

**Networks Group**

Department of Computer Science  
University of Cyprus

# **Congestion control in IP networks using Fuzzy Logic control**

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<http://www.cs.ucy.ac.cy/networksgroup>

# PRESENTATION OVERVIEW

- Networks Group at UCY
- Congestion Control challenge
- Diff-Serv Congestion Control – AQM mechanisms
- Fuzzy Logic based AQM (FEM, FIO)
- Evaluation - Simulation Results
- Conclusions – Future Work

# A recent remark

**‘Networks are very complex.  
Do not kid yourselves  
otherwise.’**

Debasis Mitra Senior VP Research,  
Bell Labs Panel discussion at Infocom  
2001 (Organiser: Ariel Orda) on Modelling  
of the Shrew (beast): Quest for a ‘Model’  
Network Model

# Networks Group at UCY: People

- **People involved in Networks Group:**

- **Staff:** Andreas Pitsillides (Head), Vasos Vassiliou,
- **Networks Group Researchers:**
  - PhD candidates: Chrysostomos Chrysostomou, Yiannos Mylonas, George Hadjipollas, Pavlos Antoniou, Josephine Antoniou,
  - Master's candidates: Marinos Stylianos, Christoforos Christoforou, Michalis Neophytou, Antonis Antoniou, Haralambos Segiou, Eliana Stavrou, Panayiotis Andreou
- **Internal Collaborators:** Christos Panayiotou (ECE), Marios Polycarpou (ECE)
- **External Collaborators:** Prof. Petros Ioannou (USC), Marios Lestas (USC), Dr. Ahmet Sekercioglou (Monash), Partners in SEACORN & B-BONE IST projects (PTIN, ADETTI, UT, IST, WMC, AUEB, AUTH, Motorola, Alcatel, Ericsson)

# Networks Group at UCY: Resources

- European Commission and locally **funded projects**
  - B-BONE, C-MOBILE, MOTIVE, VIDEO, AD-VIDEO, DITIS, etc... (external funding of over 2 million Euros, during the past 3 years)
- Research Lab
  - **Simulation tools**
    - OPNET (60 licences)
    - Ns-2
    - UMTS simulators based on Ns-2 and OPNET developed as part of the European Commission funded projects SEACORN, B-BONE and C-MOBILE (budget over 4 mil.Euro)
  - CISCO and LINUX based testbed
    - Testbeds – Pilot networks
      - using 'home' build LINUX based routers and gateways
        - under the supervision of projects that are part of the MSc Networking course, MSc thesis, etc

# Congestion control issues

- **Congestion/overload control** still **critical issue**, even for Internet
  - Despite literally hundreds of proposed possible, and probably good, solutions addressing diverse needs of today's Internet
  - But, difficulty in changing deployed protocols, together with 'robust' behaviour of ubiquitous Jacobson TCP congestion control, are resisting the introduction of new algorithms
- **However**, the congestion control/overload problem will **not be easily resolved**,
  - at the moment only congestion control for TCP traffic
    - UDP, and other newer protocols are not 'covered'
  - pressure from different architectures and topologies where Jacobson TCP congestion control is ineffective
    - Intserv and Diff-Serv architectures
    - Mobile and Wireless Networks,
      - e.g. in WLANs cross layer issues with MAC backoff mechanism
    - Ad-hoc and sensor topologies,
      - e.g. controlling overload conditions by limiting input (not always desirable or feasible), routing changes, assisted by cross layer feedback (MAC, modulation, Power)

# Congestion Control using Control Theoretic Techniques

- Our research aims to:
  - address **key issues** at a **generic level** and
  - **apply** such theoretical results in the development of efficient and effective control techniques.
  - We aim to show the **effectiveness of formal control theory** in **delivering efficient solutions in complex networks**, e.g the Internet and newer architectures and topologies.
  - Research issues under consideration include
    - **Adaptive Non-linear Control** (with University of Southern California)
      - Integrated Dynamic Congestion Controller (IDCC) for a Differentiated-Services Framework
    - **Proven Global Asymptotic Stability** of a Max-Min Congestion Control Scheme for arbitrary topologies
    - **Adaptive Congestion Protocol (ACP)**
      - Max-Min Congestion Control Scheme with Learning Capability.
    - **Fuzzy Logic Control** (with Monash University, Melbourne Australia and ECE dept., UCY) :
      - Congestion Control in TCP/IP Best-Effort and Differentiated Services Networks

# FUZZY LOGIC BASED CONGESTION CONTROL

- Fuzzy Logic Control has been applied successfully for controlling systems
  - in which analytical models are not easily obtainable
  - or the model itself, if available, is too complex and possibly highly non-linear.
- Application of fuzzy control techniques to problem of congestion control in networks is appealing
  - due to difficulties in obtaining a precise mathematical model using conventional analytical methods,
  - while some intuitive understanding of congestion control is available.

# FUZZY LOGIC CONTROL for Diff-Serv

- Adopting Active Queue Management (AQM)
  - **Fuzzy Explicit Marking (FEM) In/Out (FIO)** proposed for Diff-Serv architecture
    - fuzzy logic control approach
    - supports explicit congestion notification (ECN)
    - implemented within
      - a Best Effort environment and
    - **extended** to handle classes of service:
      - high low priority/best-effort (assigned as Out of profile)
      - priority/assured (assigned as In profile)
- in a differentiated services environment (Diff-Serv)

# FUZZY LOGIC BASED CONGESTION CONTROL (cnt'd)

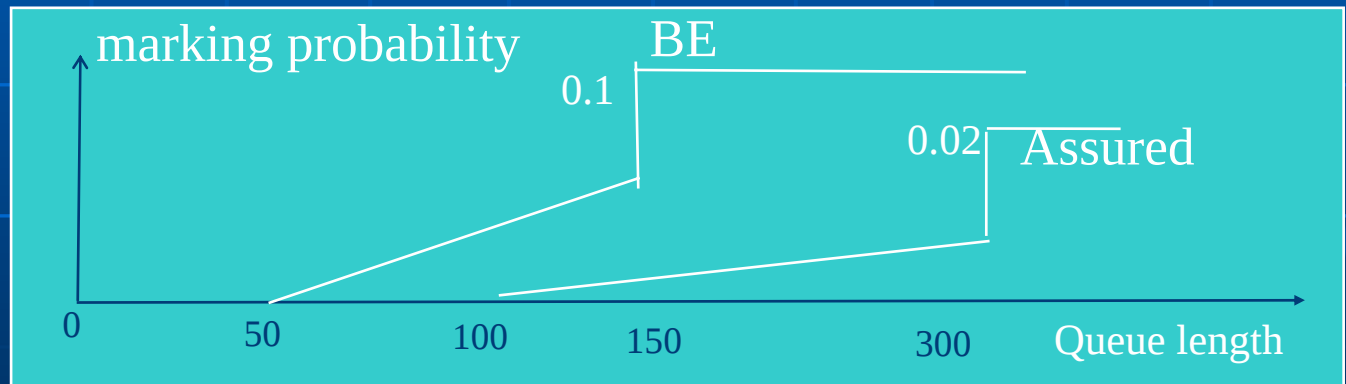
- The proposed fuzzy logic approach
  - allows the use of linguistic knowledge to capture the dynamics of non-linear probability marking functions
  - uses multiple inputs to capture the dynamic state of the network more accurately.
  - Located at the Core Network nodes
  - a simple to implement approach is adopted to investigate the potential

# FUZZY LOGIC BASED CONGESTION CONTROL (cnt'd)

- Proposed fuzzy control system designed to
  - regulate queues of IP routers at predefined levels
    - by achieving a specified target queue length (TQL)
    - to maintain both high utilization, low loss, and low mean delay.
- A Fuzzy Inference Engine (FIE) designed to operate on router buffer queues
  - uses linguistic rules to *mark* packets in TCP/IP networks.
- Rule selection and tuning are done by experimentation

# Diff-Serv RED LIKE AQM CONGESTION CONTROL

- Diff-Serv architecture proposed
  - to deliver (aggregated) QoS in IP networks.
- Red In/Out (RIO): Diff-Serv congestion control
  - most popular implementation based on RED:
    - preferentially drop/mark non-contract conforming (Out) against conforming (In) packets



- properties of RED and its variants extensively studied in past years
  - Many issues of concern were raised

# Diff-Serv FIO CONGESTION CONTROL

- A. two-class FEM controller, **FEM In/Out (FIO)**, is proposed.
  - provides **effective differentiation (and aggregated QoS)** to Assured and Best-effort classes of service, whilst maintaining high utilization
  - Extensive **simulation study** (multiple bottleneck links and traffic conditions) demonstrate FIO approach outperforms RED implementation for Diff-Serv (RIO) in terms of
    - Dynamic response, link utilization, packet losses, and queue fluctuations and delays.

# FUZZY LOGIC BASED AQM (cnt'd)

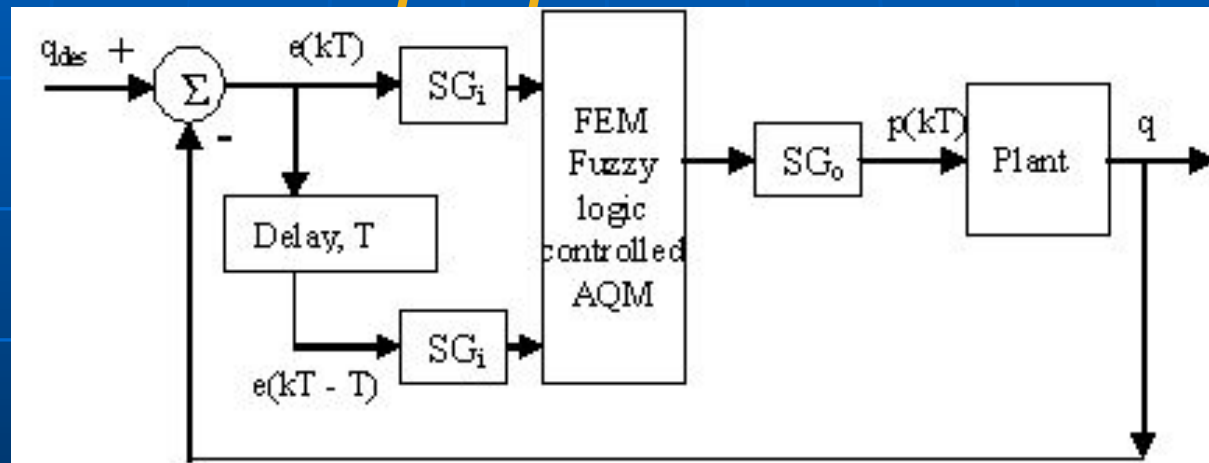
- In a Diff-Serv framework, a **two-class Fuzzy Explicit Marking controller** is designed to operate on the core routers' buffer queues, called **FEM In/Out (FIO)**.
  - two identical FEM controllers are used
    - one for each differentiated class of service (high priority/assured and low-priority/best-effort)
  - **two different TQLs on the total queue length** are introduced, one for each FEM controller.

# FUZZY LOGIC BASED AQM (cnt'd)

## ■ System model of FEM

The FIE dynamically calculates the **mark probability** behavior based on two network-queue state inputs:

- **the error on the queue length** for **two consecutive sample periods**



- **$e(kT)$**  =  $q_{des} - q$
- **$SG_i$**  &  **$SG_o$**  are scaling gains (the maximum values of the universe of discourse of the FIE input and output variables, respectively)
- **$p(kT)$**  is the packet mark probability

# FUZZY LOGIC BASED AQM (cnt'd)

## ■ System model of FEM

- The multi-input FIE uses **linguistic rules** to calculate the *mark* prob.

TABLE I  
LINGUISTIC RULES – RULE BASE

| $p(kT)$ | $Q_{des}(kT - T)$ |    |    |    |    |    |     |
|---------|-------------------|----|----|----|----|----|-----|
|         | NVB               | NB | NS | Z  | PS | PB | PVB |
| NVB     | H                 | H  | H  | H  | H  | H  | H   |
| NB      | B                 | B  | B  | VB | VB | H  | H   |
| NS      | T                 | VS | S  | S  | B  | VB | VB  |
| Z       | Z                 | Z  | Z  | T  | VS | S  | B   |
| PS      | Z                 | Z  | Z  | Z  | T  | T  | VS  |
| PB      | Z                 | Z  | Z  | Z  | Z  | Z  | T   |
| PVB     | Z                 | Z  | Z  | Z  | Z  | Z  | Z   |

$Q_{des}-Q$

### ■ Example:

- IF  $e(kT)$  is NVB AND  $e(kT - T)$  is NB, THEN  $p(kT)$  is H
- IF  $e(kT)$  is PVB AND  $e(kT - T)$  is PB, THEN  $p(kT)$  is Z
- *mark* probability calculated using richer system dynamics than classical RED approach.
- 49 fuzzy rules

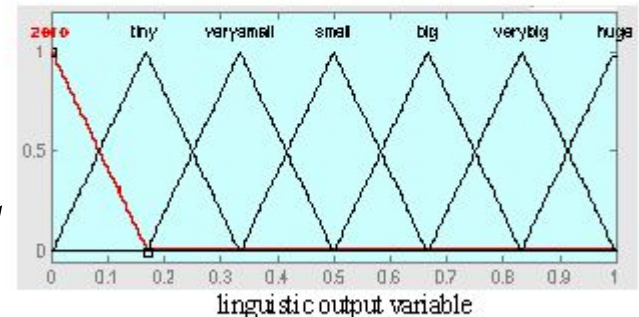
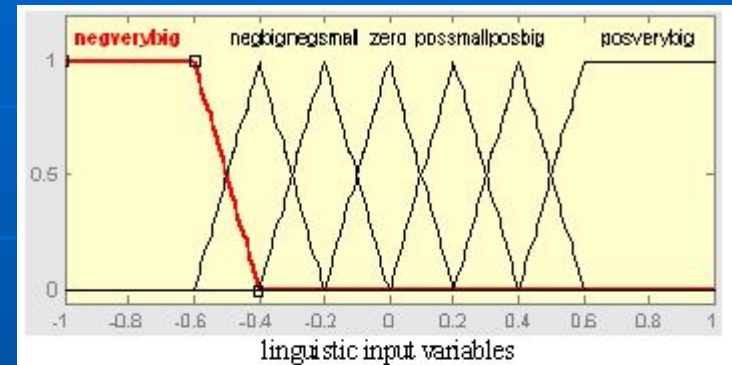
# FUZZY LOGIC BASED AQM (cnt'd)

## ■ System model of FEM

- Design of a **Rule Base**:

- First, the **linguistic rules** are set (surface structure)
- Afterwards, **membership functions of the linguistic values** are determined (deep structure)

For computational simplicity triangular and trapezoidal shaped functions were selected

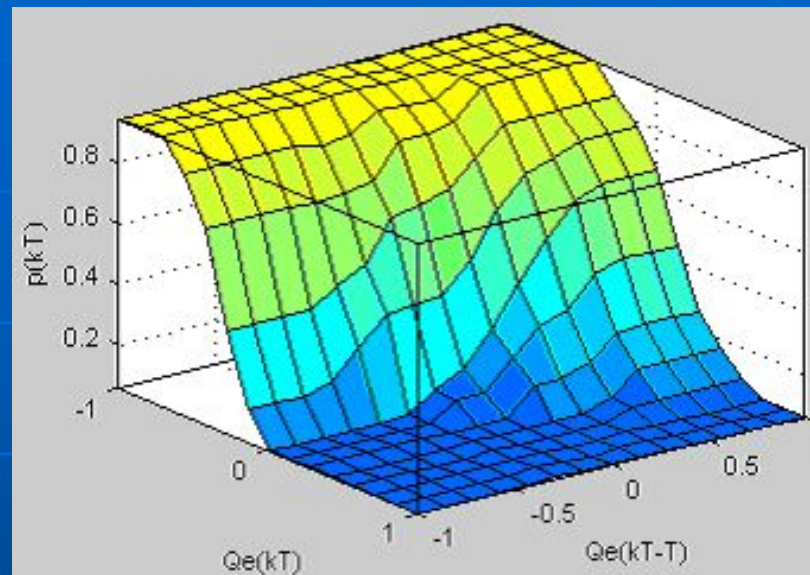


Membership functions of the linguistic values representing the input variables "normalized error on queue length for two consecutive sample periods", and the output variable "mark probability".

# FUZZY LOGIC BASED AQM (cnt'd)

## ■ System model of FEM

- **Decision surface** of the FIE
  - The control surface is shaped by the **rule base** and the **linguistic values of the linguistic variables**



- An inspection of the decision surface and the linguistic rules provides hints on the operation of FEM:
  - The *mark* probability behavior under the region of equilibrium (where the error on the queue length is close to zero) is smoothly calculated.
  - On the other hand, the rules are aggressive about increasing the probability of packet *marking* sharply in the region beyond the equilibrium point.

# FUZZY LOGIC BASED AQM (cnt'd)

- Two different TQLs introduced, one for each FEM controller.
  - The TQL for best-effort is lower than TQL for assured traffic.
    - Best-effort packets are more likely to be *marked* than the assured ones, in the presence of congestion.
- **Objective:** regulate queue, if possible, to lower TQL, in order to get a *mark* probability for assured traffic close to zero.
  - for large amount of assured traffic, compared with best-effort, queue can be regulated at higher TQL, where *mark* probability for best-effort traffic would be  $\sim 1$ .
  - Therefore, can accomplish bounded delay, by regulating queue between two TQLs, depending on dynamic network traffic conditions.
- FIO can achieve an **adequate differentiation** between the two classes of service in presence of congestion,
  - it provides aggregated **quality of service**
    - by preferentially *marking* the lowest-priority best-effort packets,
    - giving priority/preference to assured-tagged traffic,
    - while controlling queue at predefined levels.

# SIMULATIVE EVALUATION

- We evaluate the performance and robustness of the proposed fuzzy logic based schemes, **FEM** and **FIO**, in a wide range of environments.
- The **performance-QoS metrics** used to compare the AQM schemes are:
  - Throughput/Utilization of the bottleneck links
  - Loss rate
  - Mean queuing delay and its standard deviation

# SIMULATIVE EVALUATION (cnt'd)

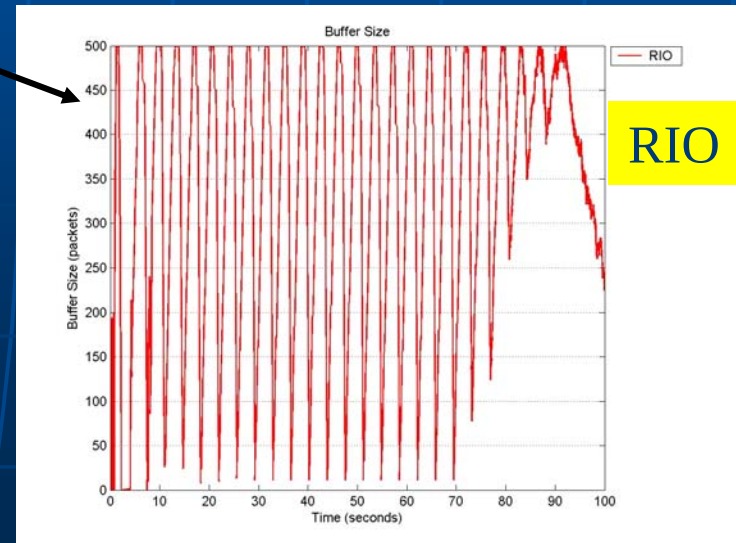
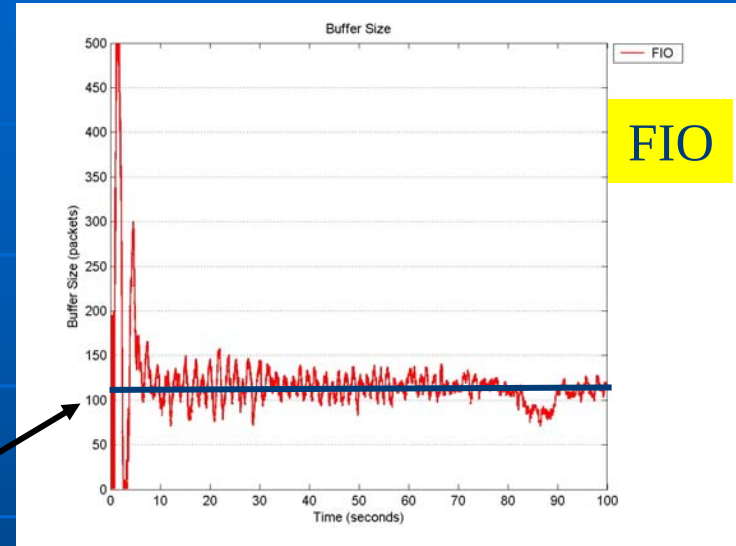
- The **comparison** is made with other published results by taking RIO, the RED variant to Diff-Serv AQM scheme, using **NS-2 simulator**.
- FIO controllers are shown to exhibit many desirable properties, like
  - fast system response,
  - behave better than other AQM schemes under comparison
    - in terms of
      - queue fluctuations and delays,
      - packet losses
      - link utilization
  - cope with high traffic variability and uncertainty in network
  - **achieve** an **adequate differentiation** between the two classes of service.

# SIMULATION RESULTS: single bottleneck links

## ■ network topologies with single bottleneck links: TCP/IP Diff-Serv network

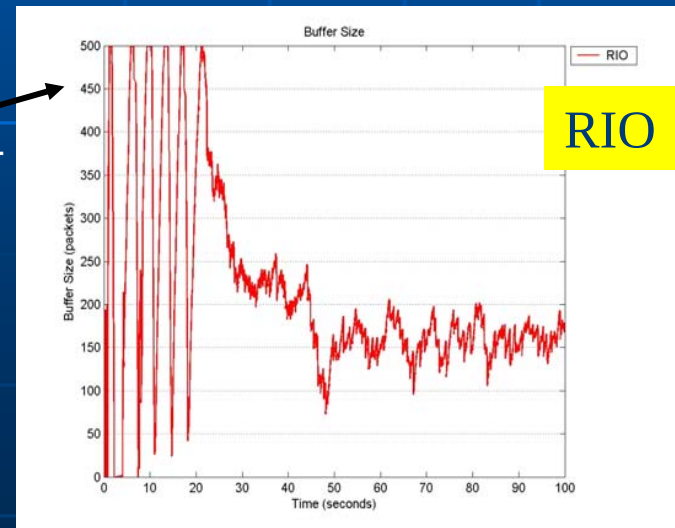
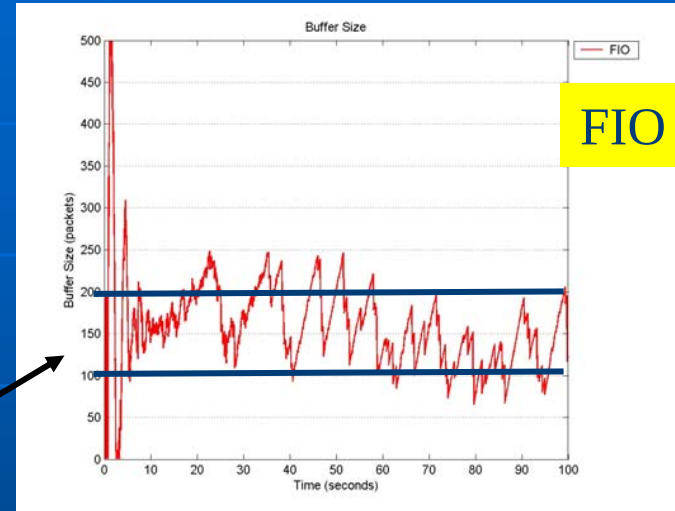
- FIO compared with RIO
- Best Effort TQL = 100 packets
- Assured TQL = 200 packets
- 100 flows (2 assured, 98 best-effort)
- → Minimum amount of assured traffic

- FIO regulates its queue to the lower TQL
- RIO exhibits large queue fluctuations that result in degraded utilization, losses and high variance of queuing delay.
- FIO achieves an adequate differentiation between the two traffic classes; RIO cannot provide sufficient link utilization for assured class.



# SIMULATION RESULTS: single bottleneck links

- network topologies with single bottleneck links: TCP/IP Diff-Serv network (cnt'd)
- Best Effort TQL = 100 packets
- Assured TQL = 200 packets
- 100 flows (10 assured, 90 best-effort)
- → Increase of assured traffic
  - FIO accomplishes a bounded queuing delay, between the two TQLs, that result in high link utilization and minimal losses.
  - RIO slowly regulates its queue, after a significant transient period with large overshoots that result in lower utilization and higher losses than FIO has.
  - FIO achieves a much higher differentiation between the two classes, as compared with RIO



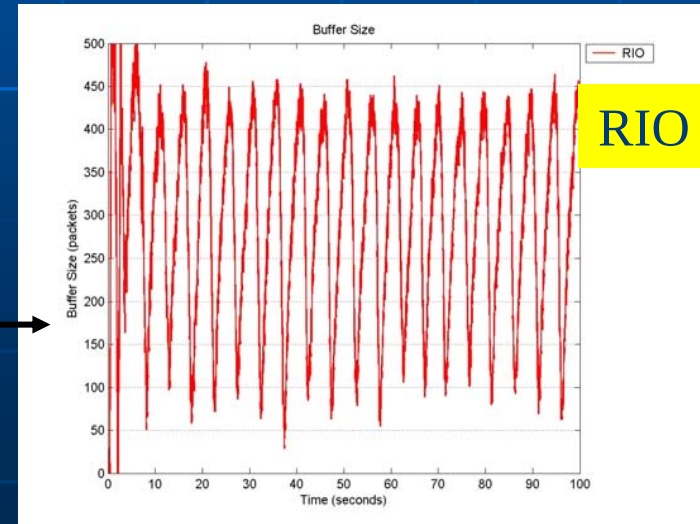
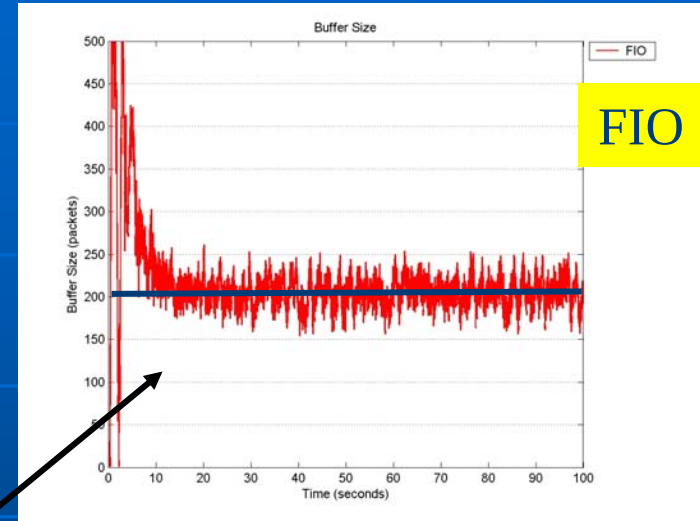
# SIMULATION RESULTS: single bottleneck links

- network topologies with single bottleneck links: TCP/IP Diff-Serv network (cnt'd)

- Best Effort TQL = 100 packets
- Assured TQL = 200 packets
- 100 flows (90 assured, 10 best-effort)

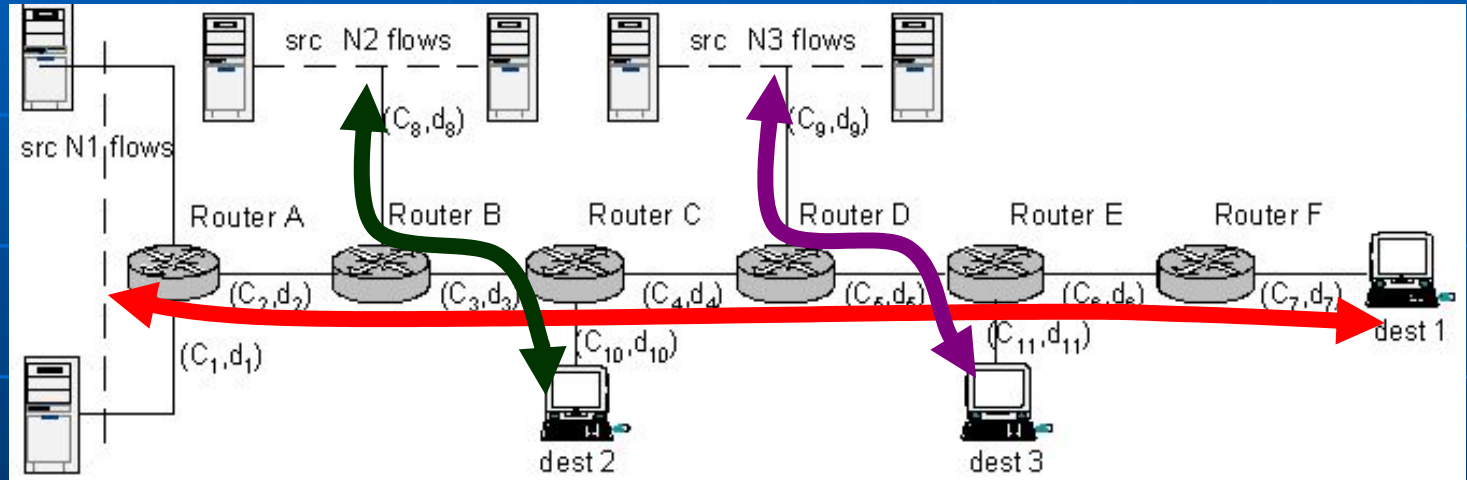
→ Larger amount of assured traffic than the best-effort traffic) with heterogeneous RTTs

- FIO regulates its queue at the higher TQL, thus exhibits stable queue length dynamics that result in high link utilization with minimal losses.
- RIO exhibits large queue fluctuations that result in lower utilization and higher losses than FIO has.



# SIMULATION RESULTS: Multiple bottleneck links

- We consider network topologies with multiple bottleneck links
  - More realistic scenarios



- 6 scenarios designed to show ability
  - of FIO to control and differentiate
  - to perform under dynamic changes in network traffic
  - to perform under web traffic

TABLE II  
SUMMARY OF STATISTICAL RESULTS

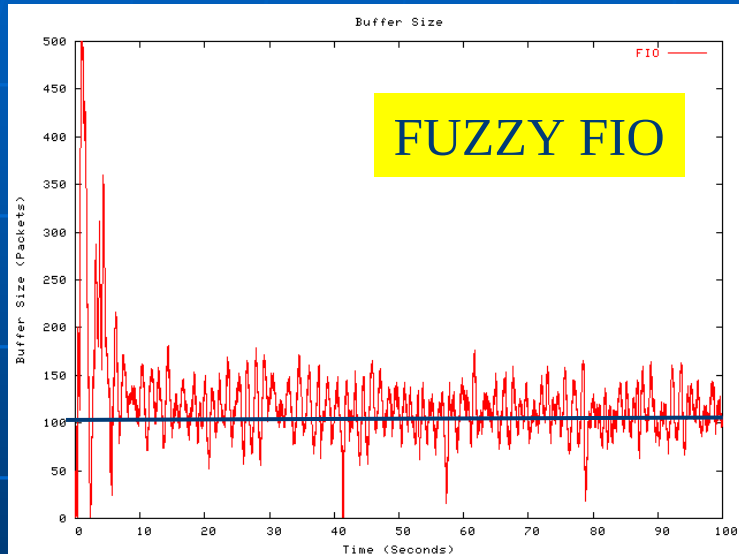
| Scenarios | AQM | Utilization (%) |         |       | Loss Rate (%) |         |       | Delay (ms) |               |
|-----------|-----|-----------------|---------|-------|---------------|---------|-------|------------|---------------|
|           |     | Best-effort     | Assured | Total | Best-effort   | Assured | Total | Mean-Delay | Std-Deviation |
| 1         | FIO | 67.09           | 32.58   | 99.67 | 0.13          | 0       | 0.09  | 63.29      | 24.07         |
|           | RIO | 97.38           | 0.16    | 97.54 | 1.68          | 0       | 1.68  | 217.89     | 48.00         |
| 2         | FIO | 6.80            | 92.82   | 99.62 | 1.49          | 0.05    | 0.15  | 94.56      | 26.71         |
|           | RIO | 28.72           | 67.62   | 96.34 | 8.76          | 0.07    | 3.01  | 105.07     | 49.94         |
| 3         | FIO | 34.66           | 58.92   | 93.58 | 0.30          | 0.08    | 0.16  | 88.04      | 36.08         |
|           | RIO | 50.20           | 43.23   | 93.43 | 5.87          | 0.11    | 3.37  | 80.78      | 70.90         |
| 4         | FIO | 0.50            | 98.56   | 99.06 | 0             | 0.38    | 0.38  | 110.36     | 24.84         |
|           | RIO | 0.58            | 97.29   | 97.87 | 21.21         | 1.33    | 1.34  | 162.38     | 37.68         |
| 5         | FIO | 16.36           | 82.37   | 98.73 | 0.009         | 0       | 0.007 | 57.15      | 16.94         |
|           | RIO | 20.66           | 77.59   | 98.25 | 0.24          | 0.01    | 0.19  | 78.80      | 61.03         |
| 6         | FIO | 0.015           | 99.95   | 99.97 | 0             | 0.49    | 0.49  | 103.31     | 21.25         |
|           | RIO | 0.01            | 99.95   | 99.96 | 57.83         | 3.35    | 3.36  | 149.84     | 44.63         |

- *Scenario 1 all sources (N1, N2, and N3 flows) greedy sustained FTP applications.*
  - Only 2 out of 100 N1 flows assured class, 98 flows best-effort.
- *Scenario 2 increases assured traffic*
- *Scenario 3 introduces dynamic traffic changes*
- *Scenario 4 increases assured traffic more*
- *Scenario 5 introduces TCP/Web-like traffic too*
- *Scenario 6 increases assured traffic (includes TCP/Web-like traffic)*

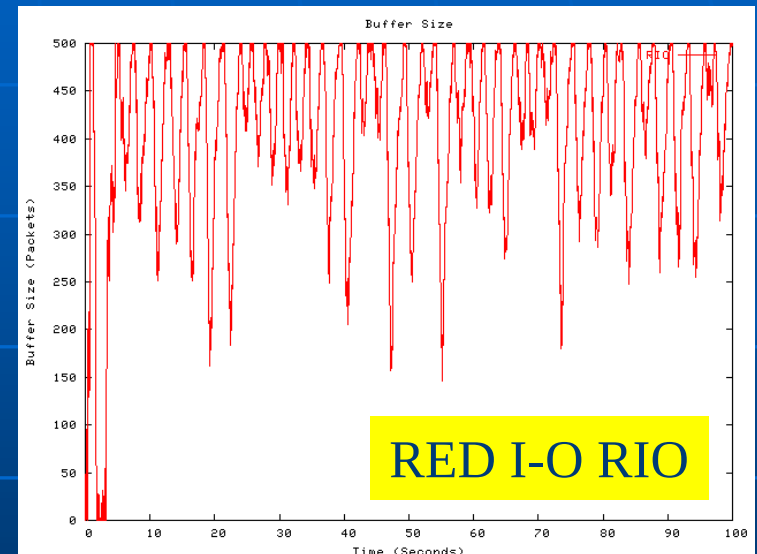
# SIMULATION RESULTS: Multiple bottleneck links (cont.)

Best Effort TQL = 100 packets      Assured TQL = 200 packets

Minimum amount of assured traffic



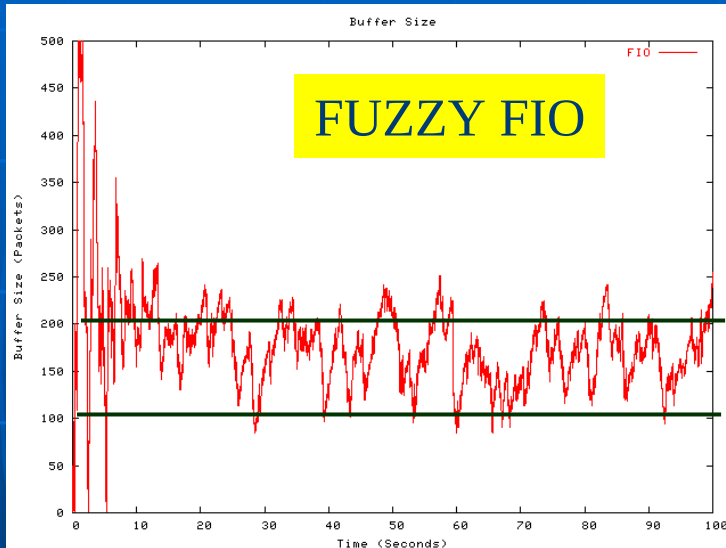
FIO regulates its queue to the lower TQL  
FIO achieves an adequate differentiation  
between the two traffic classes



RIO cannot provide sufficient link  
utilization for assured class.  
RIO exhibits large queue  
fluctuations thus high variance of  
queuing delay and increased losses

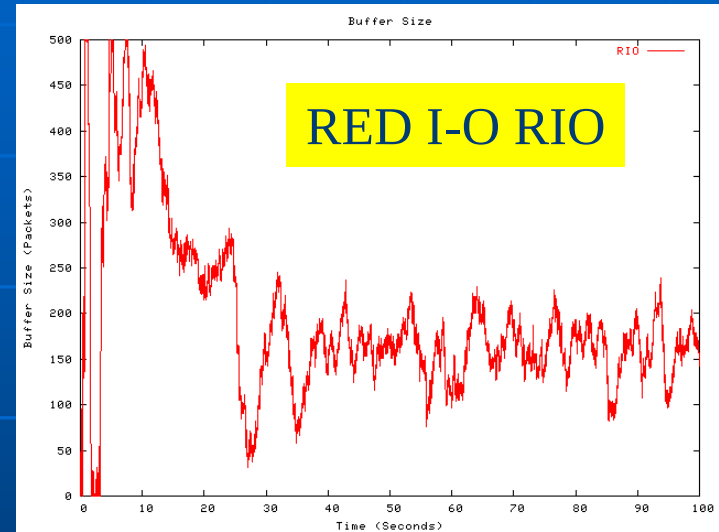
# SIMULATION RESULTS: Multiple bottleneck links (cont.)

- Best Effort TQL = 100 packets Assured TQL = 200 packets
- Increase of assured traffic



FIO accomplishes a bounded queuing delay, between the two TQLs, that result in high link utilization and minimal losses.

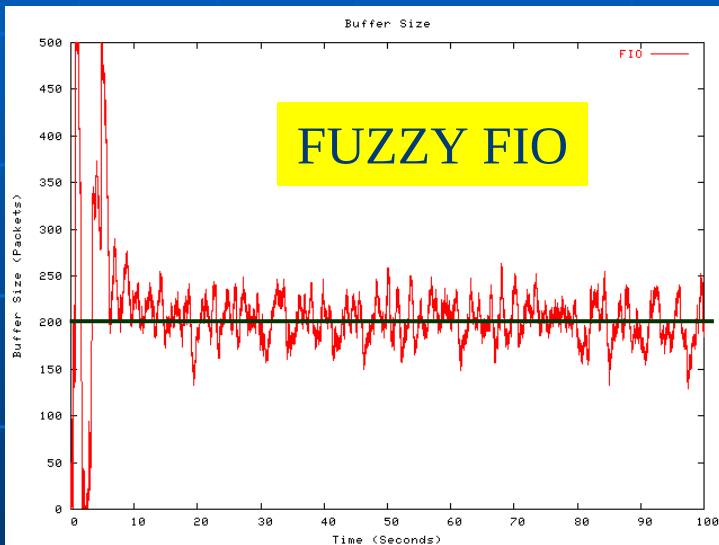
FIO achieves a much **higher differentiation** between the two classes, as compared with RIO.



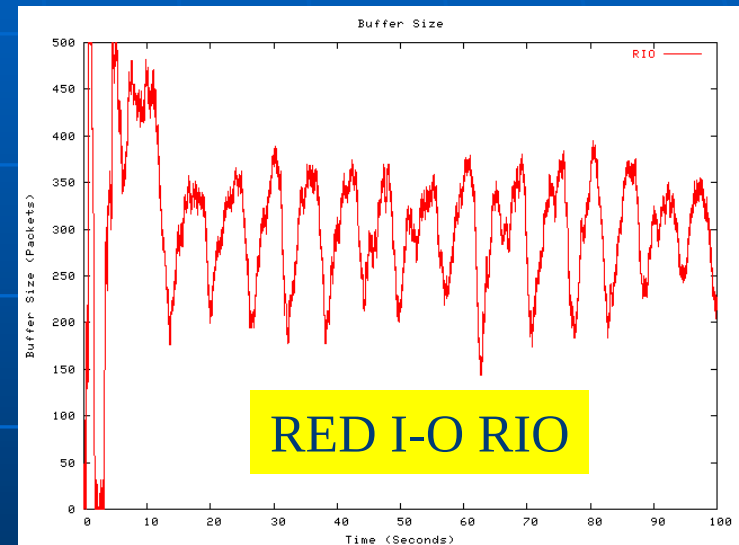
RIO slowly regulates its queue, after a significant transient period with large overshoots that result in lower utilization, higher delay variations, and higher losses than FIO has.

# SIMULATION RESULTS: Multiple bottleneck links (cont.)

- Best Effort TQL = 100 packets      Assured TQL = 200 packets
- **Larger amount of assured traffic** than the best-effort traffic



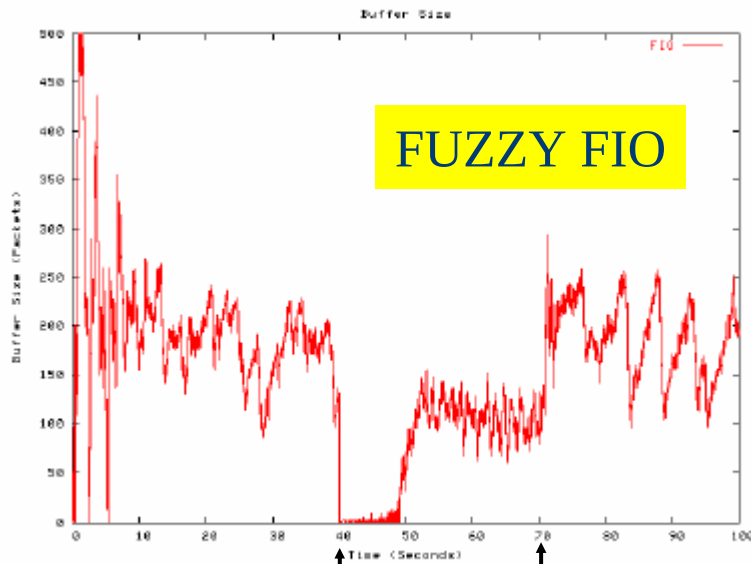
FIO regulates its queue at the higher TQL, thus exhibits stable queue length dynamics that result in high link utilization with minimal losses.



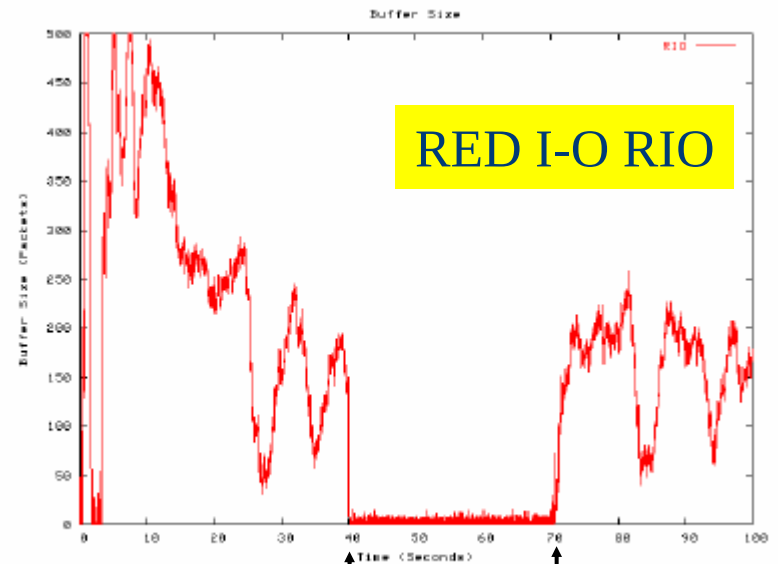
RIO exhibits large queue fluctuations that result in lower utilization, higher delay variation, and higher losses than FIO has.

# SIMULATION RESULTS: Multiple bottleneck links (cont.)

A sudden change in traffic conditions



(a) FIO



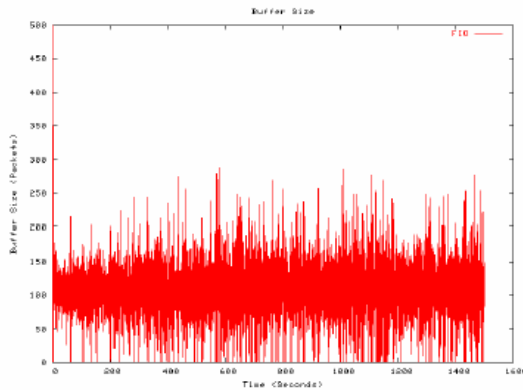
(b) RIO

Fig. 7. Scenario 3: Queue lengths.

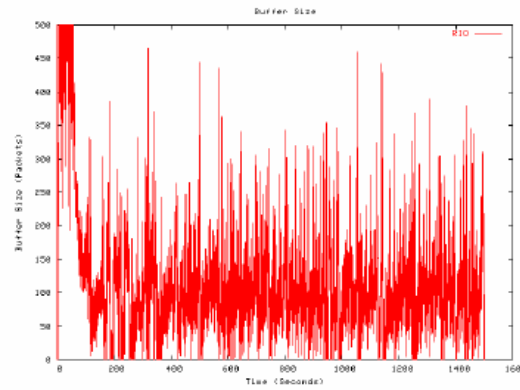


from  $t=40s$  to  $t=70s$  only best effort traffic

# SIMULATION RESULTS: Multiple bottleneck links (cont.)

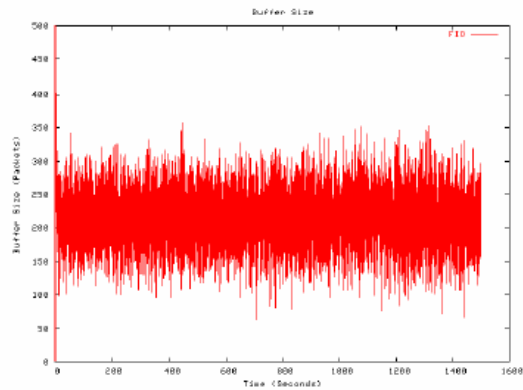


(a) FIO

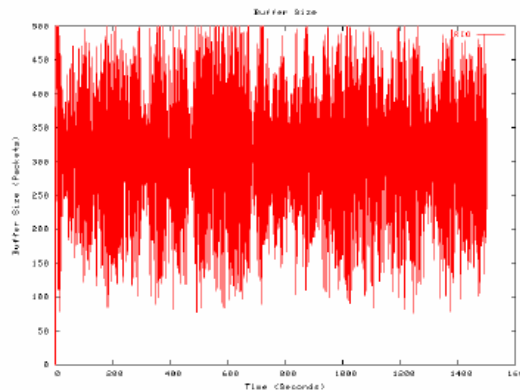


(b) RIO

Fig. 9. Scenario 5: Queue lengths  
(queue ranges from 0-500 packets with a time evolution of 1500sec;  
similarly for Fig. 10).



(a) FIO



(b) RIO

Fig. 10. Scenario 6: Queue lengths.

FUZZY FIO

RED I-O RIO

Web traffic  
introduced

o Queue variance  
increases

o FIO better than RIO

# CONCLUSIONS FOR FUZZY IN-OUT (FIO)

- Successfully used fuzzy logic to provide effective congestion control and QoS support within a TCP/IP Diff-Serv environment
  - addressed limitations of existing AQM schemes:
  - clearly shown in simulative evaluation.
    - FIO mechanisms exhibit many desirable properties, like robustness and fast system response, and behaves better than other representative schemes in terms of link utilization, packet losses, queue fluctuations and delays.
  - FIO also achieves adequate differentiation between the two classes of service.
- Fuzzy Control methodology is expected to offer significant improvements on controlling congestion in TCP/IP networks and thus providing (differentiated/aggregated) QoS

# Future directions for Fuzzy Control

- Simulation techniques need to be supplemented by other techniques -- more work is clearly needed in this area
  - **Mathematical formulation** and proof of behaviour
    - Large scale implementation
    - Adaptive tuning of rules
  - **'real' system tests**
    - Currently being implemented in LINUX based pilot Diff-Serv network in UCY Networks Lab
- Evaluate performance of these algorithms in a **mobile environment**
  - Mobile networks have challenged existing congestion controls, especially loss reactive, like TCP congestion control, due to radio interface losses
  - Handover (delay, probable loss of TCP connection, etc..) adds an additional control problem

# Group directions

- Continue work on congestion and overload control, especially new topologies, as e.g. ad-hoc / sensor
  - Special focus on overload control, in these environments using control theoretic approaches
- Continue work on 3<sup>rd</sup> and 4<sup>th</sup> Generation wireless networks, including cellular and WLAN
  - Multicast/broadcast over UMTS (B-BONE, C-MOBILE, 6<sup>th</sup> FP IST projects)
- Resource management, e.g. Handover in WLANs
  - focus on Radio Resource Management techniques (RRM)

# Some recent publications

- C. Chrysostomou, A. Pitsillides, "Using Fuzzy Logic Control to Address Challenges in AQM Congestion Control in TCP/IP Networks", 1<sup>st</sup> Workshop on Modeling and Control of Complex Systems (**MCCS 2005**), Cyprus, June 30 – July 1, 2005.
- C. Chrysostomou, A. Pitsillides, G. Hadjipollas, M. Polycarpou, A. Sekercioglu, "Congestion Control in Differentiated Services Networks using Fuzzy Logic", 43<sup>rd</sup> IEEE Conference on Decision and Control (**CDC 2004**), Bahamas, December 14-17, 2004.
- C. Chrysostomou, A. Pitsillides, G. Hadjipollas, M. Polycarpou, A. Sekercioglu, Fuzzy Logic Control for Active Queue Management in TCP/IP Networks, 12<sup>th</sup> Mediterranean Conference on Control and Automation (**MED'04**), Kusadasi, Aydin, Turkey, 6-9 June 2004
- C. Chrysostomou, A. Pitsillides, L. Rossides, A. Sekercioglu, "Fuzzy Logic Controlled RED: Congestion Control in TCP/IP Differentiated Services Networks", Special Issue on "The Management of Uncertainty in Computing Applications" in **Soft Computing Journal** - A Fusion of Foundations, Methodologies and Applications, Vol 8, Number 2, pp. 79 - 92, Dec. 2003.
- C. Chrysostomou, A. Pitsillides, L. Rossides, M. Polycarpou, A. Sekercioglu, "Congestion Control in Differentiated Services Networks using Fuzzy-RED," Special Issue on "Control Methods for Telecommunication Networks" in **IFAC Control Engineering Practice (CEP) Journal**, Vol. 11, Issue 10, pp. 1153-1170, September 2003.

# Some recent publications

- C. Chrysostomou, A. Pitsillides, G. Hadjipollas, M. Polycarpou, A. Sekercioglu, “Fuzzy Logic Based Congestion Control in TCP/IP Networks for Quality of Service Provisioning”, in Proceedings of the International Conference on Next Generation Teletraffic and Wired/Wireless Advanced Networking (**NEW2AN'04**), St. Petersburg, Russia, 2 - 6 February 2004, pp. 235-243.
- C. Chrysostomou, A. Pitsillides, G. Hadjipollas, A. Sekercioglu, M. Polycarpou, Fuzzy Logic Congestion Control in TCP/IP Best-Effort Networks, in Proceedings of the Australian Telecommunications, Networks and Applications Conference (**ATNAC 2003**), Melbourne, Australia, 8 – 10 December 2003.
- C. Chrysostomou, A. Pitsillides, G. Hadjipollas, A. Sekercioglu, M. Polycarpou, “Fuzzy Explicit Marking for Congestion Control in Differentiated Services Networks,” in Proceedings of the 8th IEEE Symposium on Computers and Communications (**ISCC'2003**), Antalya, Turkey, 30 June - 3 July 2003, Vol. 1, pp. 312-319.
- L. Rossides, C. Chrysostomou, A. Pitsillides, A. Sekercioglu, Overview of Fuzzy-RED in Diff-Serv Networks, in Proceedings of the International Conference on Computing in an Imperfect World (**Soft-Ware 2002**), Belfast, Northern Ireland, 8 - 10 April 2002, pp. 1-13.
- L. Rossides, A. Sekercioglu, A. Pitsillides, A. Vassilakos, S. Kohler, P. Tran-Gia, Fuzzy RED: Congestion control for TCP/IP Diff-Serv, in book on **Advances in Computational Intelligence and Learning: Methods and Applications** (eds. H.J. Zimmerman, G. Tselentis, M. Van Someren, G. Dunias), **Kluwer Academic Publishers**, February 2002, pp. 343-352, ISBN 0-7923-7645-5, Hardbound.
- A. Pitsillides, A. Sekercioglu, “Congestion Control,” in **book on Computational Intelligence in Telecommunications Networks**, (Ed. W. Pedrycz, A. V. Vasilakos), **CRC Press**, ISBN: 0-8493-1075-X, September 2000, pp- 109-158.

# Discussion

# Supporting slides

# CONGESTION CONTROL – AQM MECHANISMS

- **AQM mechanisms** recently proposed
  - to provide high link utilization with low loss rate and queuing delay, while responding quickly to load changes.
  - drop/mark packets early so as to notify traffic sources about incipient stages of congestion.



# Diff-Serv Architecture

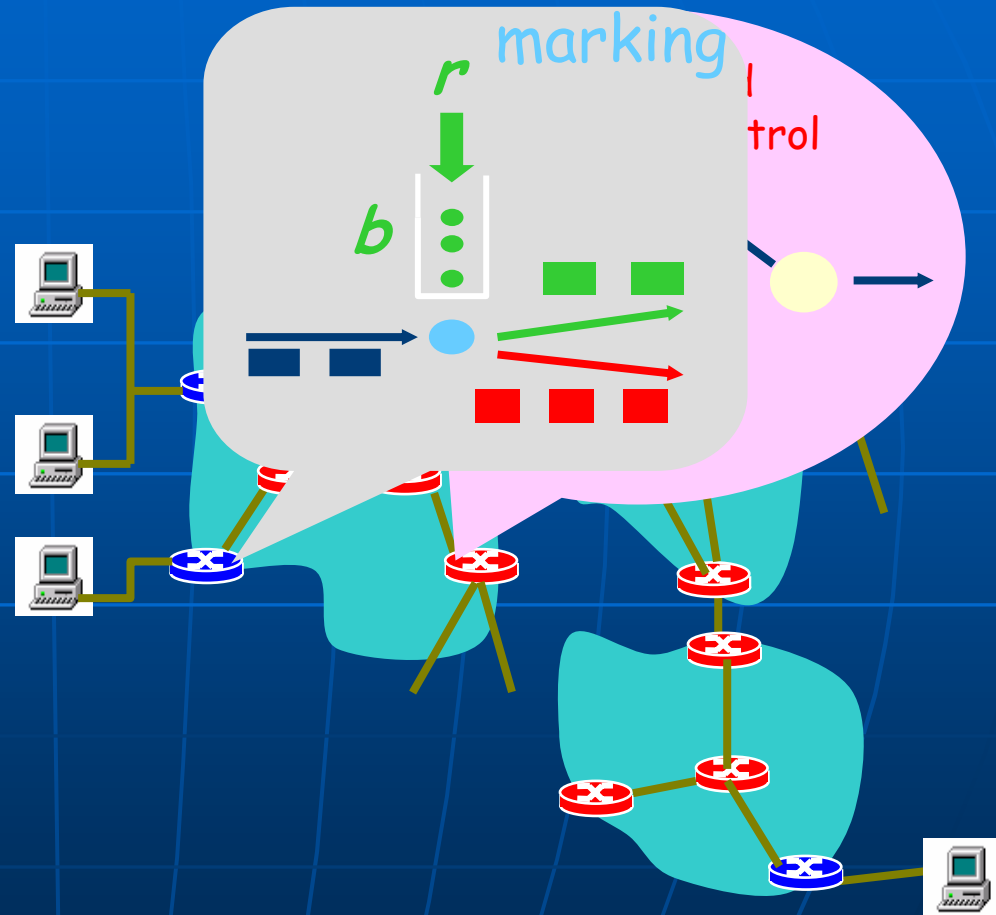
Adapted from Kurose and Ross Book

Edge router: 

- per-flow traffic management
- marks packets as **in-profile** and **out-profile**

Core router: 

- **per class** traffic management
- buffering, scheduling, and control based on **marking** at edge
- preference given to **in-profile** packets
- Assured Forwarding



We have concentrated some of our work on providing control strategies for the Diff-Serv architecture



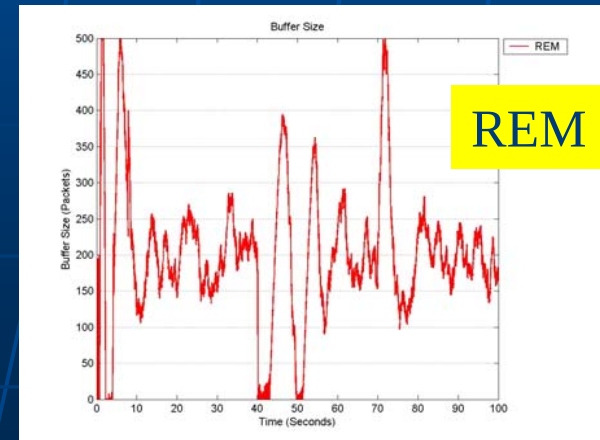
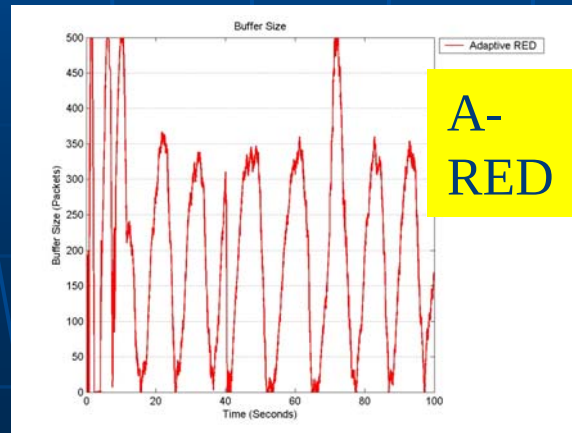
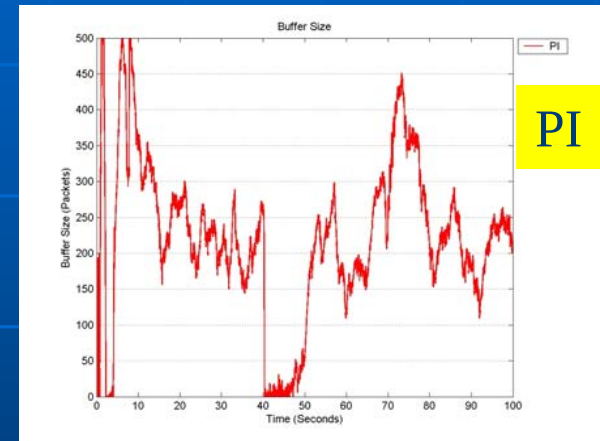
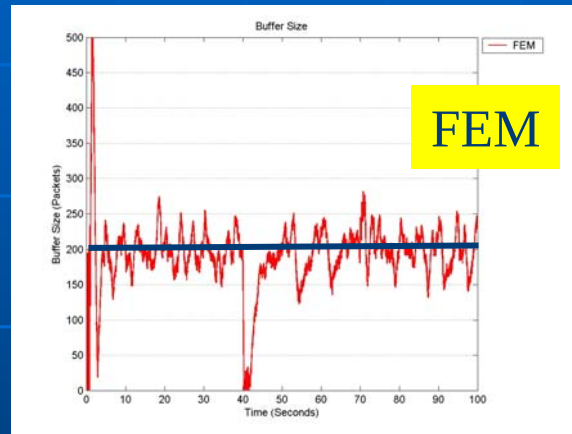
# CONGESTION CONTROL – AQM MECHANISMS (cnt'd)

- Several schemes proposed for best-effort networks:
  - Random early detection (RED)
    - sets some min and max *marking* thresholds in the router queues
    - If average queue size is bwn min & max thresholds, RED starts randomly *marking* packets based on a prob depending on the average queue size
    - If average queue size exceeds the max threshold, every packet is dropped
  - Adaptive-RED (A-RED)
    - addresses acknowledged RED problems
    - adjusts the value of the maximum *mark* probability to keep the average queue length within a target range half way between the min and max thresholds
  - Random exponential marking (REM)
    - uses the instantaneous queue size and its difference from a target value to calculate the *mark* probability based on an exponential law
  - Proportional-Integral (PI) controller
    - uses classical control theory techniques to stabilize the router queue length around a target value

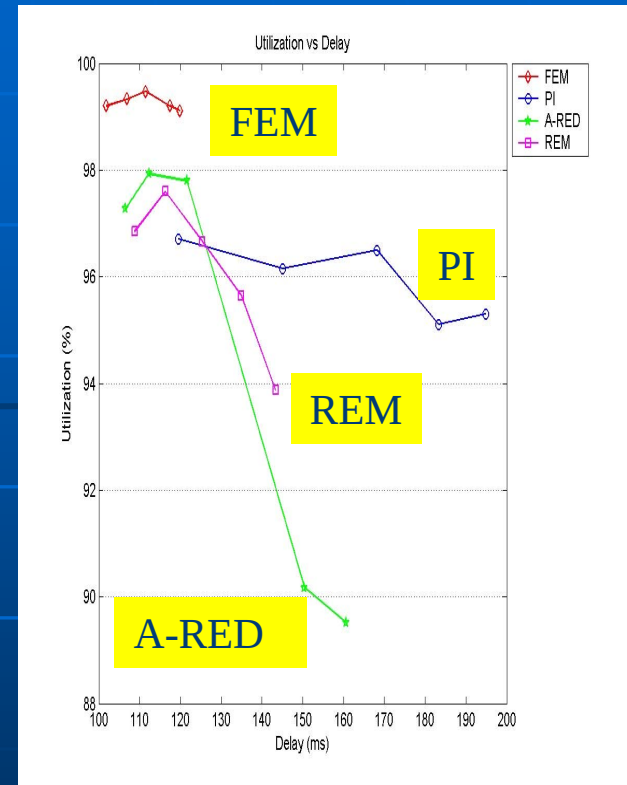
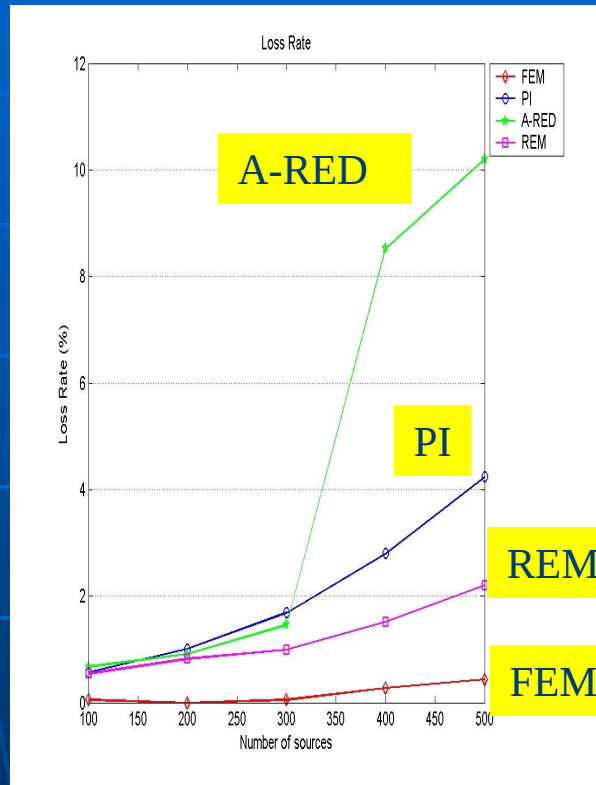
# Comparative evaluation of Best Effort schemes: FEM, A-RED, REM, PID

## ■ TCP/IP Best-effort network: single bottleneck links

- TQL = 200 packets, large propagation delays to examine the effect of RTT
- dynamic traffic changes (at  $t=40\text{sec}$  half of sources stop, resuming at  $t=70\text{sec}$ )
- The results show the superior steady performance of FEM with stable queue length dynamics.
  - PI, A-RED, and REM exhibit large queue fluctuations that result in degraded utilization and high variance of queuing delay.



# Comparative evaluation of Best Effort schemes: FEM, A-RED, REM, PID



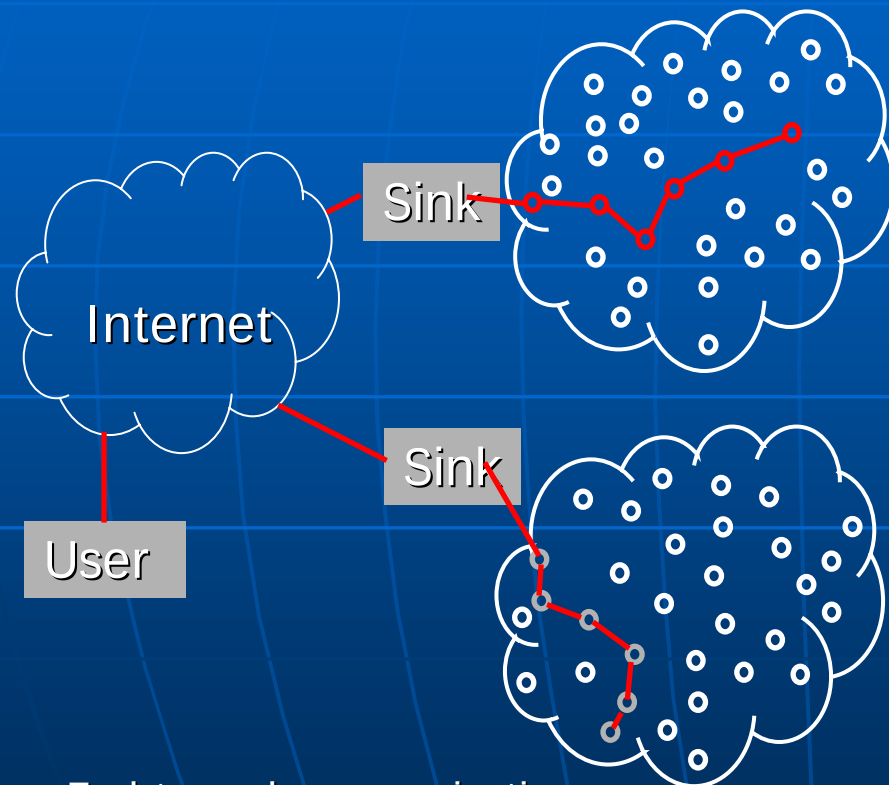
- investigate traffic load factor (from 100 up to 500 active flows)
  - FEM has the lowest drops with a steady performance, while A-RED has the largest drops.
  - FEM outperforms the other schemes on both high utilization and low mean delay, thus it exhibits a more stable, and robust behavior.
  - Others show poor performance, achieving much lower link utilization, and large queuing delays, far beyond the expected one.



# Congestion (overload) control: new challenges

- Focus on the **ad-hoc** and **sensor networks** optimization and control issues
  - new way of thinking is necessary
  - transport and network layer functionalities need redefinition
- Sensor nets add yet more **problems (challenges) for control**
  - Models akin to control theory treatment are still lacking (this is true also for the internet)
  - Constraints are often so stringent that probably each application requires protocols optimized for the application
  - Cross layer protocols and optimization are most probably necessary. E.g. overload control using physical layer functionalities, such as modulation scheme, MAC scheme, power control.

# Overload control: new challenges in Sensor networks



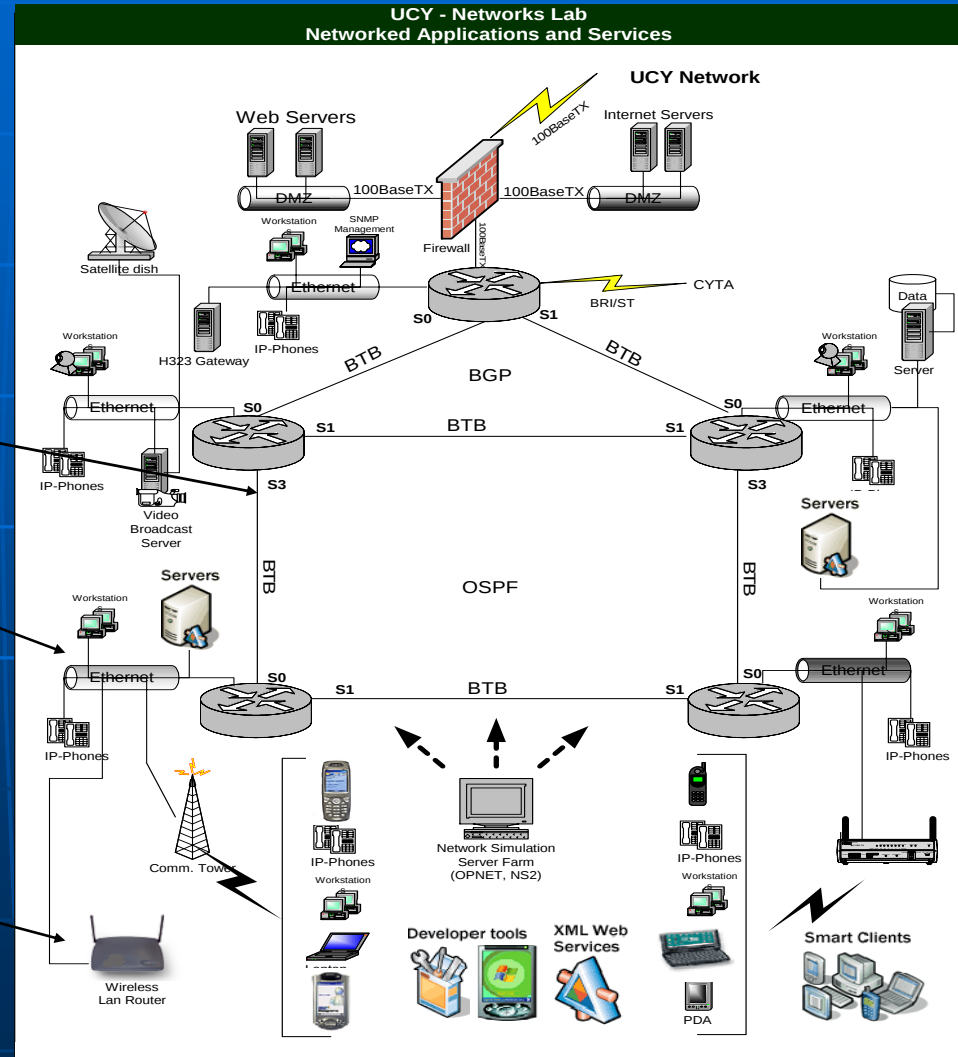
- Huge number of spatially distributed, energy-constrained, self-configuring and self-aware nodes
- Tend to be autonomous and require a high degree of cooperation and adaptation to perform the desired coordinated tasks and networking functionalities
- Power constraint (limit transmissions-high power user)
- Forward and Feedback paths are less predictable than in fixed Internet
- Mobility and connectivity (coverage)
- Higher link and node failures
- Low bandwidth
- Higher losses expected
- Data implosion, often due to critical events (e.g. earthquake)
- Data aggregation may impact on a feedback signal
- Resource blindness (lack of unique global address)

- End-to-end communication between a sensor node and user:
  - End to end reliability and Congestion control do not have the same meaning.

# Research Lab

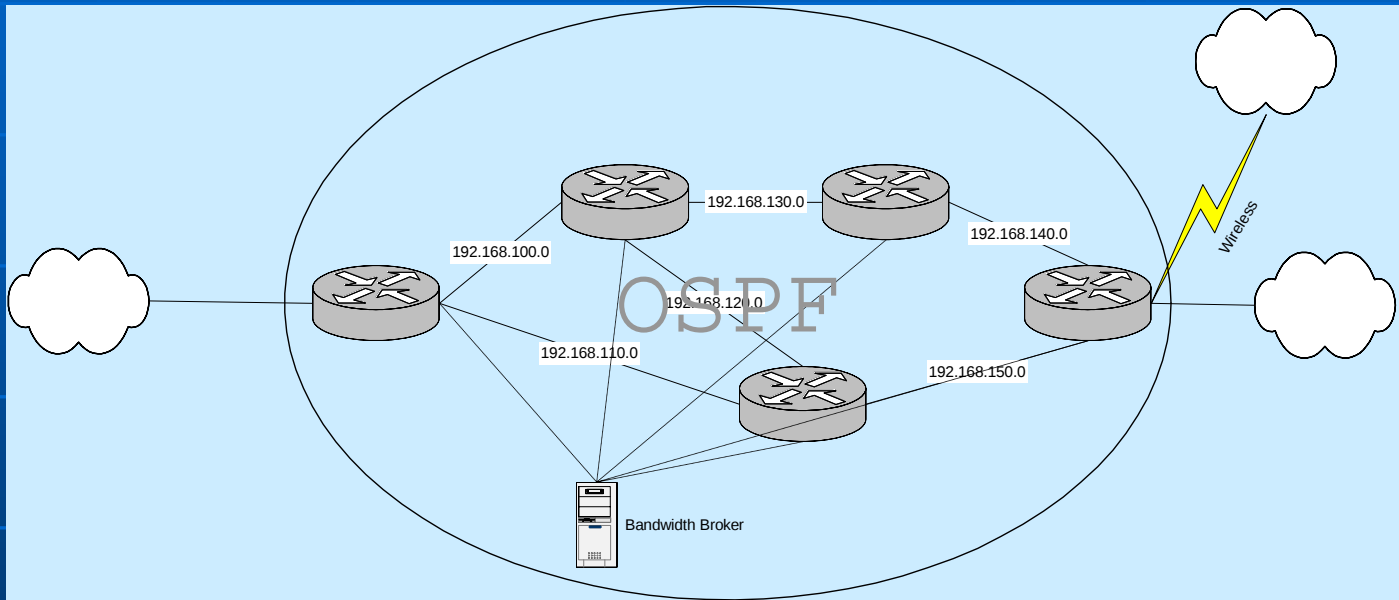
## *Networks and Internet Lab*

- CISCO router based core network
- Multimedia content (incl. video servers, IP telephony, satellite feed)
- Wireless and Wired access points

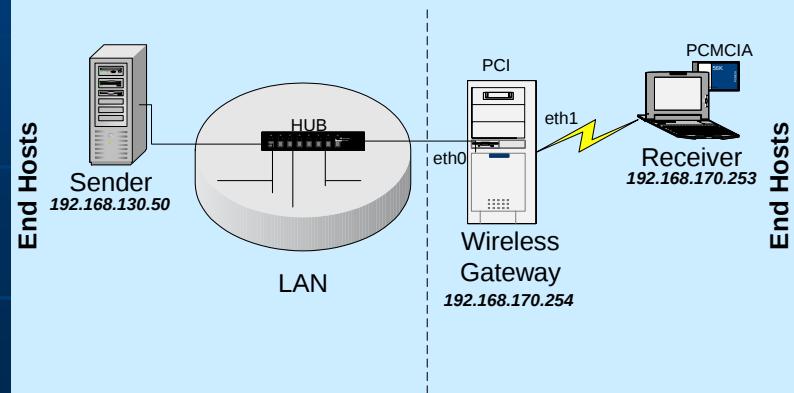


# Research Lab (cnt'd)

- Linux Diff-Serv Test bed



Wireless testbed



# Non-Linear Control for Diff-Derv framework

- Integrated Dynamic Congestion Controller
  - scheme for controlling traffic using information on the status of each queue in the network
    - using non-linear control theory
  - The IDCC scheme is based on a non-linear model of the network that is generated using fluid flow considerations.
  - A differentiated-services network framework was assumed and the proposed control strategy was formulated in the same spirit as IP Diff-Serv for three types of services.

# Integrated Dynamic Congestion Controller (IDCC)

- Collaborative work with University of Southern California since 1995. (Prof. Petros Ioannou, Marios Lestas)
- A generic scheme for congestion control in a Differentiated Services framework.
- It is derived from non-linear adaptive control theory using a simple non-linear fluid flow model.
- Important control attributes of the scheme are:
  - Provably stable and robust.
  - High utilization.
  - Good steady state and transient behavior.
  - No maintenance of per flow states within the network.
  - It achieves max-min fairness.
  - It features a small set of design parameters.
- This work resulted in a number of publications, including Infocom 1996, ISCC 2000, IEEE/ACM ToN, February 2005

