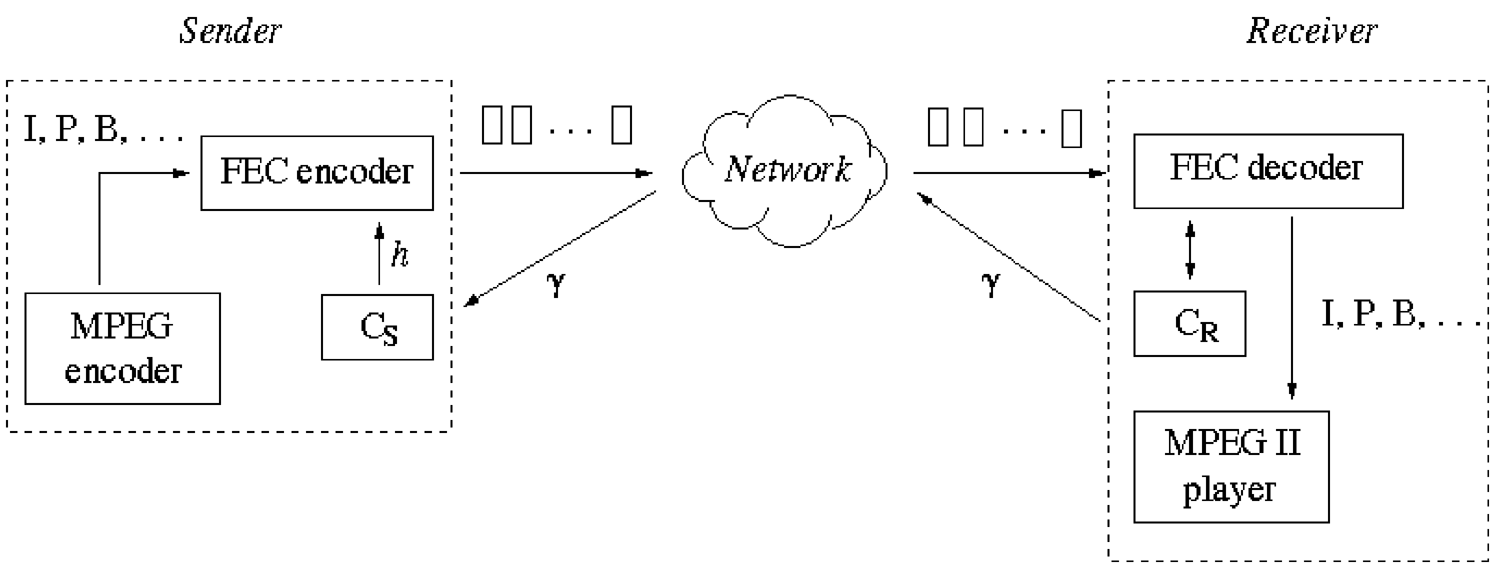




$\longrightarrow$ stability & optimality

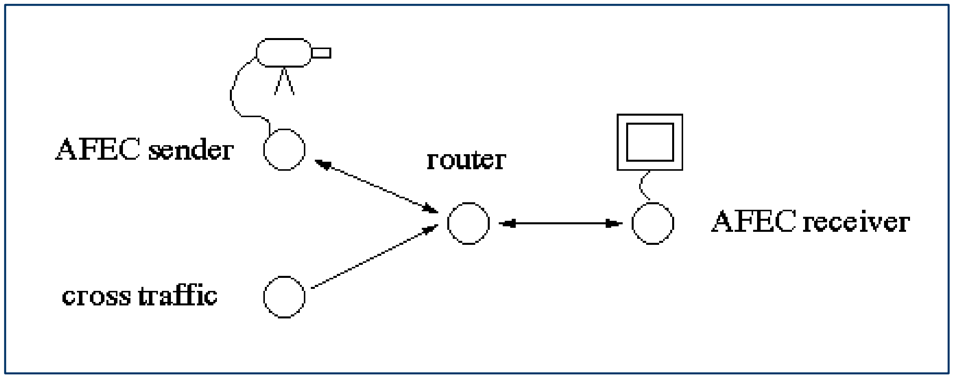
Adaptive Redundancy Control (cont.)

- AFEC structure:



Adaptive Redundancy Control (cont.)

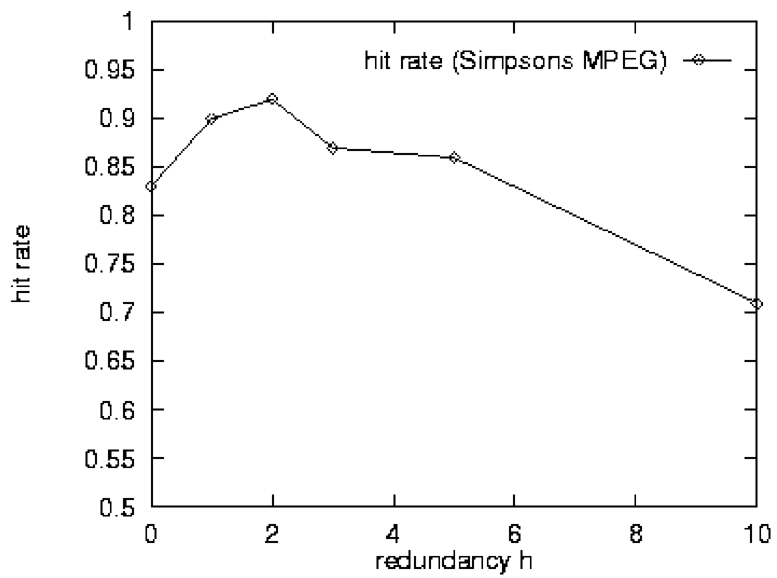
- Experimental set-up:

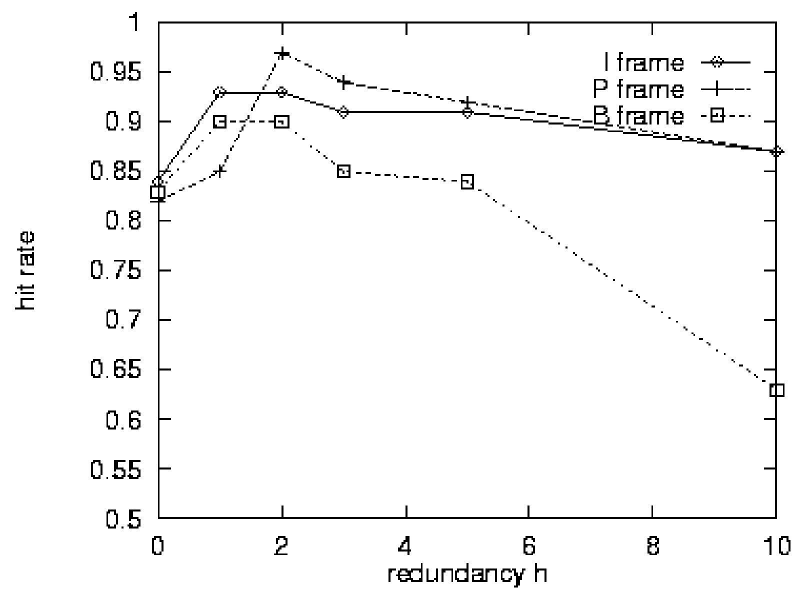


- UltraSparc 1 & 2, SGI, x86
- Solaris UNIX, Windows NT
- Optibase, Futuretel MPEG I & II compression boards
- Sony DCR-VX 1000, Panasonic F250

Adaptive Redundancy Control (cont.)

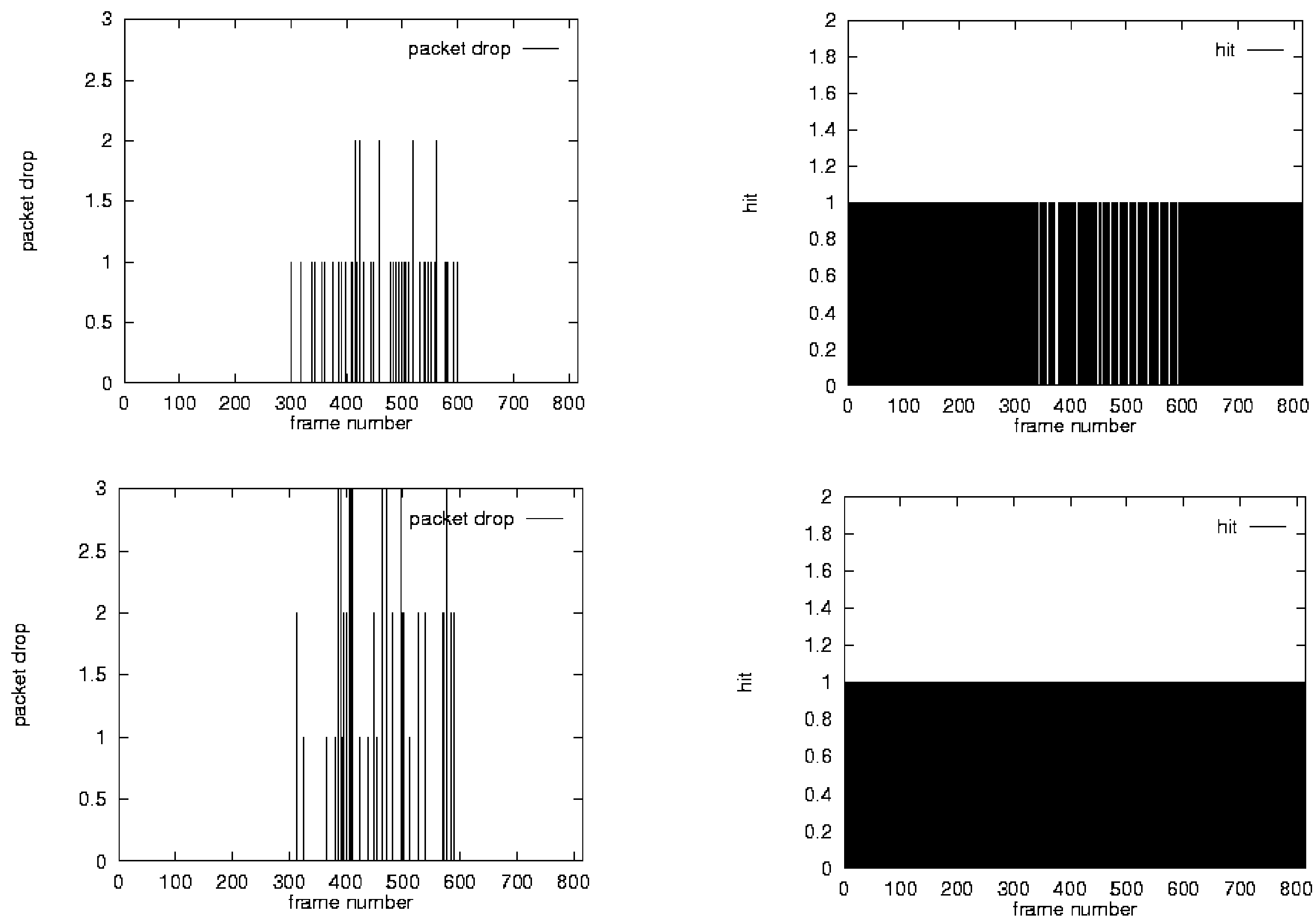
- Impact of redundancy: Static FEC





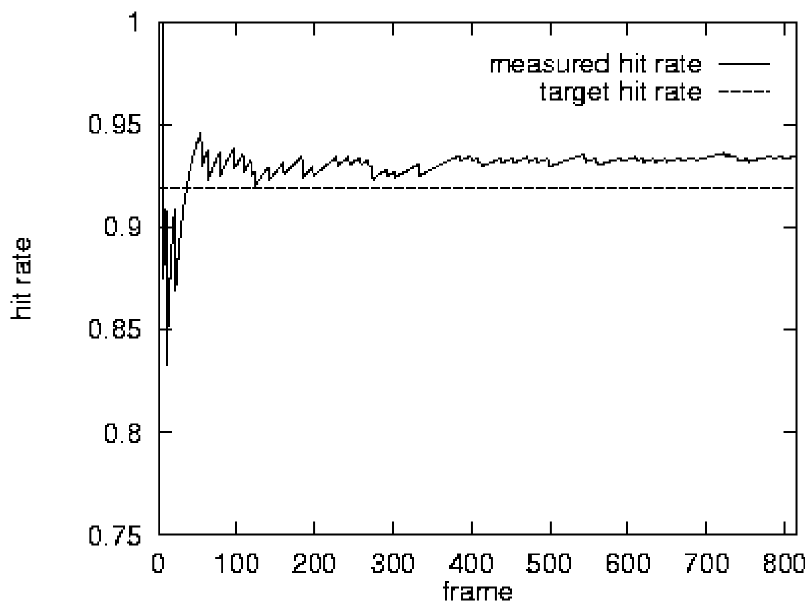
Adaptive Redundancy Control (cont.)

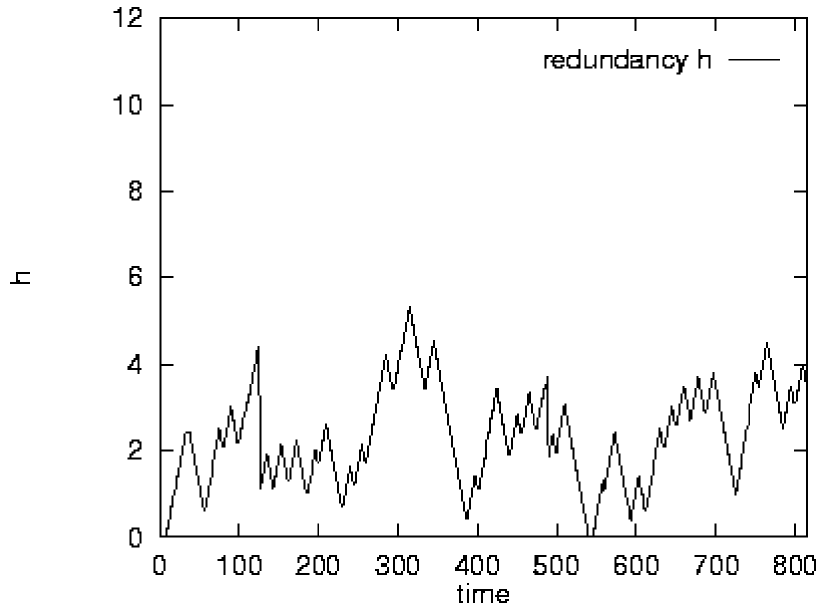
- Adaptive FEC vs. static FEC



Adaptive Redundancy Control (cont.)

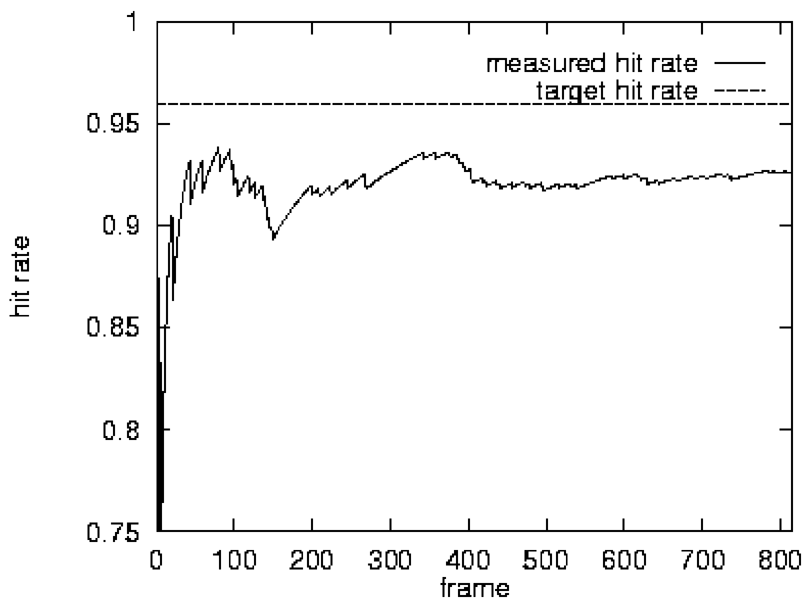
- Stable target QoS: symmetric control

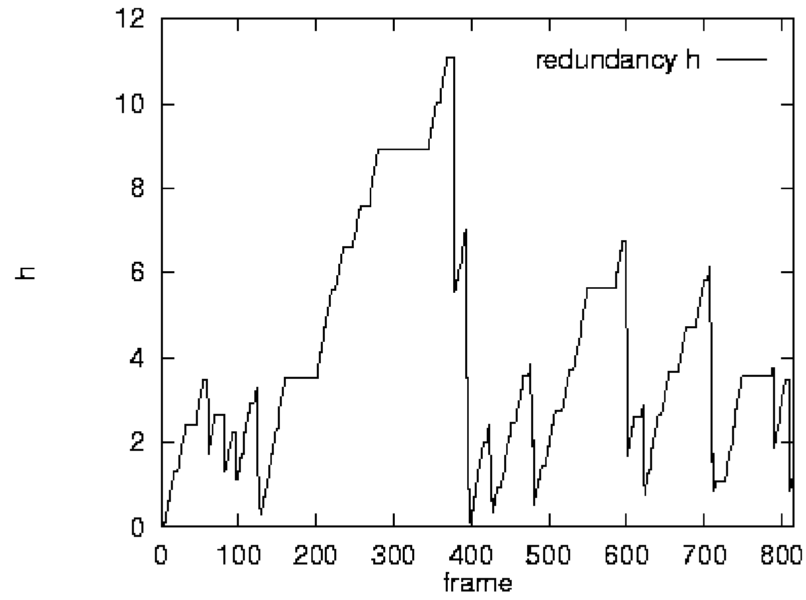




Adaptive Redundancy Control (cont.)

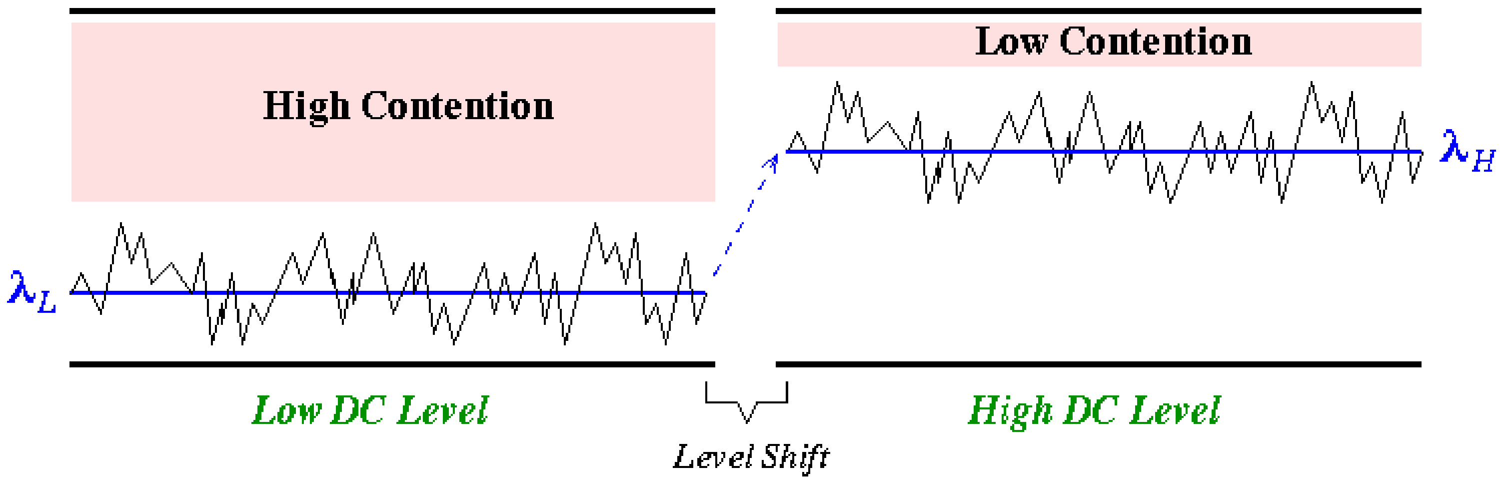
- Unstable target QoS: asymmetric control





Adaptive Redundancy Control (cont.)

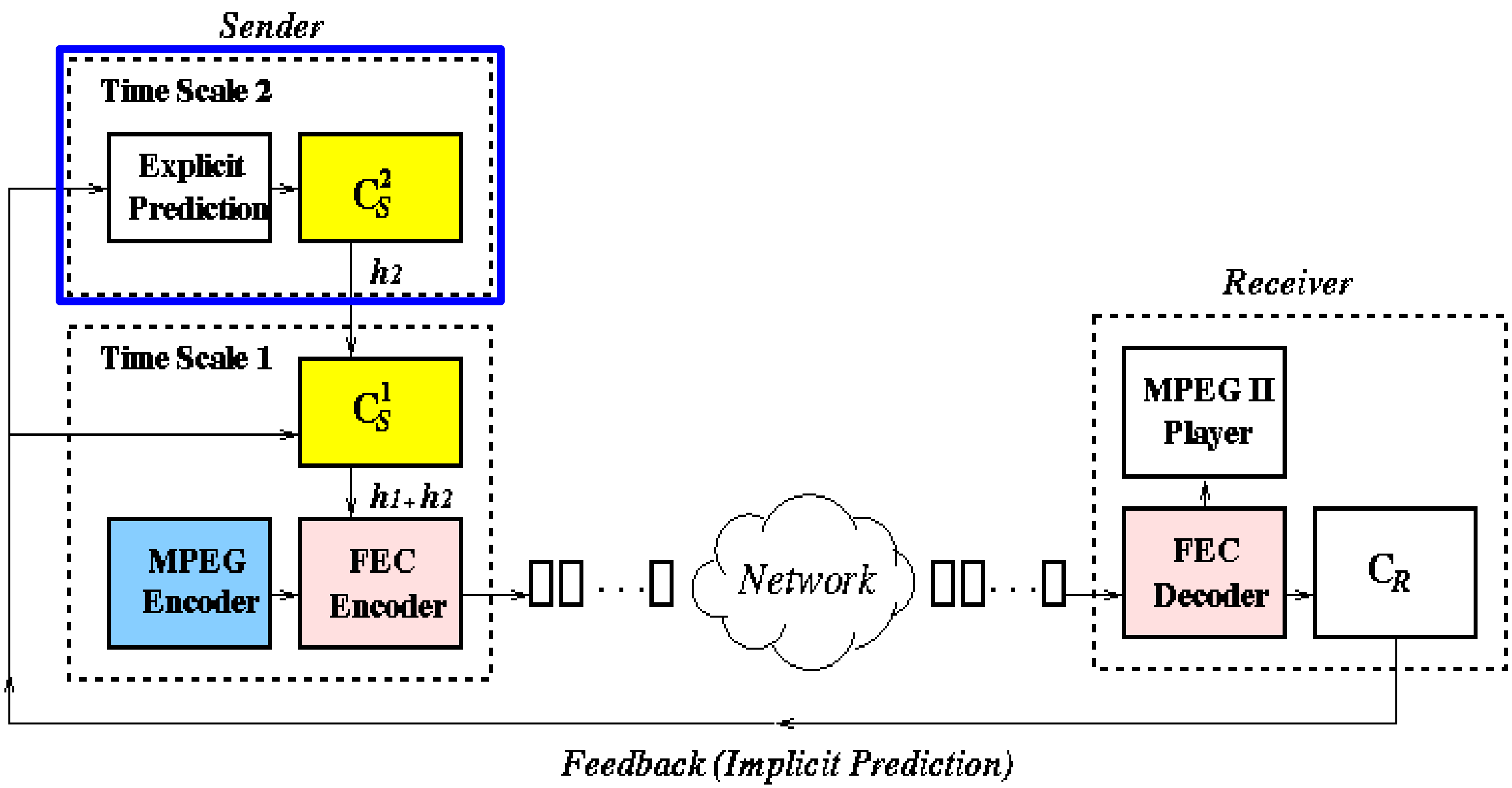
- Multiple time scale redundancy control



$\rightarrow$ level control

Adaptive Redundancy Control (cont.)

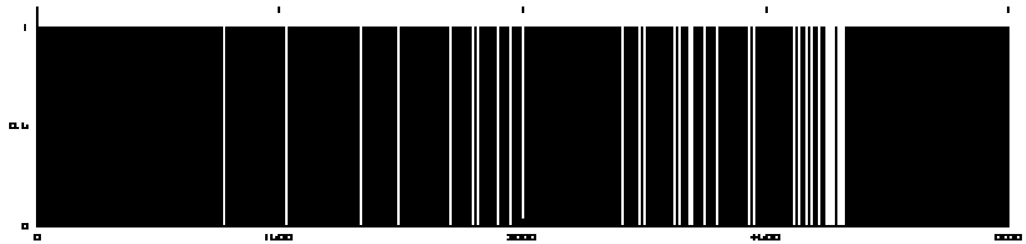
- AFEC-MT structure:



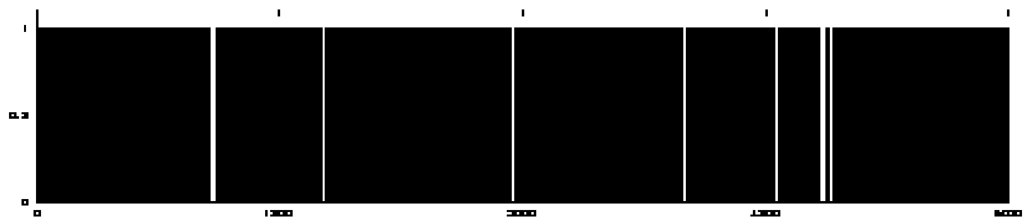
Adaptive Redundancy Control (cont.)

- AFEC-MT:

hit trace:



static FEC

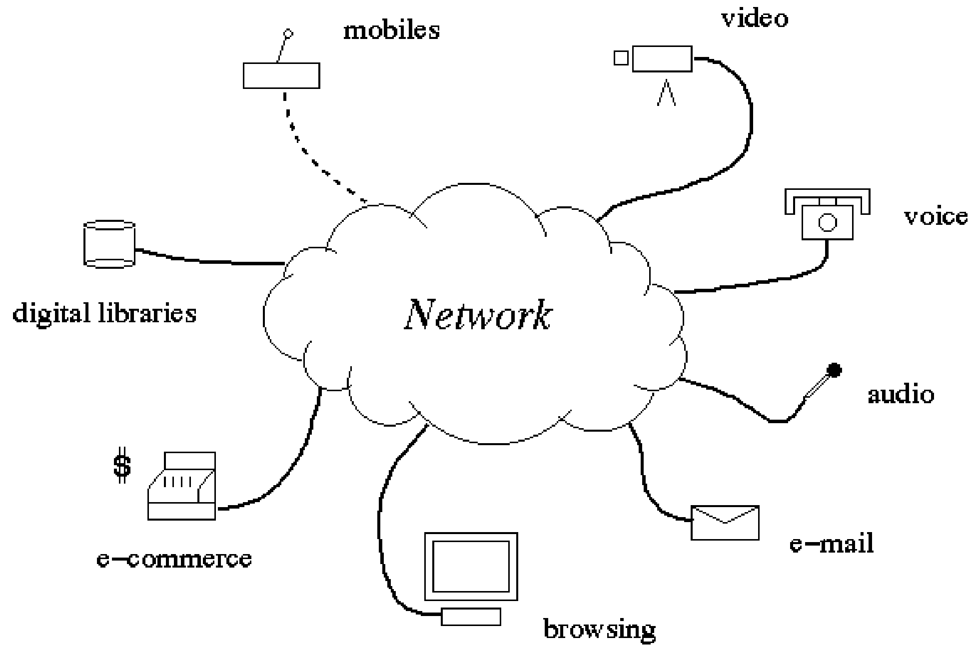


AFEC

AFEC-MT

Adaptive Label Control

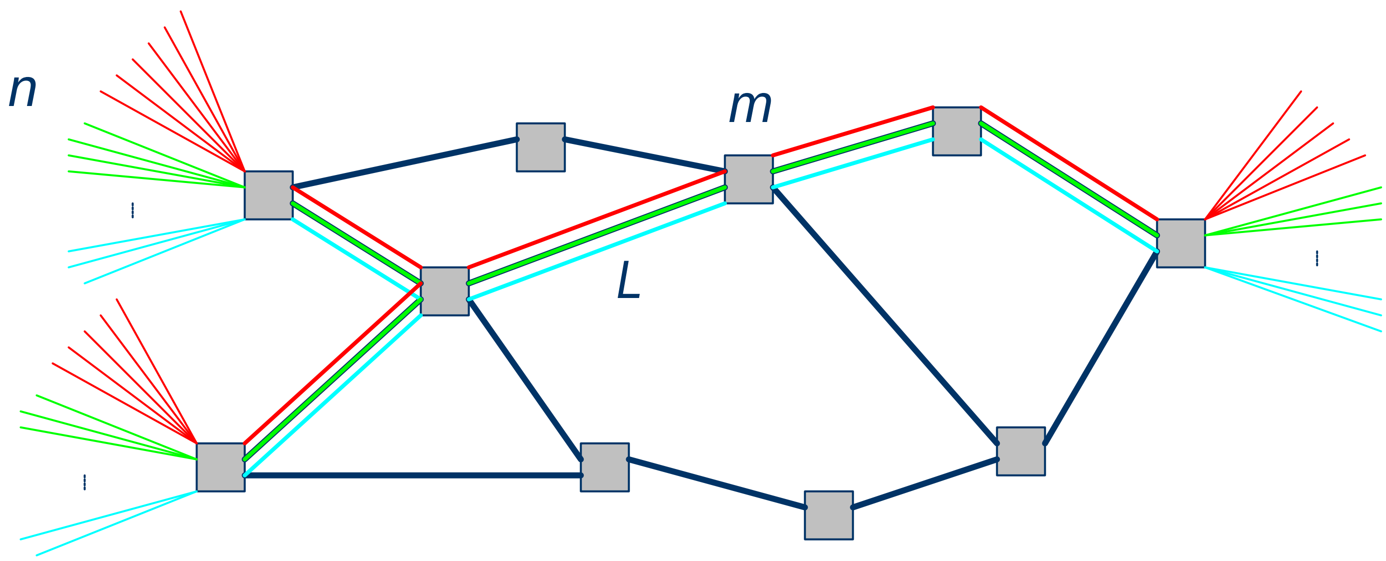
Motivation:



- diverse QoS requirements
- shared network environment

Adaptive Label Control (cont.)

Differentiated services network:

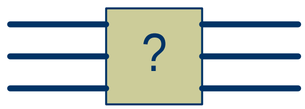


n users » *L* labels (colors) ≥ *m* classes

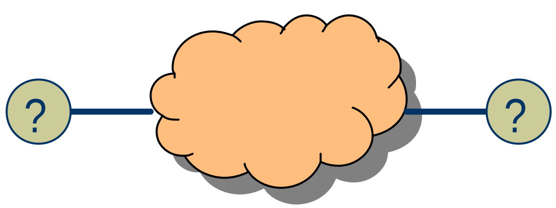
Adaptive Label Control (cont.)

Questions:

- What is a “good” (optimal) per-hop control?
  - → optimal aggregate-flow per-hop behavior

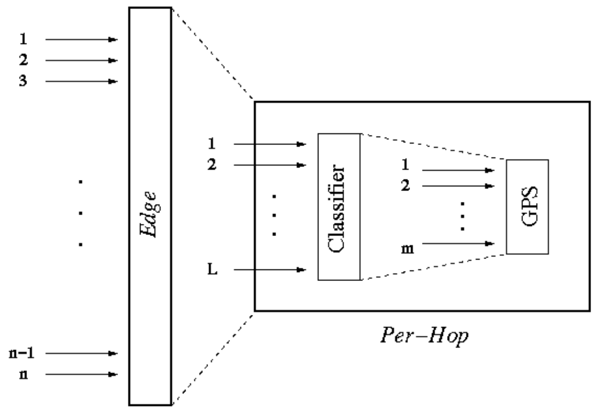


- What is a “good” (optimal) edge control?



Adaptive Label Control (cont.)

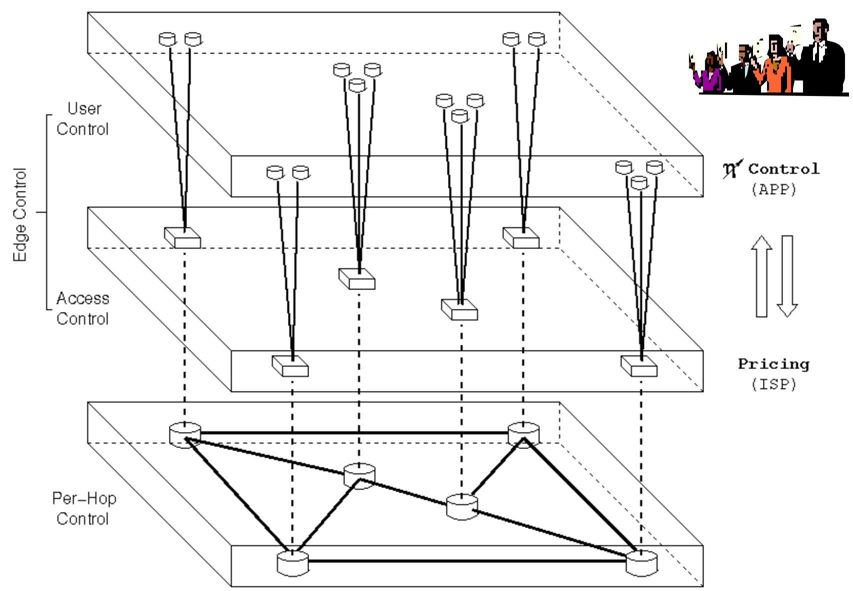
- What is the loss of power due to aggregation?
  - → $n \gg L \geq m$
  - → loss of resolution vis-à-vis per-flow switching



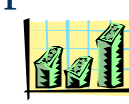
- What is the impact of finite, discrete label set $\{1, 2, \ldots, L\}$?
  - → $\eta \in \mathbf{Z}_+, \ \mathbf{R}_+, \ [0,1], \ \text{or } \mathbf{R}_+^S$

Adaptive Label Control (cont.)

- What is the system dynamics when driven by selfish users?
  - → end-to-end label control
  - → stability (Nash equilibria) and efficiency (system optimality)



pricing



- What is the impact of selfish service provider (ISP)?

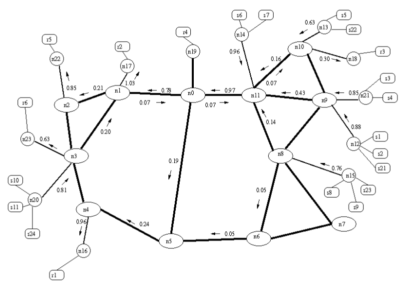
Adaptive Label Control (cont.)

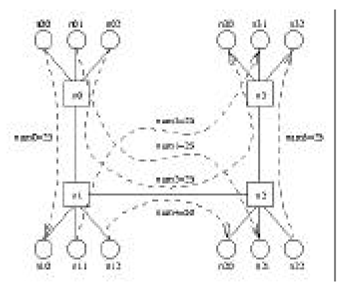
Theory

- optimal PHB
  - differentiation/shaping
  - efficiency
- adaptive label control
- selfish users
- selfish service provider
- performance analysis

Simulation

QSim: WAN QoS Simulator





Implementation

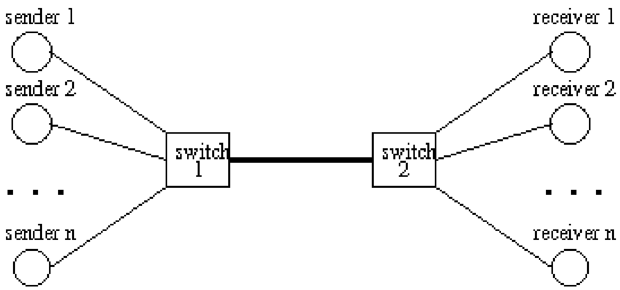
Purdue Infobahn

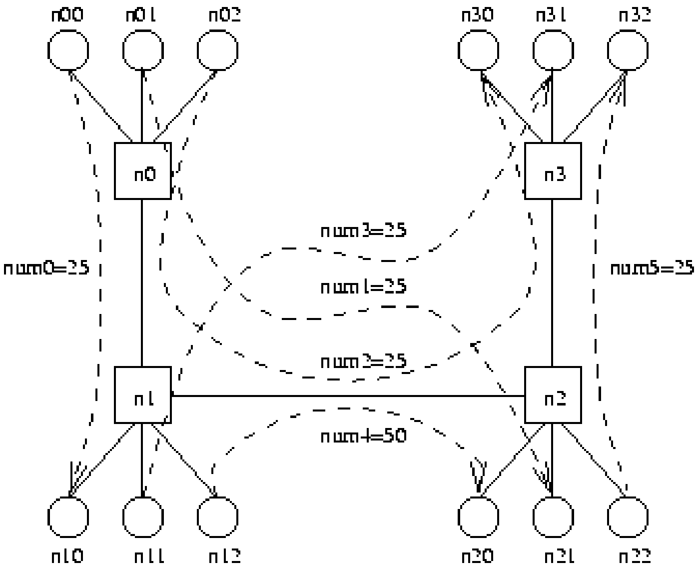
Cisco 7206 VXR IP-over-SONET QoS Testbed

Adaptive Label Control (cont.)

Performance Results

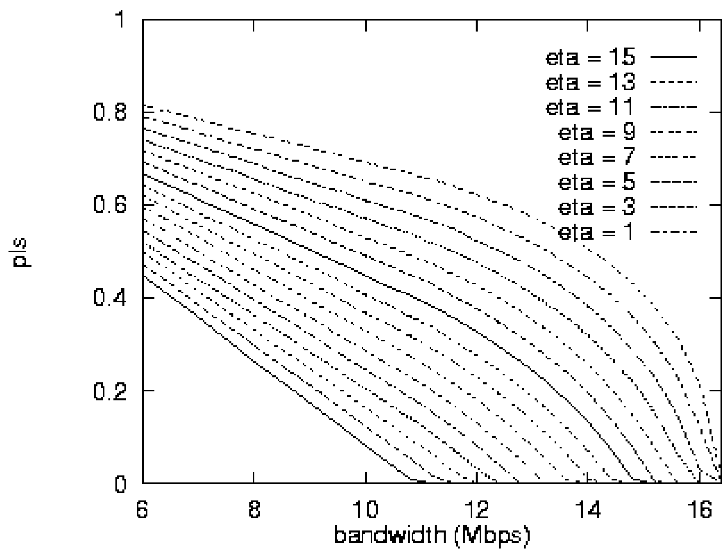
- QSim: *ns* based WAN QoS simulation environment

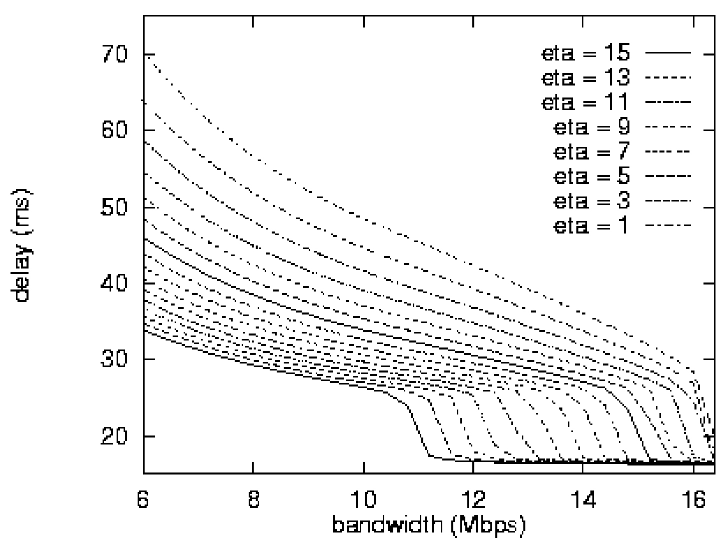




Adaptive Label Control (cont.)

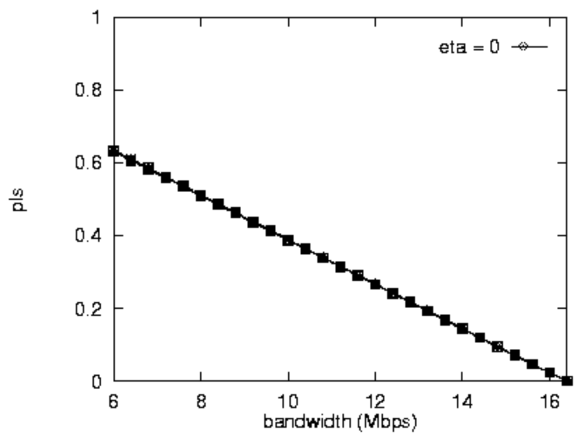
- Structural: bottleneck BW, L = 16 (m = 16)

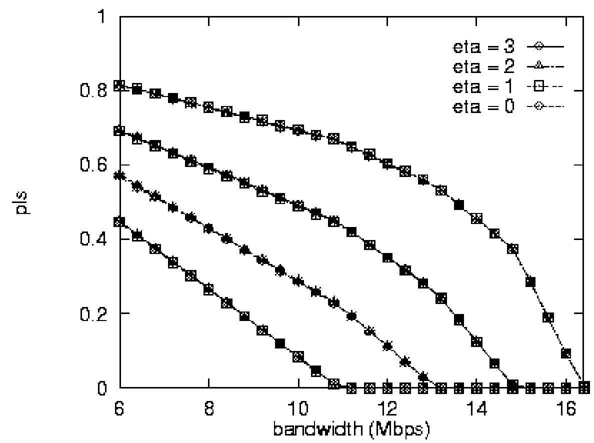


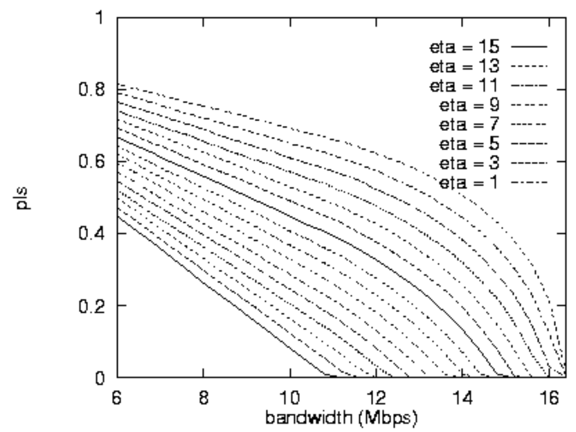


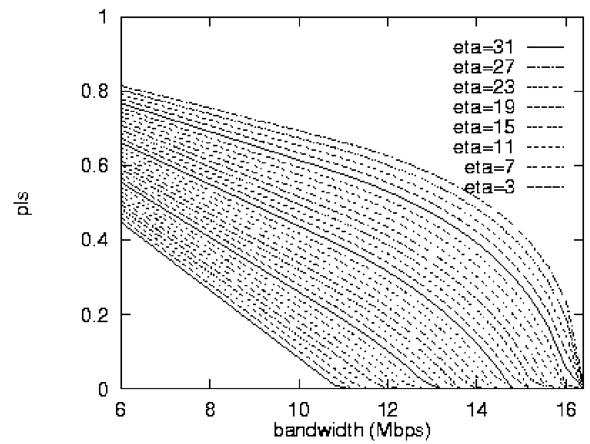
Adaptive Label Control (cont.)

- Structural: *L* = 1, 4, 16, 32



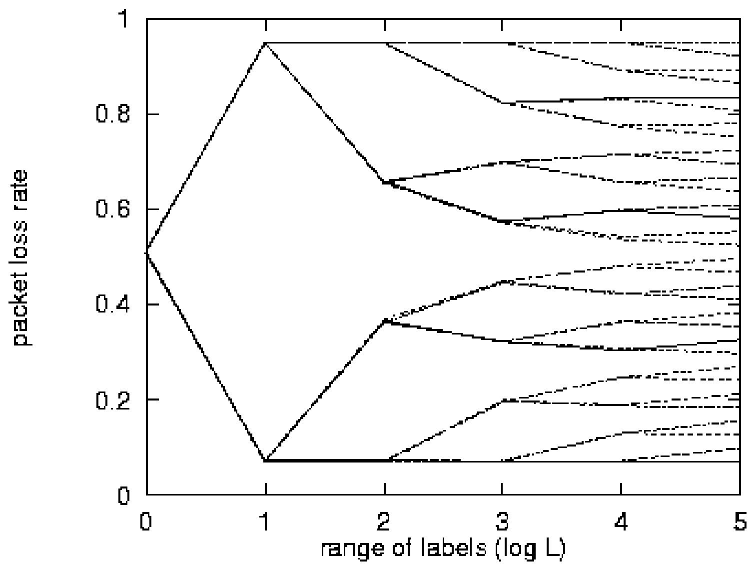


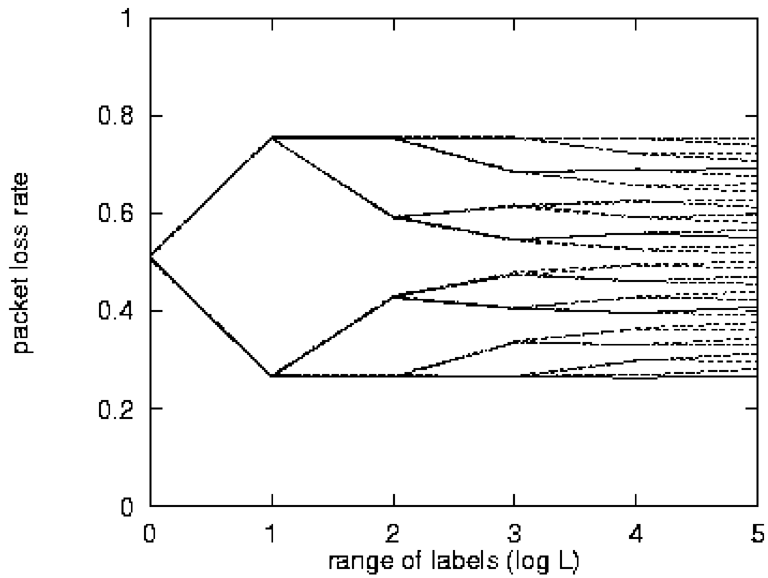




Adaptive Label Control (cont.)

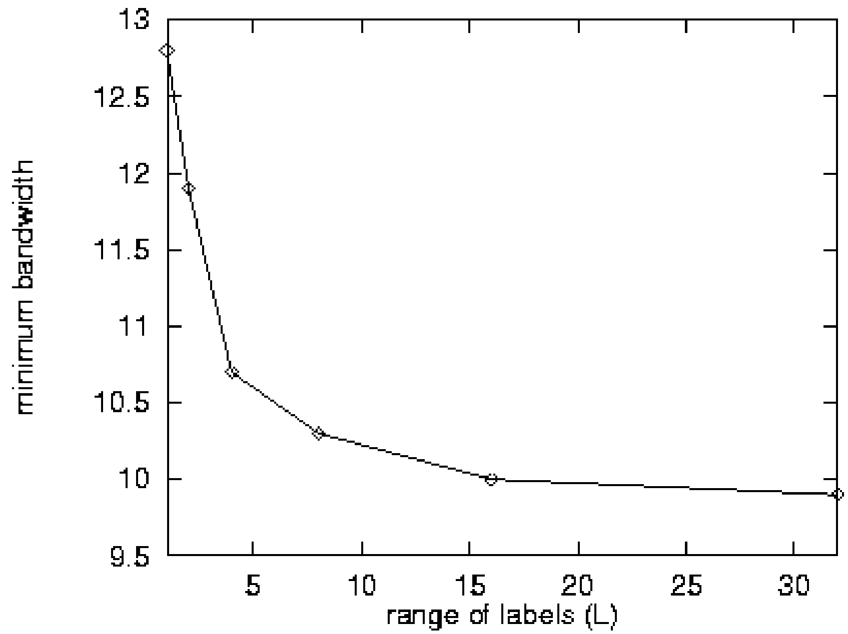
- Structural: log *L* = 0, 1, 2, 3, 4, 5 (bits)





Adaptive Label Control (cont.)

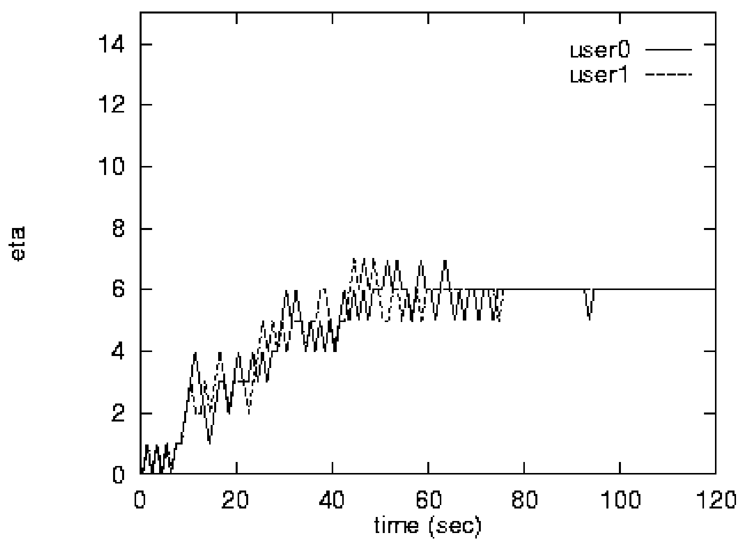
- Structural: system optimal BW requirement

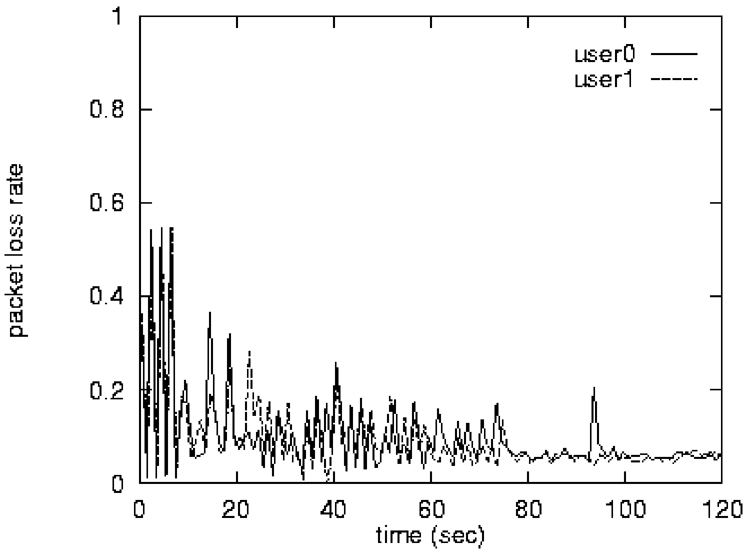


Adaptive Label Control (cont.)

- Dynamical: adaptive label control (*end-to-end*)

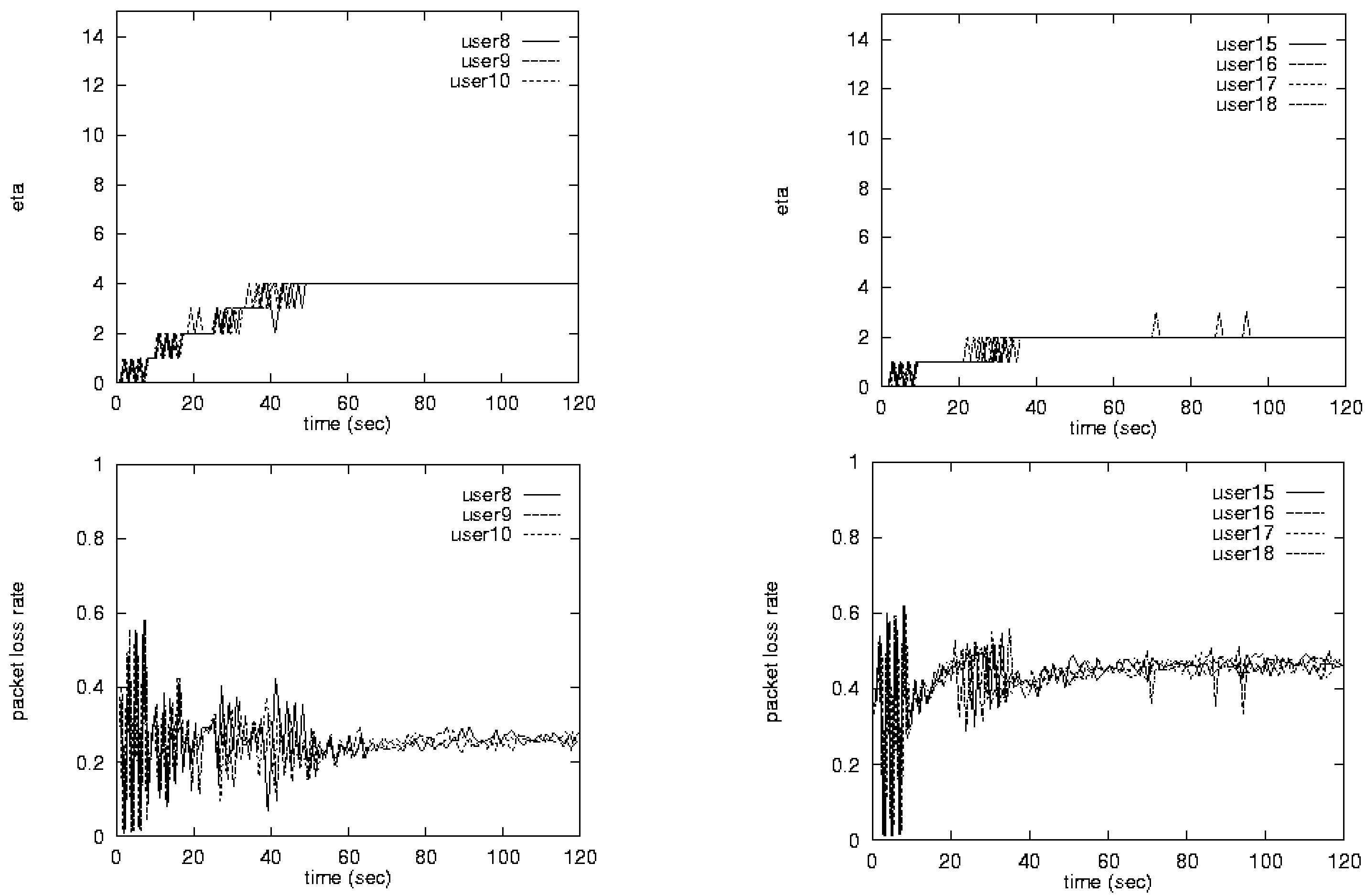
  → reachability





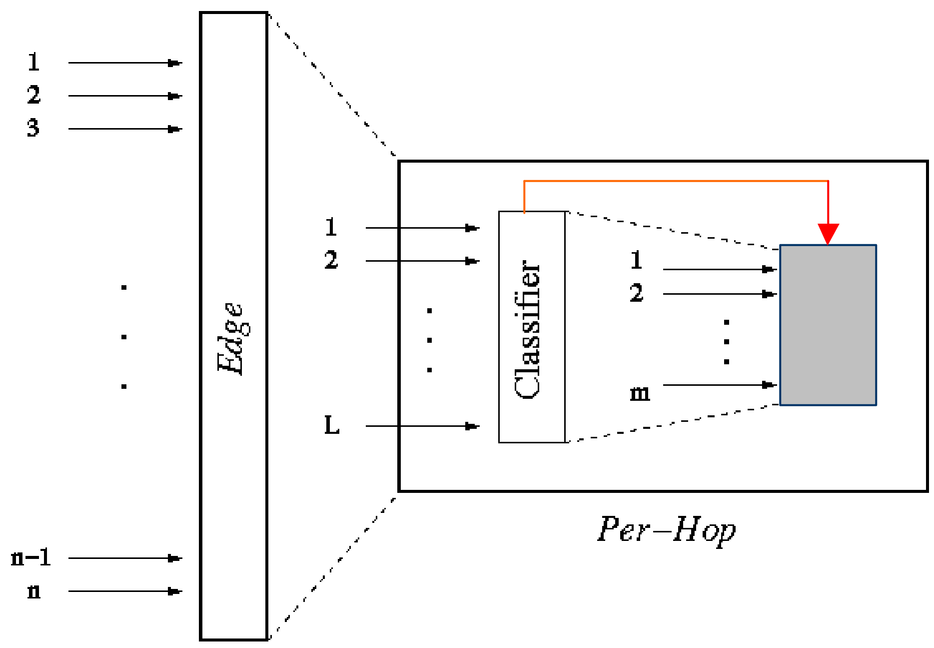
Adaptive Label Control (cont.)

- Dynamical: adaptive label control (cont.)



Adaptive Label Control (cont.)

Optimal aggregate-flow per-hop control:



$n \gg L \geq m$

→ *n* users, *L* labels, and *m* service classes

Adaptive Label Control (cont.)

- Of interest: $n \gg L \geq m$
- Special case: $n = m$
  - → per-flow per-hop control
- Of special interest: $L = m$
  - → as many service classes as label values

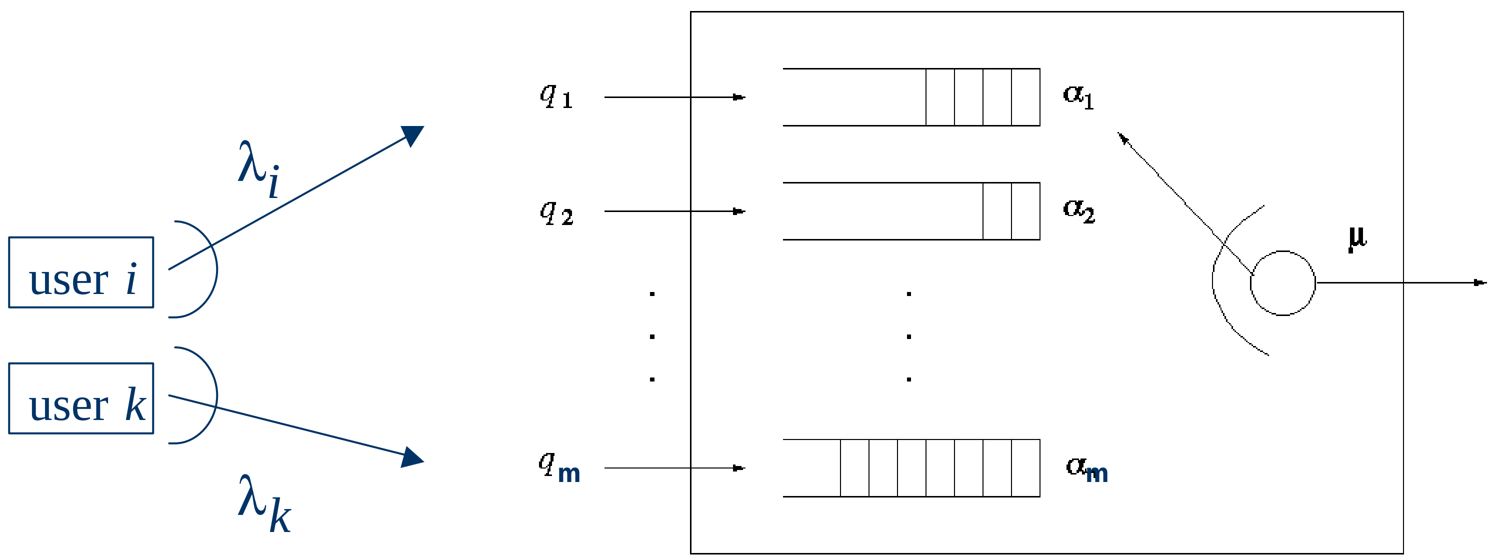
Optimality I: service differentiation/shaping

Adaptive Label Control (cont.)

- Per-flow Control ($n = m$):
  - Label value η viewed as "code" of user requirement
    - → e.g., 1.5 Mbps, relative share of link bandwidth, etc.
  - If infinite resources, then no interaction/coupling
    - → e.g., INDEX
  - In resource-bounded systems, $\exists$ coupling (externality)

Adaptive Label Control (cont.)

- Illustration of coupling in simple single switch case:



GPS switch

Adaptive Label Control (cont.)

- INDEX (Varaiya et al.)

Platinum Service	BW_1	$Price_1$
Gold Service	BW_2	$Price_2$
Silver Service	BW_3	$Price_3$
Bronze Service	BW_4	$Price_4$

→ service class: volume insensitive

→ infinite resoures

→ no *externality*

Adaptive Label Control (cont.)

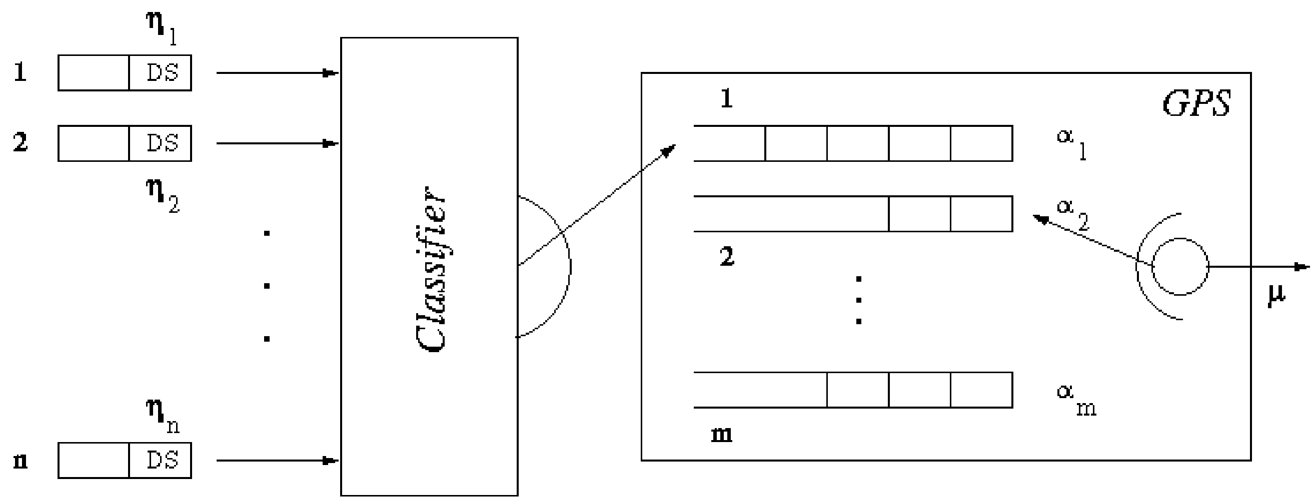
- Assume label set is metric space (totally ordered)
  - → e.g., Euclidean distance (L_2 norm)
  - → e.g., η = 1 < 2 < ... < L
- Mean square measure of goodness:

  Given η, find resource configuration v s.t.

$$\min_{v} \sum_{i=1}^{n} (h_i - v_i)^2$$

Adaptive Label Control (cont.)

- GPS: $\varpi_i = \alpha_i / \lambda^i$



$\eta_i \in \{1,2,\ldots,L\}; \quad \xi : \{1,\ldots,L\} \rightarrow \{1,\ldots,m\}$

Adaptive Label Control (cont.)

- Normalization: $$\frac{h_i - h_{\min}}{h_{\max} - h_{\min}} \in [0,1]$$

- Solution: $$a_i = (1-u)\frac{l^i h^i}{\sum_k l^k h^k} + u\frac{l^i}{\sum_k l^k}$$

Adaptive Label Control (cont.)

- Optimal aggregate-flow classifier:

  Given η, find resource configuration v s.t.

$$\min_{v} \sum_{i=1}^{n} (h_i - v_i)^2$$

- Optimal solution:

  Reduce to per-flow optimal solution

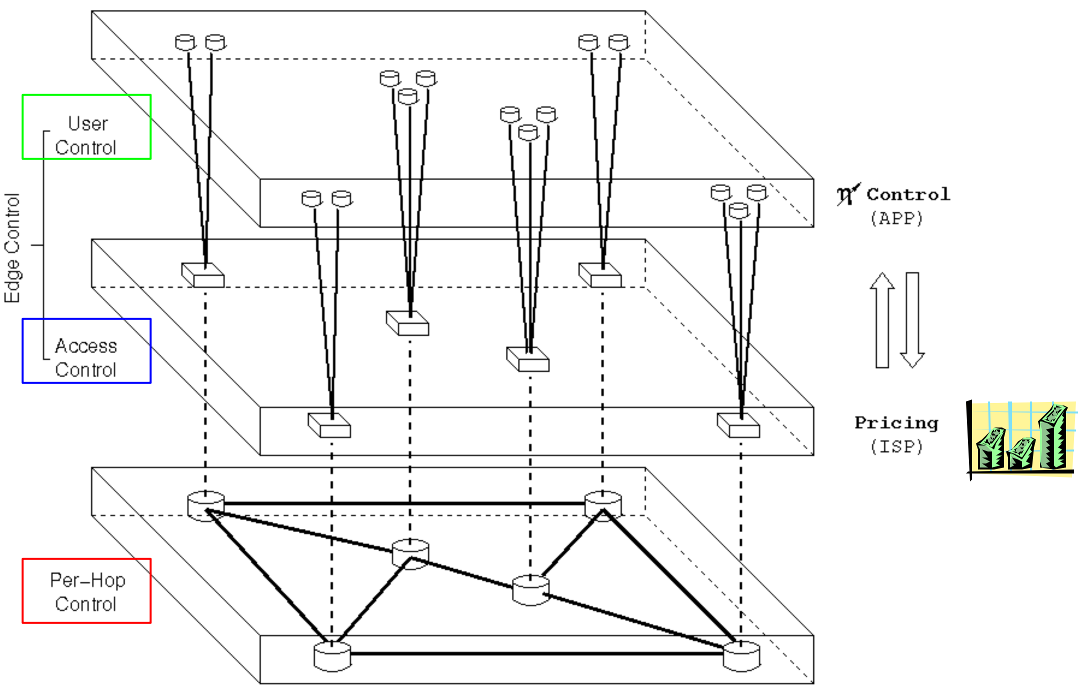
  $\rightarrow$ optimal clustering problem

Adaptive Label Control (cont.)

- Properties (A1), (A2), and (B)
  - (A1) If η_i increases, then QoS of user i improves
  - (A2) If η_i increases, then QoS of user j deproves
  - (B) If $\eta_i \geq \eta_j$ then QoS of user i is better than QoS of user j
- Optimal per-flow classifier satisfies (A1), (A2), (B)
- Optimal aggregate-flow classifier with $L = m$ satisfies (A1), (A2), (B)

Adaptive Label Control (cont.)

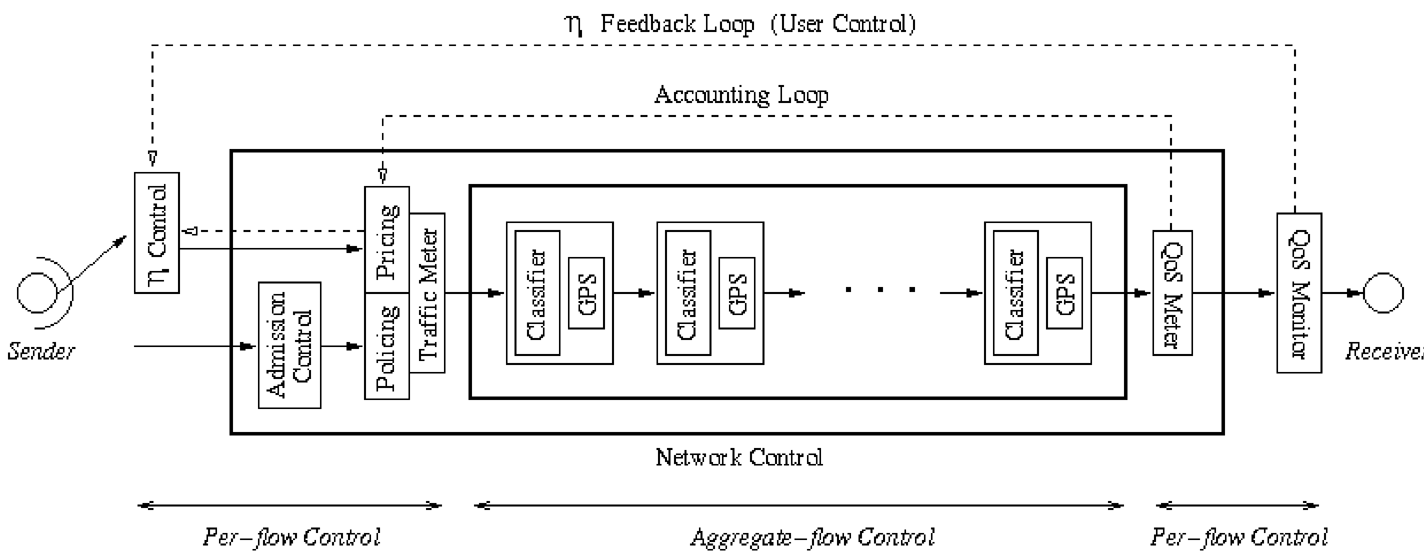
Overall Architecture



→ three control planes

Adaptive Label Control (cont.)

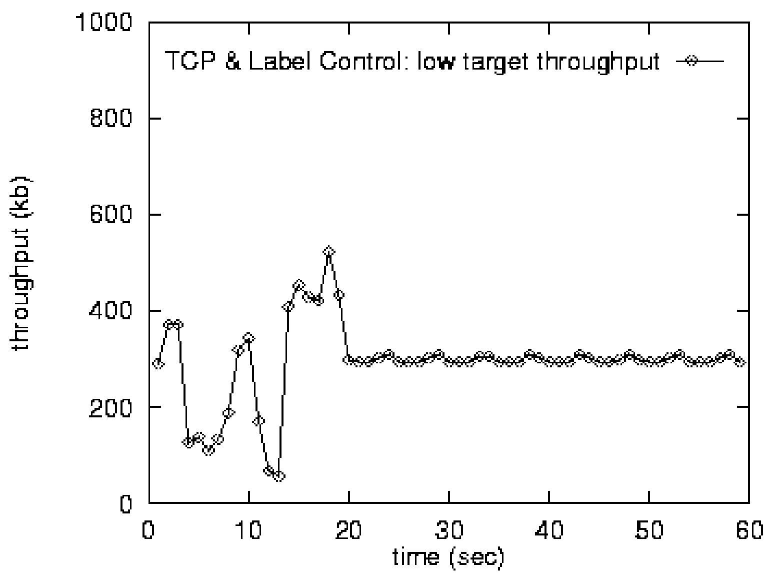
- End-to-end QoS control: *label control*

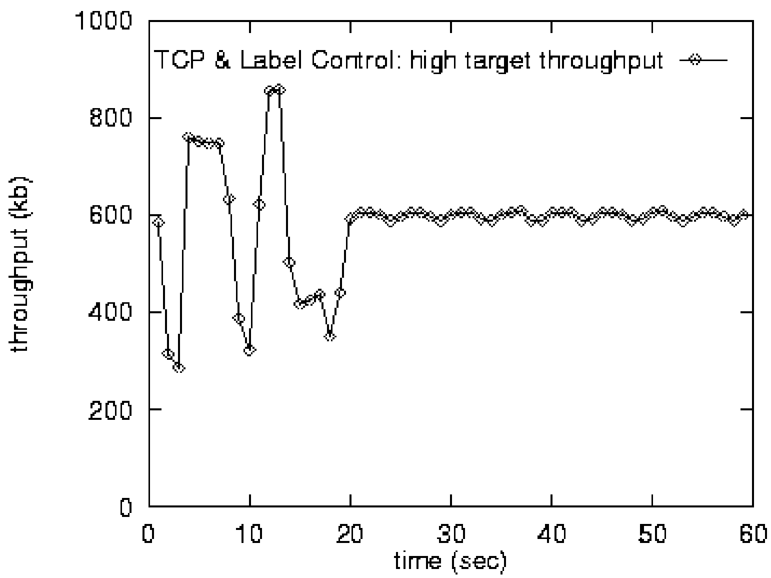


- open-loop
- closed-loop
  - → adaptive label control

Adaptive Label Control (cont.)

- Integrated QoS control:
  - e.g., TCP over adaptive label control





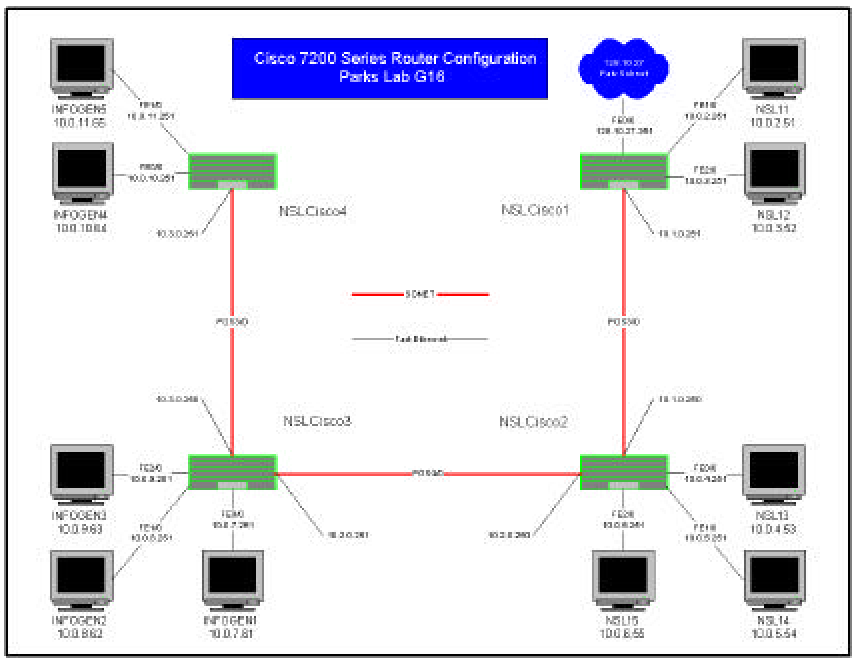
Adaptive Label Control (cont.)

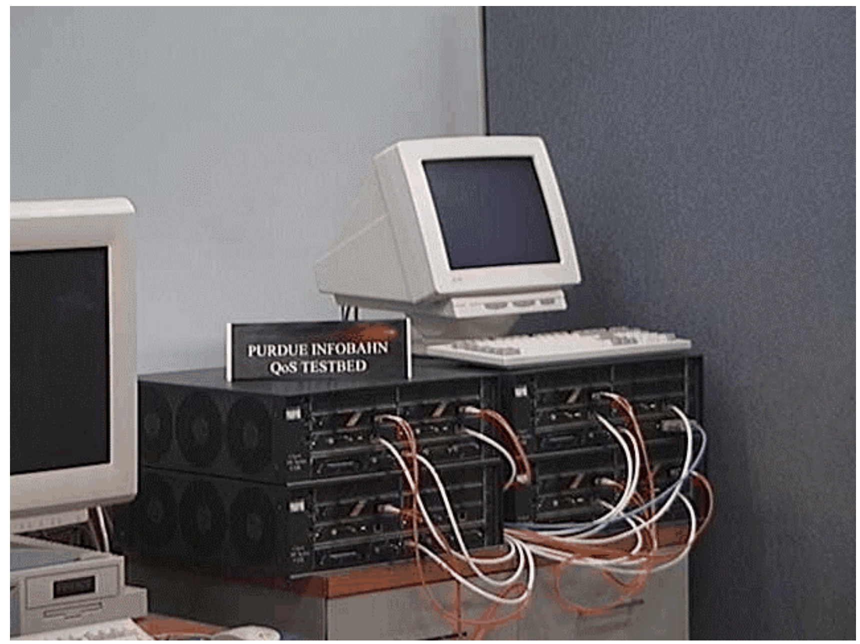
Benchmark Environment

- Purdue Infobahn QoS testbed: 4 Cisco 7206 VXR routers
  - → IP-over-SONET backbone
  - → custom classifier implementation in Cisco IOS (Fred Baker)
- NSF vBNS and Abilene connectivity (DS-3)
  - → Purdue vBNS/Internet2 Advisory Committee
  - → Internet2 collaboration
- Fore ATM, FastEthernet switches

Adaptive Label Control (cont.)

Purdue Infobahn





Adaptive Label Control (cont.)

- Real-time MPEG I & II video/audio compression engines
  - → Optibase, Futuretel (Windows NT)
- Video/audio capture equipment
- 35+ Sun/Intel/SGI workstations & PCs
- Prototype software systems: UNIX, Windows NT

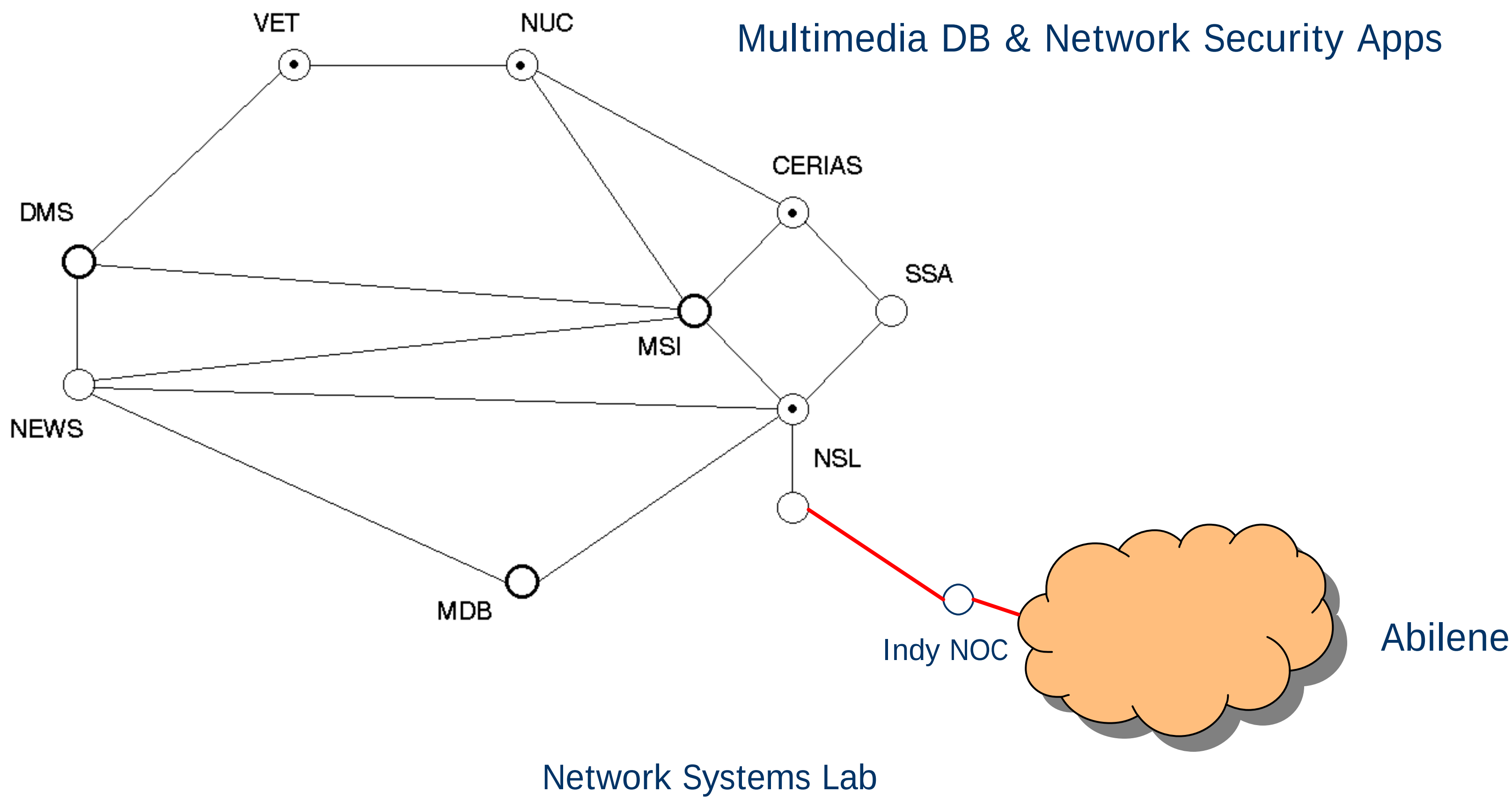
Adaptive Label Control (cont.)

Performance Evaluation and Benchmarking

- Internet2 benchmarking of
  - Multiple time scale traffic control (TCP-MT, AFEC-MT)
  - Adaptive redundancy control (AFEC)
  - Adaptive label control (Diff-Serv router support)
    - → vBNS/Abilene
- Commodity Internet benchmarking
- Evaluate effectiveness of end-to-end QoS amplification
    - → model of future Internet (NGI)

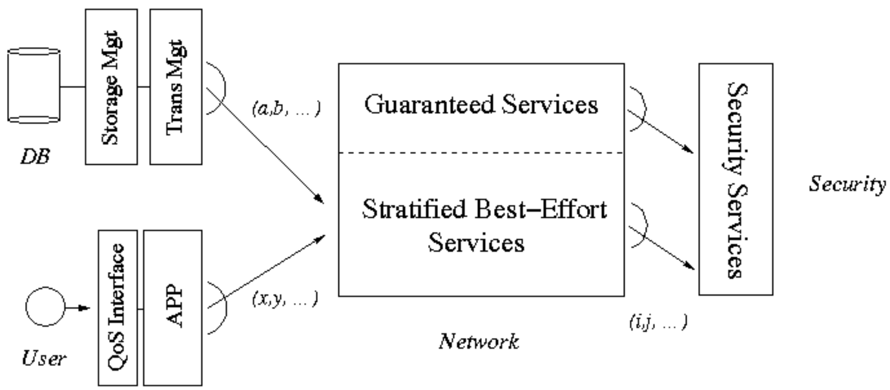
Adaptive Label Control (cont.)

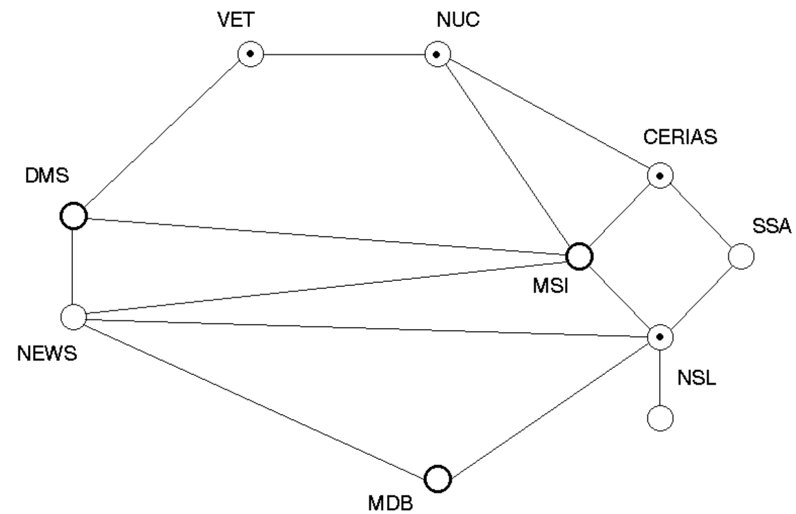
- Integration with Purdue Infobahn & QoS peering



Adaptive Label Control (cont.)

- Application Benchmarking:





Collaborations

- Academic:
  - Boston Univ. (A. Bestavros)
  - Ohio State Univ. (J. Hou)
  - Santa Fe Institute (Fellow-at-Large)
  - Univ. of Wisconsin (P. Barford; WAWM)
  - Seoul National Univ. (S. Bahk)
- Industry/Research Labs:
  - AT&T Research (W. Willinger)
  - Cisco (F. Baker)
  - Sprint (K. Metzger)

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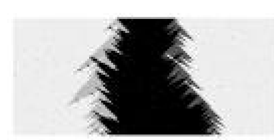
  - Santa Fe Institute
  - Sprint
  - CERIAS, SERC
- Research assistants & postdocs:
  - RAs: A. Balakrishnan, S. Chen, J. Cruz, G. Nalawade, H. Ren, M. Tripunitara, T. Tuan, W. Wang
  - Postdocs/visting scientists: S. Bahk, H. Lee, J. Park

- Network Systems Lab
  - **http://www.cs.purdue.edu/nsl**



Acknowledgments & More Info (cont.)

- Related publications:

  - Chen & Park. An architecture for noncooperative QoS provision in many-switch systems. In *Proc. IEEE INFOCOM*, 1999.
  - Cruz & Park. Towards performance-driven system support for distributed computing in clustered environments. *Journal of Parallel and Distributed Computing*, 1999.
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  - Tuan & Park. Multiple time scale congestion control for self-similar network traffic. *Performance Evaluation*, 1999.
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