IP over WDM Network for the Next-Generation Internet

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Advanced Network Architecture Research

IP over WDM for the Next-Generation Internet

Contents:

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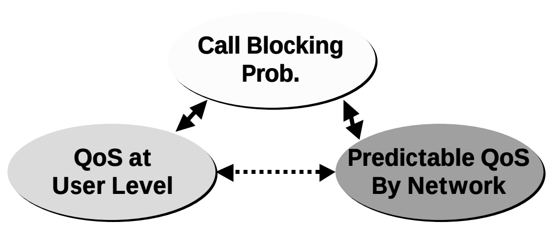
What is QoS in Data Applications?

- ***The current Internet provides***
  - QoS guarantee mechanisms only for real-time applications by int-serv
  - QoS discriminations for aggregated flow by diff-serv
  - No QoS guarantees for data
- ***Data is essentially greedy for bandwidth***
  - Some ISP offers the bandwidth-guaranteed service to end users
    - More than 64Kbps is not allowed
    - It implies “call blocking” due to lack of the modem lines
    - No guarantee in the backbone

QoS in Telecommunications



1. ***Past statistics***
   - Traffic characteristics is well known
2. ***Single carrier, single network***
3. ***Erlang loss formula***
   - Robust (Poisson arrivals and general service times)
4. ***QoS measurement = call blocking stat.***
   - Can be obtained by carrier

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Target Applications in Telecommunications

- ❑ ***Real-time Applications; Voice and Video***
  - ✘ **Require bandwidth guarantees, and that's all**
  - ✘ **For real-time QoS in the Internet with RSVP, bandwidth can be well engineered by Erlang loss formula**
    - ✔ **Scalability; the # of flows/intermediate routers**
- ❑ ***Distribution service for real-time multimedia (streaming): playout control can improve QoS***

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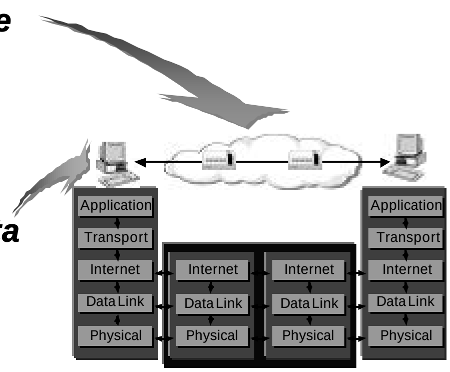
Where Complicated Functions Are Put?

- ❑ ***Connection-oriented Service (Telecommunication Network)***
  - ✘ **Network layer (i.e., switching node)**
  - ✘ **Suitable to telephone service**
- ❑ ***Connectionless Service (Data Network)***
  - ✘ **Transport layer (i.e., end host)**
  - ✘ **Protocol processing is performed by end host computers**



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What is Ultimate Communication Technology?

- ***"ATM is a final technology for integrated network supporting multimedia information."***
  - **What is multimedia?**
    - **Multimedia document does not need real-time transmission**
  - **Do we really need an integrated network?**
  - **End-system is not "dumb-terminal"**

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Why Native ATM is not Widely Deployed?

- ***Statistical multiplexing was only for theoretical study***
- ***ATM was expected to support "everything"***
- ***ATM is not suitable to data communications***
- ***End system is not dumb terminal, but intelligent computer***
- ***API of ATM is not open to end users***
  - **Web and browsers are not invented by network researchers, but by network users**
  - **Chicken and egg?**

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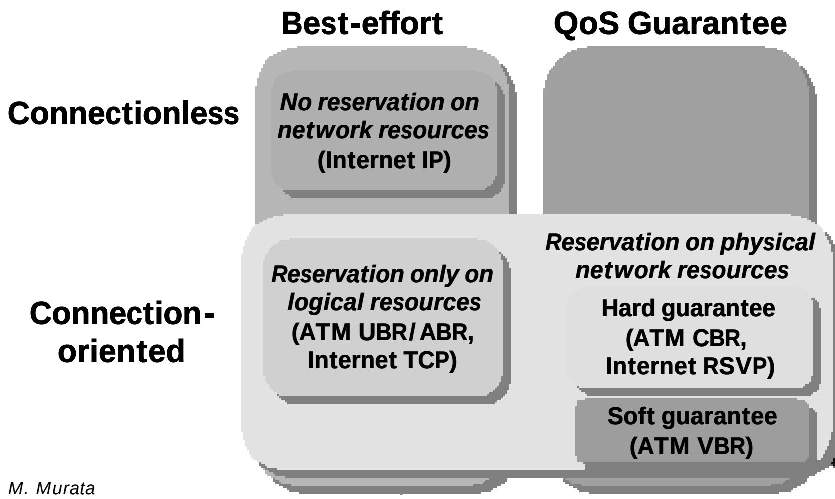
Classification of Network Services



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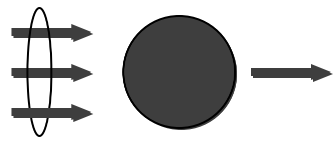
Fundamental Principles for Data Application QoS

1. ***Data applications try to use the bandwidth as much as possible.***
2. ***Neither bandwidth nor delay guarantees should not be expected.***
3. ***Competed bandwidth should be fairly shared among active users.***

Queueing Time in Processor Sharing Queue

- ❑ ***Average service time for given demand***
  $E[d | S=x] = x / (C - r L)$
  - ✘ ***x*; demand in bits for customers (packet, Web document, ...)**
  - ✘ ***C*; line capacity**
  - ✘ ***r*; total arrival rate**
  - ✘ ***L*; mean demand**



- ❑ ***Document transfer time is proportional to its demand***
  - ✘ **Fair service at the packet level is required to achieve PS**

IP over WDM for the Next-Generation Internet

Contents:

1. ***Overview of Data Applications QoS***
2. ☞ ***Challenging Problems for The Next-Generation Internet***
3. ***IP over WDM: A Solution for the Next-Generation Internet***

Challenging Problems for the Next-Generation Internet

1. *QoS Guarantees for Real-Time Multimedia*
   - ✘ Diff-serv is not a solution!
2. *High-Speed Backbone and Switching*
3. *High-Performance Protocol*
4. *High-Performance End-host*
5. *Reallocation of Network Functionalities*
6. *Fairness among Users*
7. *Network Dimensioning*
8. *Fundamental Theory for the Internet*

2. High-Speed Backbone

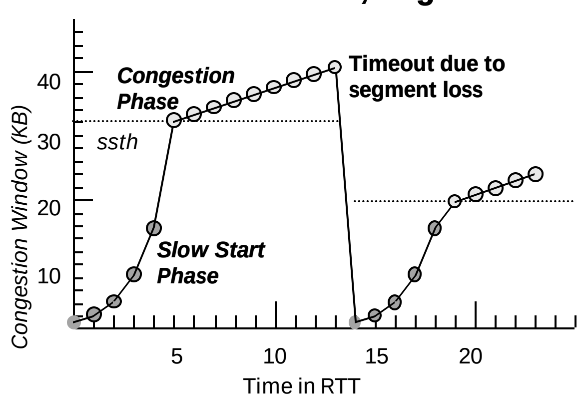
- ❑ *Functionalities provided by WDM?*
  - ✘ Connection establishment, congestion control, routing control
- ❑ *WDM can support high-reliability by partially supporting IP functionalities*
  - ✘ High-reliability by protection mechanisms
    - ✔ link protection
    - ✔ dedicated-path protection
    - ✔ shared-path protection
  - ✘ High-performance packet forwarding
    - ✔ Direct optical paths using lambda switching (MPLS)
  - ✘ We need an adequate network dimensioning method
    - ✔ Dynamic bandwidth dimensioning using wavelength routing

3. High-Performance Protocols

- ***Past Researches***
  - ✘ **Hardware and/or parallel protocol processing**
  - ✘ **Light-weight transport protocol**
  - ✘ **Separation of congestion and flow controls**
  - ➥ **Proprietary protocol (XTP, NETBLT)**
- ***Performance Improvement of TCP***
  - ✘ **TCP Tahoe, TCP Reno, TCP NewReno, TCP SACK, TCP Vegas (?)**
  - ✘ **Protocol migration is essential**
    - ✔ **Performance of TCP with different versions?**
    - ✔ **Change of TCP sender-side code is acceptable**

Dynamics of Window Size in TCP

Maximum Window Size: 64KB, Segment Size: 1KB



Several Versions of TCP

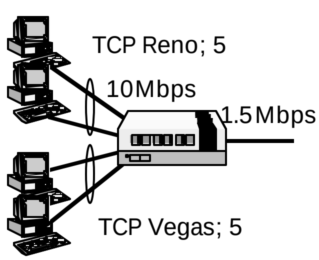
- ***Immediately retransmits the segment, if a few segments are occasionally lost***
  - ✘ **fast retransmit; *TCP Tahoe***
- ***Halves the window size***
  - ✘ **fast recovery; *TCP Reno***
- ***From Go-Back-N to Selective Repeat; TCP SACK***
- ***Adjusts the window size based on RTT observations; TCP Vegas***

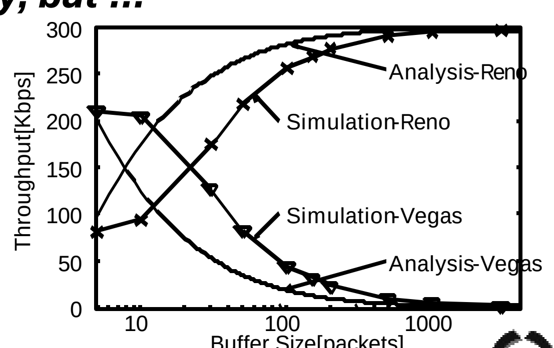
$$diff = cwnd(t) / basertt - cwnd(t) / observed\_rtt$$

$$cwnd(t+t_A) = \begin{cases} cwnd(t) + 1, & \text{if } diff < a / base\_rtt \\ cwnd(t), & \text{if } a / base\_rtt \leqq diff \leqq b / base\_rtt \\ cwnd(t) - 1, & \text{if } b / base\_rtt < diff \end{cases}$$

Throughput Comparisons of TCP Reno and Vegas

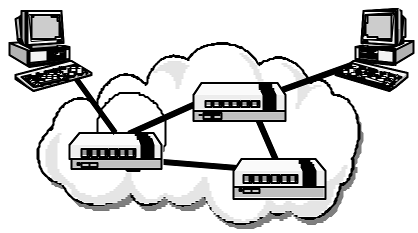
- ***Up to 40% Throughput Improvement by TCP Vegas Solely, but …***





4. High-Performance End Systems

- ***End-to-end performance is not determined only by packet transmission time; it includes***
  - **Line capacity**
  - **Router's packet processing capability**
  - **Protocol processing capability of end hosts**
  - **Applications**



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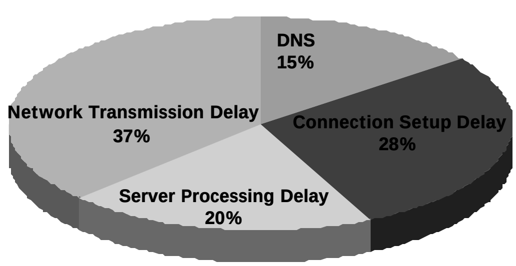
Delay Components in Web Document Download

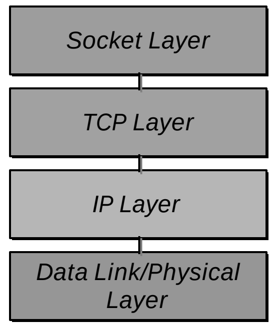
- ***Typical Web Document Download***
  - **Limitation of the Network Enhancement in Capacity**
  - **End System is Important**
  - **Well-Balanced Network Resource Allocation**

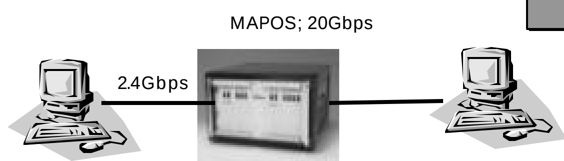


Produced from ftp://www.telcordia.com/pub/huitema/stats

High-Performance End-System Protocol Processing

- **_Buffer management at TCP socket_**
- **_Protocol processing at end hosts (e.g., zero copy, checksum offloading)_**
  - **Trapez over Myrinet**
- **_Protocol processing within the network_**
  - **Congestion control of TCP**
  - **Router packet forwarding and switching**
- **_Network line capacity_**



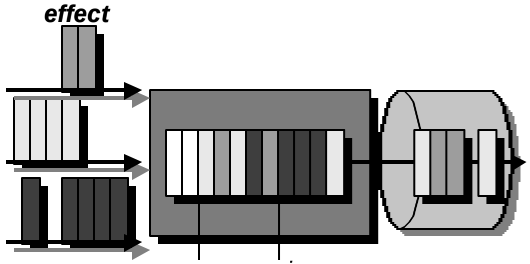


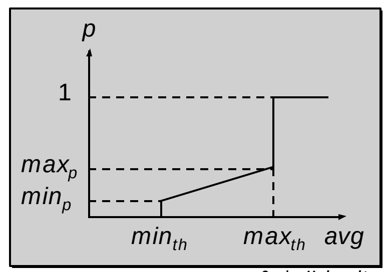
5. Reallocation of Network Functionalities

- **_Too much rely on the end host_**
  - **Congestion control by TCP**
    - **Congestion control is a network function**
  - **Inhibits the fair service**
    - **Host intentionally or unintentionally does not perform adequate congestion control (S/W bug, code change)**
    - **Obstacles against charged service**
- **_What should be reallocated to the network?_**
  - **Flow control, error control, _congestion control_, routing**
  - **RED, DRR, ECN, diff-serv, int-serv (RSVP), policy routing**
  - **We must remember too much revolution lose the merit of Internet.**

RED Mechanism

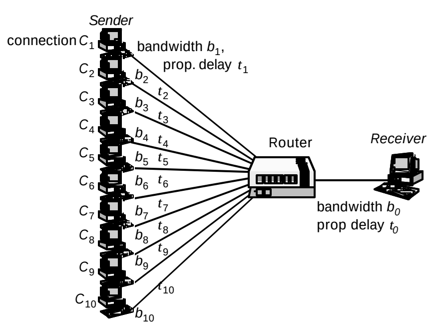
- *Controls packet dropping probability according to the queue length*
  - If *avg* < min_{th}, all arriving packets are accepted
  - If min_{th} < *avg* < max_{th}, arriving packets dropeed with prob. *p(x)*
  - If max_{th} < *avg*, all arriving packets are dropped
- *Avoids the packet loss from the same connection due to the phase effect*



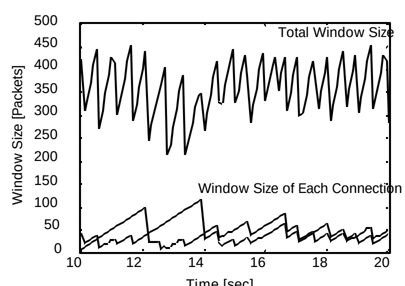


Effects of RED

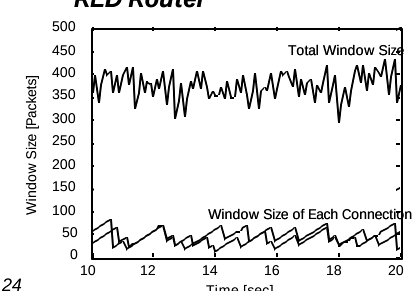
- *Activates fast retransmit*
- *By-product, instantaneous unfairness can be avoided*



Drop-Tail Router



RED Router



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6. Fairness among Connections

- Data application is always greedy
- We cannot rely on TCP for fairshare of the network resources
  - Short-term unfainess due to window size throttle
  - Even long-term unfairness due to different RTT, bandwidth
- ➥ Fair treatment at the router; RED, DRR
- ➥ Fairshare between real-time application and data application
  - TCP-Friendly congestion control

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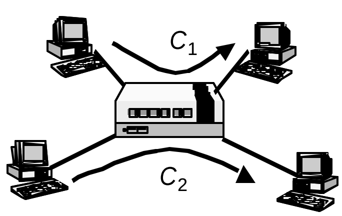
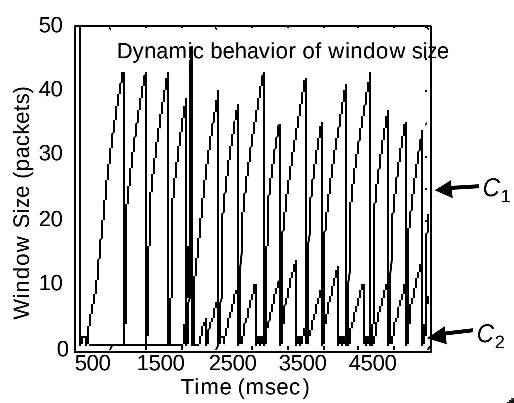
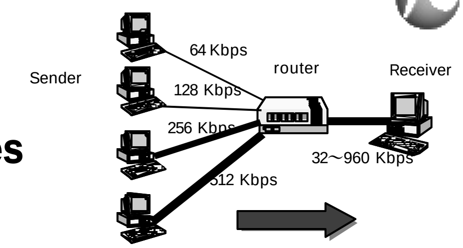
Fairness among TCP Connections; Different RTTs

- $2t_1 = t_2$

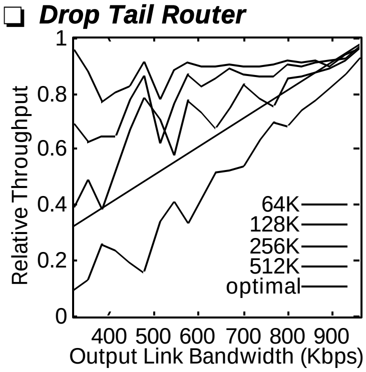




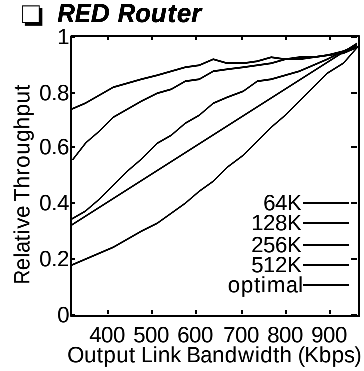
Fairness among TCP Connections; Different Capacities



- ***Drop Tail Router***

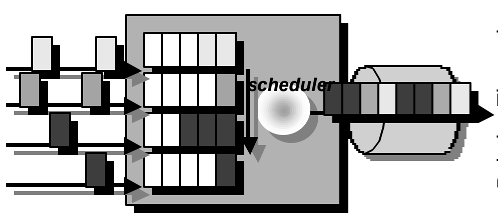


- ***RED Router***

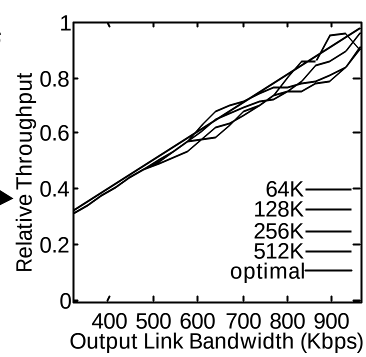


DRR Mechanism

- ***Imitates processor sharing by taking account of the weight, e.g., the access line speed***



router

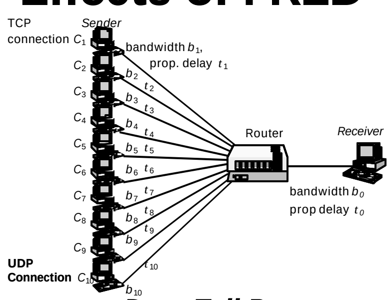


- ***Should maintain per-flow queueing physically (or logically)***
- ***Should know the mapping between IP address and the line speed***

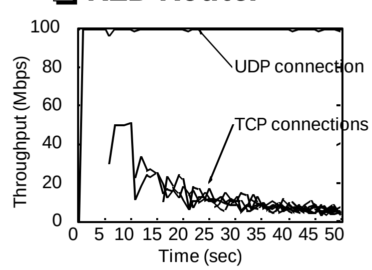
Other Layer-Four Switching Techniques for Fairshare

- ***Flow classification in stateless?***
- ***Maintain per-flow information (not per-queueing)***
  - **FRED**
    - **Counts the # of arriving/departing packets of each active flow, and calculates its buffer occupancy, which is used to differentiate RED's packet dropping probabilities.**
  - **Stabilized RED**
  - **Core Stateless Fair Queueing**
    - **At the edge router, calculates the rate of the flow and put it in the packet header. Core router determines to accept the packet according to the fairshare rate of flows by the weight obtained from the packet header. DRR-like scheduling can be used, but no need to maintain per-flow queueing.**

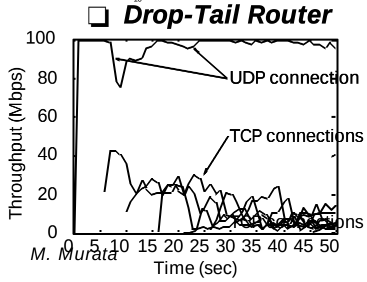
Effects of FRED



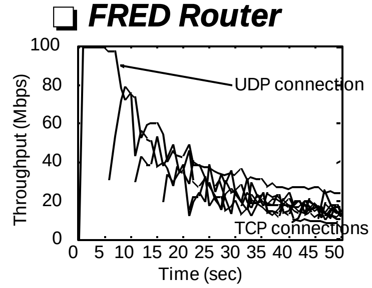
- ***RED Router***



- ***Drop-Tail Router***



- ***FRED Router***



TCP-friendly Rate Control

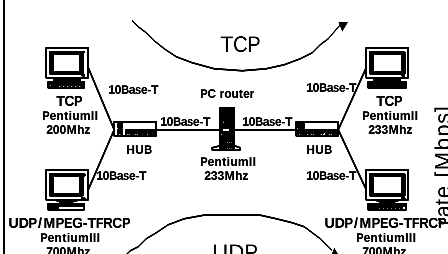
"A non-TCP connection should receive the same share of bandwidth as a TCP connection if they traverse the same path."

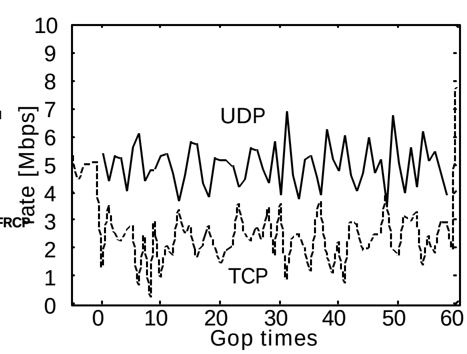
- ***TFRCP (TCP-friendly Rate Control Protocol)***
  - **Equation-based control**
    - **Determines the sending rate by TCP's throughput equation (determined by RTT, packet loss probability)**

$$r_{TCP} = \frac{1}{RTT\sqrt{\frac{2p}{3}} + T_0 \min\left(1, 3\sqrt{\frac{3p}{8}}\right) p\left(1 + 32p^2\right)}$$

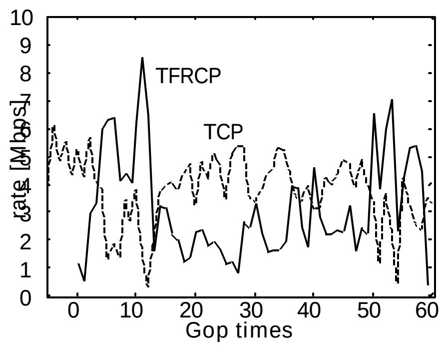
  - **AIMD control (Additive Increase/Multiplicative Decrease)**
    - **Imitates TCP's congestion window behavior**

Greedy UDP Degrades TCP Performance





Pseudo-TCP TFRCP



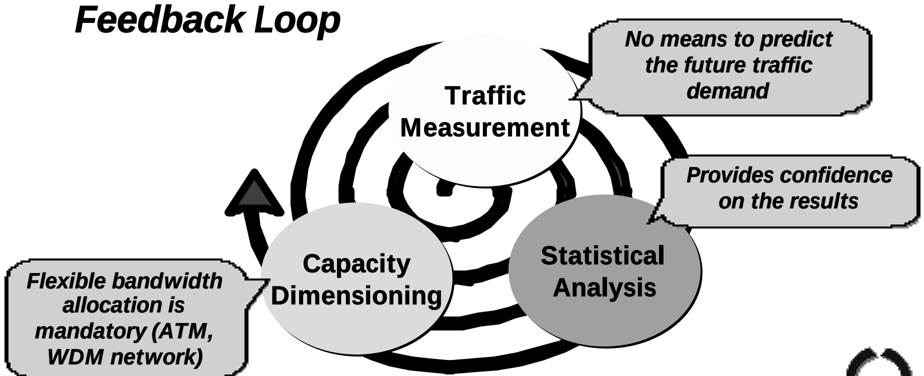
- ***Rate variation becomes relatively smaller***
- ***Average throughputs are almost same***
  - **TCP: 3.7 [Mbps]**
  - **TFRCP: 3.1 [Mbps]**
- ***MOS (Mean Opinion Score)***
  - **UDP: 2.4**
  - **Improved TFRCP: 2.6**

7. Challenges for Network Provisioning

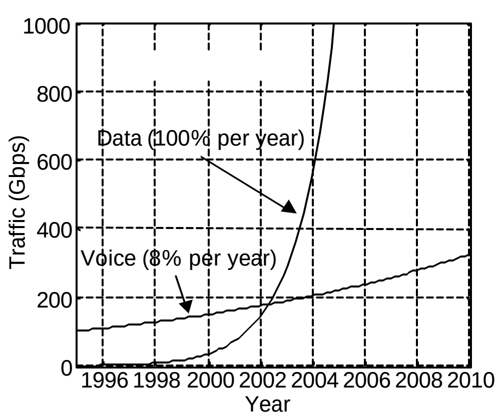
- ***QoS prediction at least at the network provisioning level***
- ***New problems we have no experiences in telecommunication***
  - **What is QoS?**
  - **How can we measure QoS?**
  - **How can we charge for the service?**
  - **Can we predict the traffic characteristics in the era of Information technology?**
  - **End-to-end performance can be known only by end users**

Spiral Approaches for Network Dimensioning

- ***Incremental Network Dimensioning by Feedback Loop***



Internet Traffic Growth



- ***Example in USA***
  - **Voice; 8% per year Data; 100% per year one magnitude per three years**
  - **K.G. Coffman and A.M. Odlyzko, "The size and growth rate of the Internet," http://www.research.att.com/~amo**
- ***Not predictable!***

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Traffic Measurement Approaches

- ❑ ***Traffic measurement projects***
  - ✘ "Cooperative Association for Internet Data Analysis," http://www.caida.org/
  - ✘ "Internet Performance Measurement and Analysis Project," http://www.merit.edu/ipma/
- ❑ ***How can we pick up meaningful statistics?***
  - ✘ Routing instability due to routing control
  - ✘ Segment retransmissions due to TCP error control
  - ✘ Rate adaptation by streaming media
  - ✘ Low utilization is because of
    - ✔Congestion control?
    - ✔Limited access speed of end users?
    - ✔Low-power end host?

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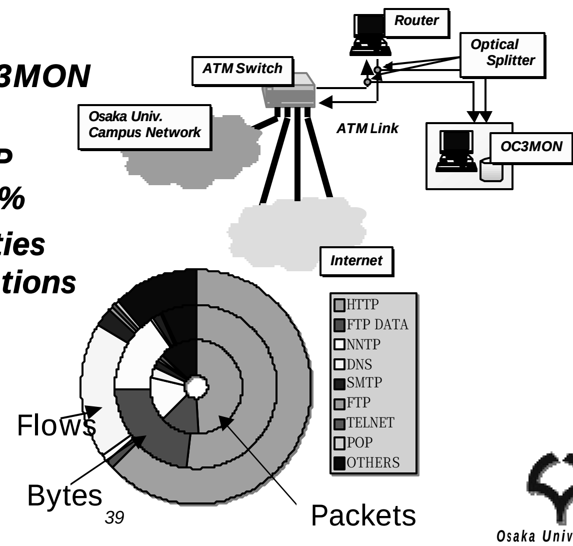
Passive and Active Traffic Measurements

- ❑ ***Passive Measurements***
  - ✘ OC3MON, OC12MON, ...
  - ✘ Only provides point observations
  - ✘ Actual traffic demands cannot be known
  - ✘ QoS at the user level cannot be known
- ❑ ***Active Measurements***
  - ✘ Pchar, Netperf, bprobe, ...
  - ✘ Provides end-to-end performance
  - ✘ Not directly related to network dimensioning (The Internet is connectionless!)

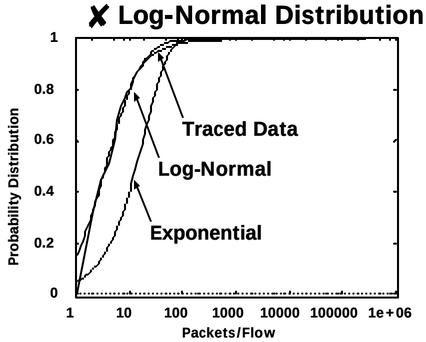
Passive Traffic Measurements

- ❑ *Collected by OC3MON on Feb., 1999*
- ❑ *The ratio of HTTP traffic is over 50 %*
- ❑ *Different properties between applications*

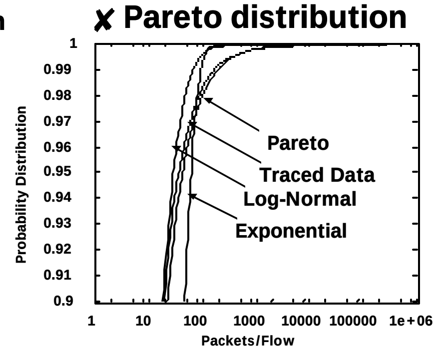


The # of Packets in the Flow

- ❑ ***Whole Distribution***
  - ✘ **Log-Normal Distribution**



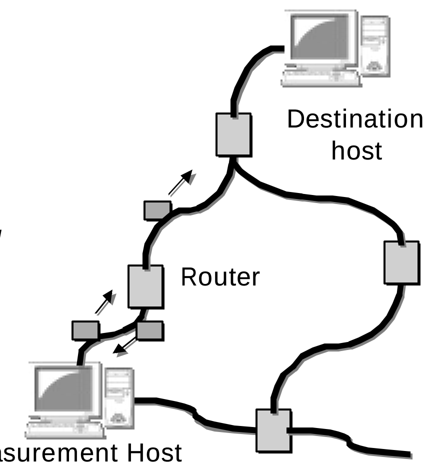
- ❑ ***Tail Distribution***
  - ✘ **Pareto distribution**



- ❑ ***Distribution on flow duration is just same as above***

Active Bandwidth Measurement Tool *Pathchar, Pchar*

- ***Send probe packets from a measurement host***
- ***Measure RTT (Round Trip Time)***
- ***Estimate link bandwidth from relation between minimum RTT and packet size***



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Relation between Minimum RTT and Packet Size

- ***Minimum RTT between source host and n*th *hop router; proportional to packet size***

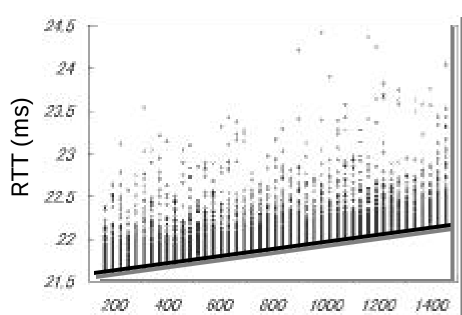
$$\min RTT_s = \sum_{j=1}^{n}\left(\frac{s+s_{ICMP}}{b_j}+2p_j\right)+\sum_{i=1}^{n} f_i$$

$$= s\sum_{j=1}^{n}\frac{1}{b_j}+a$$

$\min RTT_s$: Minimum RTT

s : Packet Size

b_j : Bandwidth of link **n**



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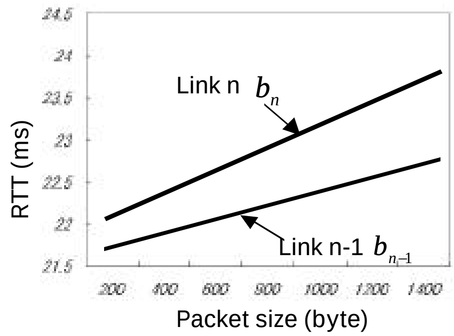
Bandwidth Estimation in Pathchar and Pchar

- ***Slope of line is determined by minimum RTTs between n*th *router and source host***

$$\sum_{j=1}^{n} \frac{1}{b_j} = \bar{b}_n$$

- ***Estimate the slope of line using the linear least square fitting method***
- ***Determine the bandwidth of n*th *link***

$$b_n = \frac{1}{\bar{b}_n - \bar{b}_{n-1}}$$



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Several Enhancements

1. ***To cope with route alternation***
   - **Clustering approach**
2. ***To give statistical confidence***
   - **Confidence intervals against the results**
3. ***To pose no assumption on the distribution of measurement errors***
   - **Nonparametric approach**
4. ***To reduce the measurement overhead***
   - **Dynamically controls the measurement intervals; stops the measurement when the sufficient confidence interval is obtained**

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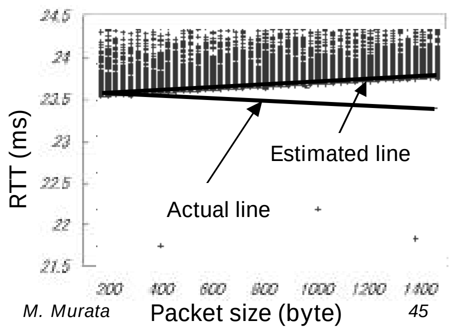
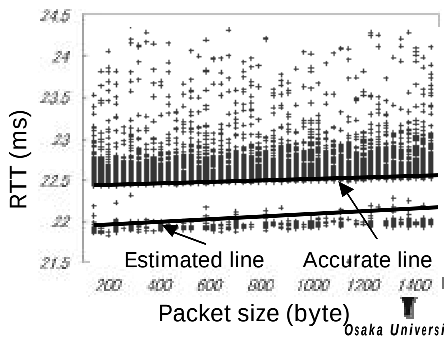
Measurement Errors

- ❑ ***Assuming the errors of minimum RTT follow the normal distribution***
- ➥ ***Sensitive to exceptional errors***

A few exceptional large errors



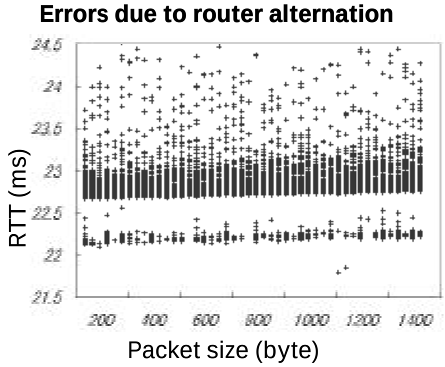
"Errors" caused by route alternation



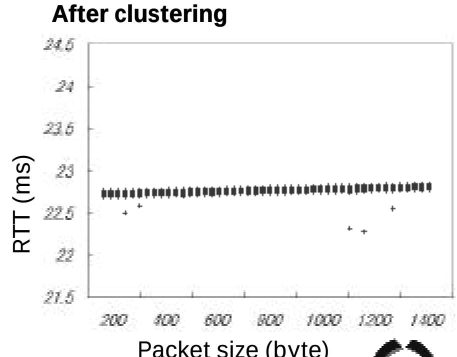
Clustering

- ❑ ***Remove "errors" caused by route alternation***

Errors due to router alternation



After clustering



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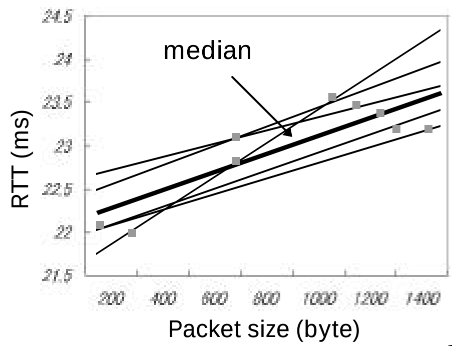
Nonparametric Estimation

- Measure minimum RTTs
- Choose every combination of two plots, and calculate slopes
- Adopt the median of slopes as a proper one
- Independent of error distributions



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Adaptive Control for Measurement Intervals

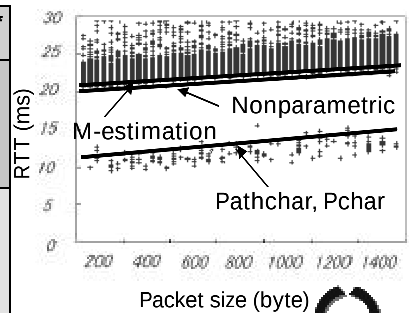
- *Control the number of probe packets*
  1. Send the fixed number of packets
  2. Calculate the confidence interval
  3. Iterate sending an additional set of packets until the confidence interval sufficiently becomes narrow

➥ *Can reduce the measurement period and the number of packets with desired confidence intervals*

Estimation Results against Route Alternation

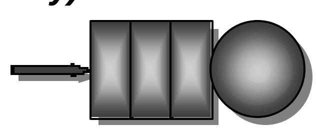
- **Effects of Clustering**
  - Can estimate correct line by the proposed method

Bandwidth	Method	Estimation Results	The # of packets
10 Mbps	Pathchar	-22.6	200
	M-estimation	10.1<12.4<16.1	200
	Wilcoxon	16.6<17.0<24.1	200
	Kendall	14.2<17.0<25.3	200
12 Mbps	Pathchar	8.25	200
	M-estimation	9.79<9.94<10.1	20
	Wilcoxon	13.3<13.8<14.4	90
	Kendall	13.6<13.8<14.1	90



Fundamental Theory for the Internet?

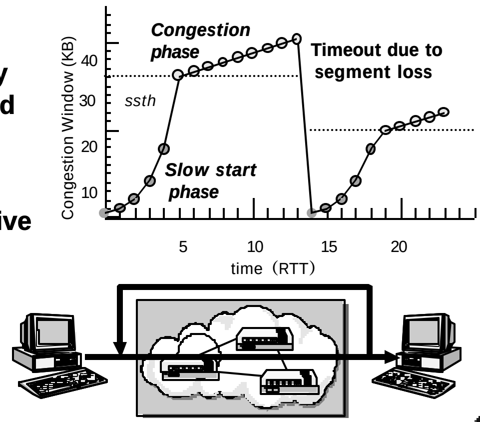
- ***M/M/1 Paradigm (Queueing Theory) is Useful?***
  - Only provides packet queueing delay and loss probabilities at the node (router's buffer at one output port)



  - ➥ Data QoS is not queueing delay at the packet level
  - In Erlang loss formula, call blocking = user level QoS
- ***Behavior at the Router?***
  - TCP is inherently a feedback system
- ***User level QoS for Data?***
  - Application level QoS such as Web document transfer time

Internet is Feedback System

- ❑ *Data applications*
  - ✘ Congestion control by TCP located at the end system
- ❑ *Streaming Media*
  - ✘ Rate and delay adaptive control by UDP/RTP and RTCP
- ➥ *Control Theoretic Approach*
  - ✘ System stability and transient behavior



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IP over WDM for the Next-Generation Internet

Contents:

1. ***Overview of Data Applications QoS***
2. ***Challenging Problems for The Next-Generation Internet***
3. ☞ ***IP over WDM: A Solution for the Next-Generation Internet?***

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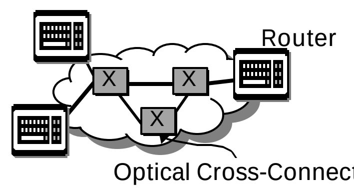
Past Researches in the Area

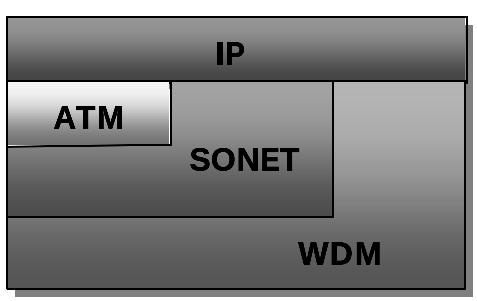
- ***Routing and Wavelength Assignment (RWA) Problem***
  - **Static assignment**
    - **Optimization problem**
  - **Dynamic assignment**
    - **Natural extension of call routing**
    - **Call blocking is primary concern**
    - **No wavelength conversion makes the problem difficult**



- ***Optical Packet Switches for ATM***
  - **Fixed packets and synchronous transmission**

Several Views for IP over WDM Networks

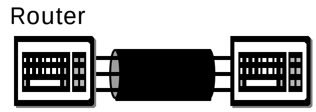
- ***IP over ATM over SONET over WDM***
- ***IP over SONET over WDM***
- ***IP over (PPP or HDLC over) WDM***



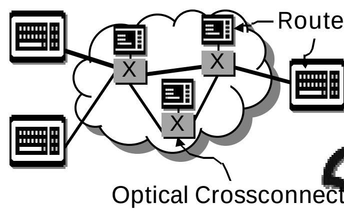
Photonic Internet Architecture

- ***Four Kinds of Architecture***

1. **WDM link network**
   - ✔ **Connects adjacent routers by WDM (multiple wavelengths increase the bandwidth**

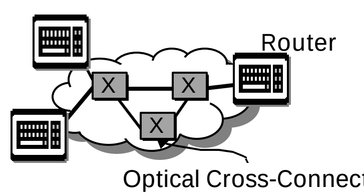


2. **WDM path network**
   - ✔ **Uses logical topology based on wavelength routing**

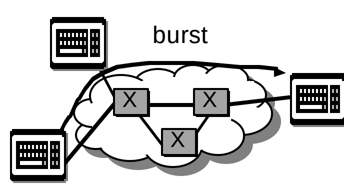


Photonic Internet Architecture (Cont'd)

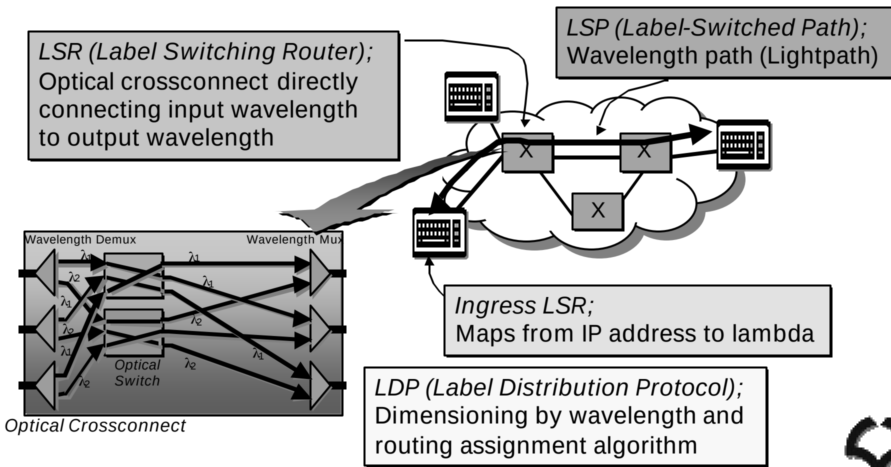
3. **WDM Path Network**
   - ✔ **Lambda switching by MPLS technology**



4. **WDM Packet-switched Network**
   - ✔ **E.g., burst switching by routing and wavelength assignment on demand basis**



Mapping from Generic MPLS to Lambda MPLS



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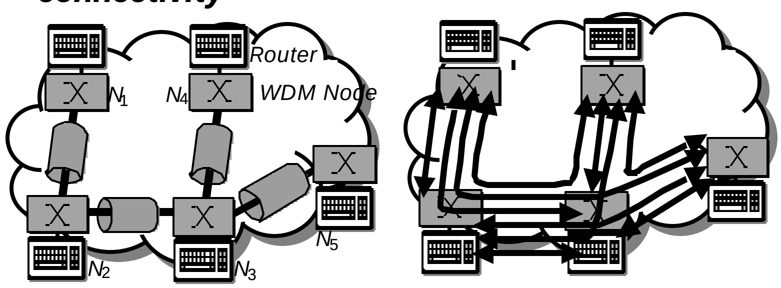
MPLS-based WDM Network

- ***Needs many wavelengths to maintain all-to-all connectivity***



- ***To reduce the # of required wavelengths, paths should be cut within the network***

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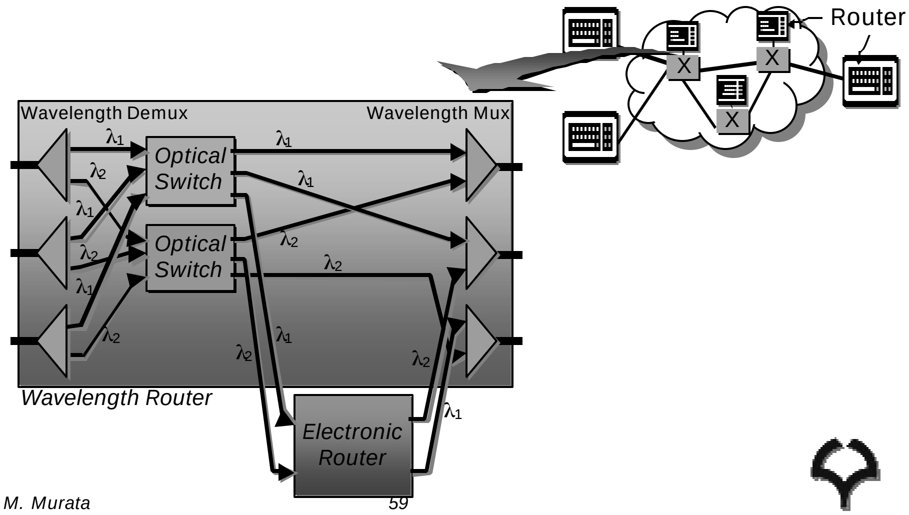
Wavelength Router in WDM Path Network



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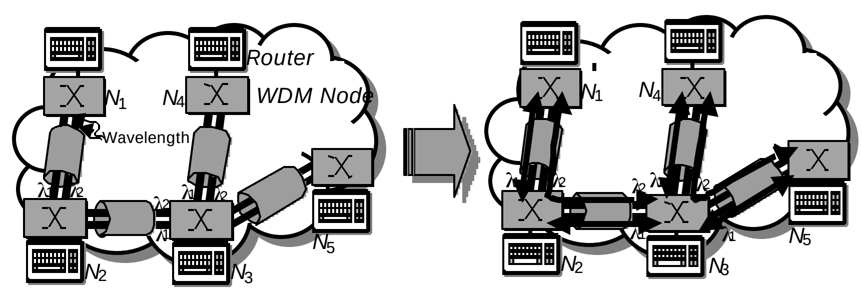
Forming Logical Topology by Wavelength Routing

- ❑ ***Physical Topology***
- ❑ ***Logical Topology***



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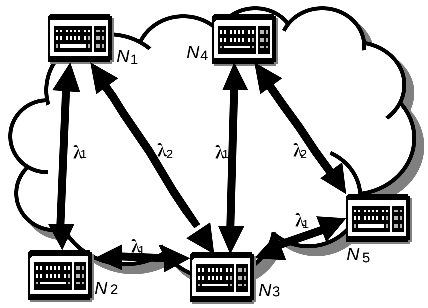
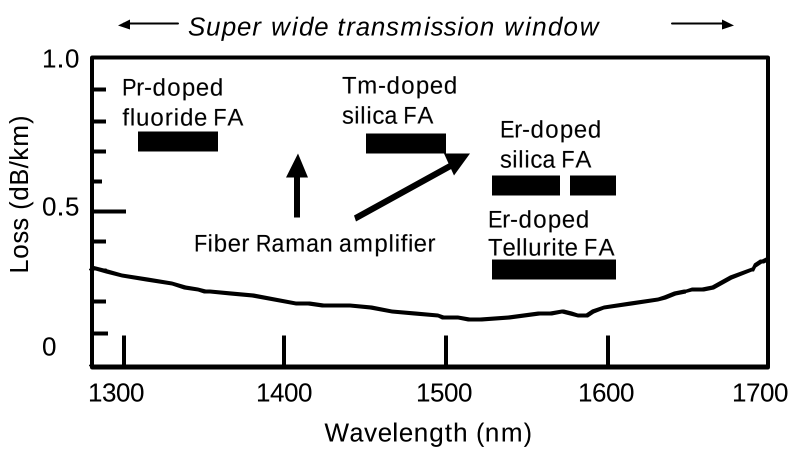
Logical View Provided to IP

- ❑ *Redundant Network with Large Degrees*
- ➥ *Smaller number of hop-counts between end-nodes*
- ➥ *Decrease load for packet forwarding at the router*
- ➥ *Relief bottleneck at the router*



Possibility of 1000-Wavelength Division Multiplexing?



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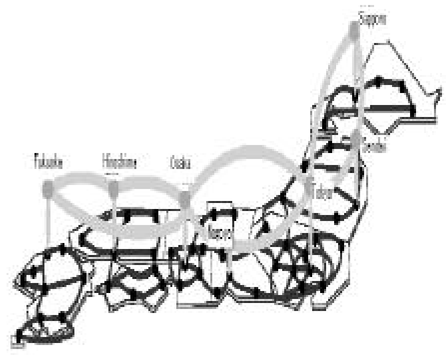
Relation between Bandwidth and # of Wavelengths/Distance

- ***50THz in Total***
  - **20 GHz**
    - **2.5 GBps,**
      2500 Wavelengths
      6,400Km
  - **50 GHz**
    - **10 Gbps**
      1,000 Wavelengths
      400Km
  - **90 GHz**
    - **40 Gbps**
      556 Wavelengths
      25Km



http://www.ntt.co.jp/databook/setubi/

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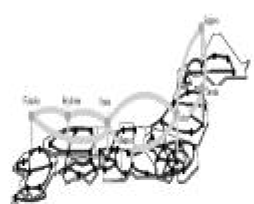
Effects of WDM with 1000 Wavelengths

- ***Given***
  - **Physical topology**
  - **Traffic demands, Traffic matrix**
- ***Derives bounds on logical topology from given physical topology***
  - **The required # of wavelengths to satisfy the degree of logical topology**
  - **The traffic volume at the router for a given degree of logical topology**
- ➥ ***Required # of wavelengths, Packet processing capability at the router***

- ***Numerical Examples***
  - **NTT's Backbone**
    - **Min degree: 2, Max degree: 9, Max hop count; 9**
  - **Traffic Matrix from NTT's Telephone Network**
    - **30 Gbps in Total (Increased by scale factor a)**
    - **http://www.ntt-east.co.jp/info-st/network/traffic/index.html**



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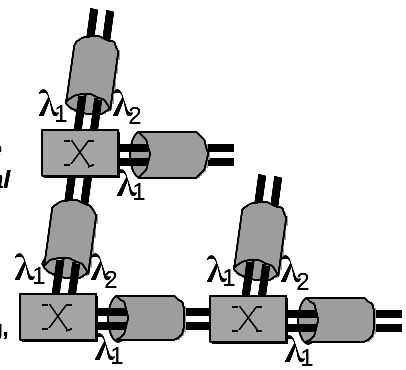
Derivations of Bounds

- ***Required # of wavelengths D:***
  - **Degree of physical topology: D_p**
  - **Degree of logical topology: D_l**
  - ➥ $D > D_l / D_p$
- ***Determine the traffic volume at the router from the degree of the logical topology***
  - **The # of one-hop paths: D_l**
    The # of two-hop paths: D_l^2
    The # of three-hop paths: D_l^3
  - **Assuming the shortest-path routing, determine the transit traffic**
  - **Get the sum of traffic on the path terminating at the router [bps] and translate it to [pps]**



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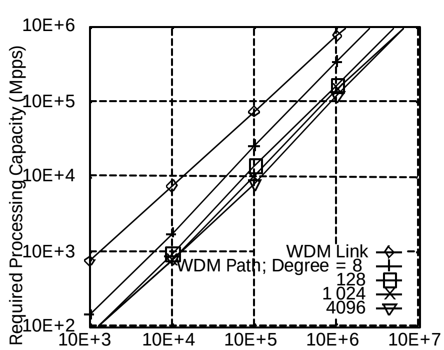
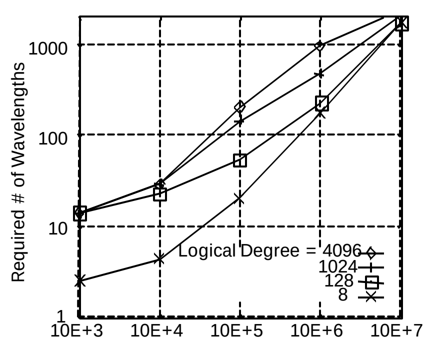
The Case of NTT Backbone Network



Traffic Volume at the Router



The Required # of Wavelengths

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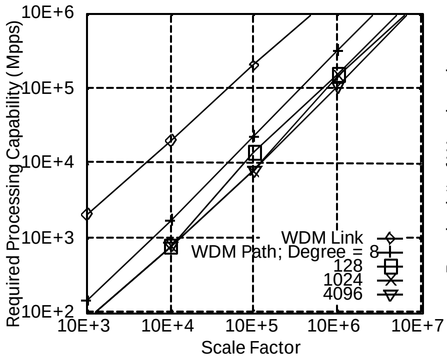
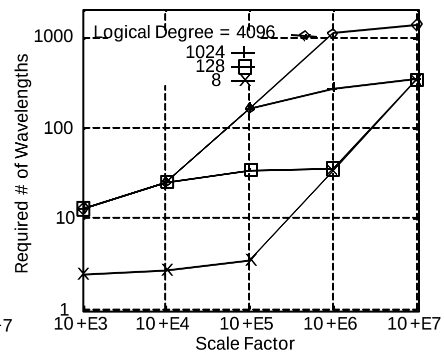
Homogeneous Traffic Case



Traffic Volume at the Router



The Required # of Wavelengths

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Do We Need More "Intelligent" WDM Network?

- ***WDM network itself has network control capabilities***
  - ✘ **Routing function**
    - ✔**IP also has it!**
  - ✘ **Congestion control function**
    - ✔**TCP also has it!**
    - ✔**TCP over ATM (ABR service class) is difficult to work well Parameter tuning of control parameters in ABR is not easy**
  - ✘ **Connection establishment**
    - ✔**IP is connectionless**
    - ✔**Multimedia application does not require 10Gbps channel**
  - ➥**Functional Partitioning vs. Multi-layered Functionalities?**
- ***Important is reliability***

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Functional Partitioning between IP and WDM?

- ***Reliability functionalities offered by two layers***
  - **IP Layer: Routing**
  - **WDM Layer: Path Protection and Restoration**
- ***WDM should provide its high-reliability mechanism to IP***
  - **Protection mechanism**
    - ✔ **link protection**
    - ✔ **dedicated-path protection**
    - ✔ **shared-path protection**
  - **Network dimensioning is important to properly acquire the required capacity of IP paths (traffic glooming)**
    - ✔ **Reconfiguration mechanism of logical topology by wavelength routing**

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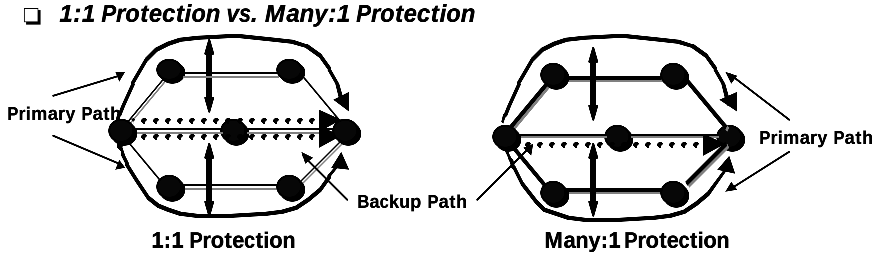
WDM Protection

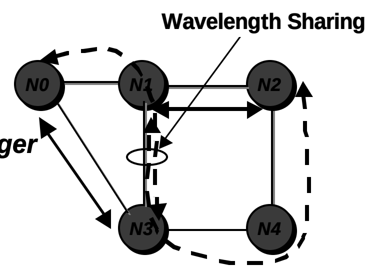
- ***Immediately switch to backup path on failure of nodes/links***
  - **In the order of 10ms**
- ***1:1 Protection vs. Many:1 Protection***



- ***Protection technique suitable to IP over WDM network?***
  - **IP has its own protection mechanism (i.e., routing) while it is slow**
  - **We want an effective usage of wavelengths**
  - **Many:1 protection is reasonable**

Formulation of Reliability Design Problem for Many-to-1 Path Protection

- *Objective*
  - Minimize the utilized wavelengths in total
- *Given Conditions*
  - The number of wavelengths on the fiber
  - Physical topology and logical topology
  - Primary routes
- ➥ *Formulated as MILP (Mixed Integer Linear Problem)*
- *Application to 5-node network*

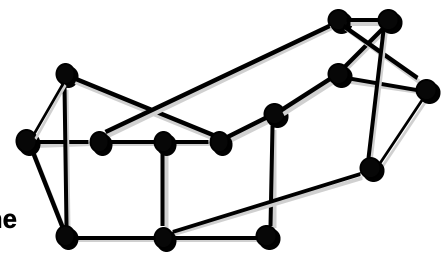


Application to Large-Scaled Network

- *Previous formulation is MILP; difficult to be applied to the large-scaled network*
- Min-hop-first approach
  - It is rare that lightpaths with a small number of hop counts contend the backup lightpaths
  - First protect the lightpaths with small hop-counts, and then protect lightpaths with large hop-counts using the remaining wavelengths
- Largest-traffic-first approach
  - Assign the paths in a descending order of the traffic loads
- Random approach
  - For only reference purpose

Network Model

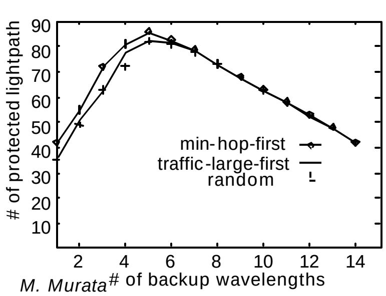
- ***NSFNET;***
  - **14 node**
  - **20 physical links**
- ***Logical topology is first determined by MLDA***
  - **First set up the lightpaths between adjacent nodes**
  - **Set up the lightpaths for the path in a descending order of traffic volume**

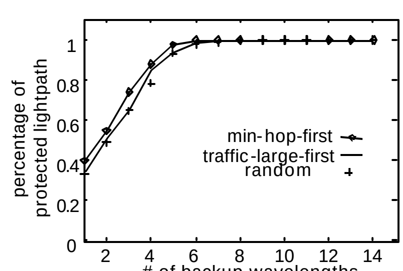


NSFNET

Effect of Min-Hop-First Approach

- ***Fix the # of wavelengths on the fiber; 16***
- ***Change the # of wavelengths dedicated to primary lightpaths to compare the # of protected lightpaths***

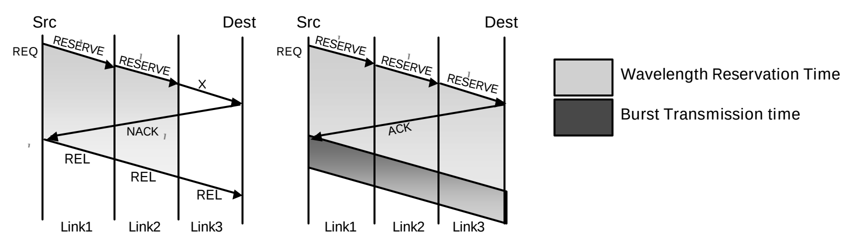




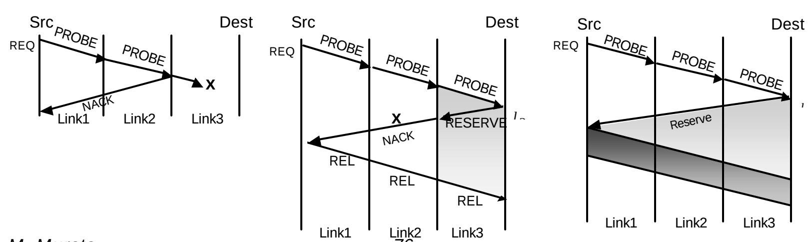
Optical Burst Switching: Pure WDM Packet Network

- ***Wavelength between source and destination is reserved on demand basis for the burst***
- ***After the wavelength is reserved, burst is transferred from source to destination***
- ***Wavelength Reservation Protocol***
  - **Forward Reservation Protocol**
    - **Wavelength reservation is performed along the *forward* path**
  - **Backward Reservation Protocol**
    - **Reservation along the *backward* path**
- ***Reservation time is overhead, and determines the performance***

Forward Reservation Protocol

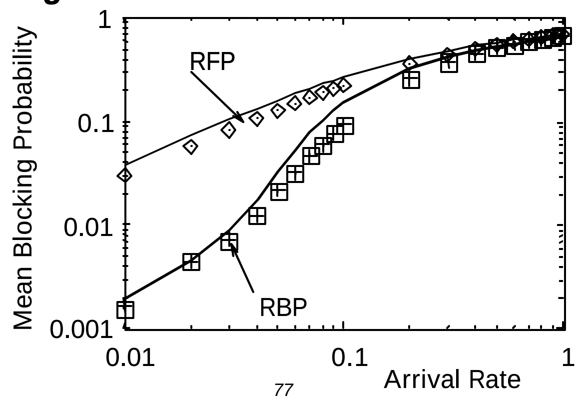


Backward Reservation Protocol



Comparisons of Forward and Backward Reservation Protocol

- ***16-node mesh Torus network with eight wavelengths***



References

- ***References can be found in***
  Masayuki Murata, "Challenges for the Next-Generation Internet and the Role of IP over Photonic Networks," to appear in IEICE Transactions on Communications, Special Issue on "Advanced Internetworking on Photonic Network Technologies," October, 2000