TIME-BASED RESOURCE RESERVATION FOR END-TO-END QUALITY OF SERVICE IN PACKET NETWORKS

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Presentation Outline

• What is “Quality of Service” (QoS)?
  – IP Protocol and Network Issues
• Applications…and Associated QoS Requirements
  – VoIP
  – Video Conferencing over IP
  – Other Applications …. 
• QoS Approaches
  – Over Provisioning
  – Prioritization (i.e., queue management) and DiffServ
  – Time-based Resource Reservation (TbRR)
    • Sequencing
    • Autonomous Flow Scheduling
    • Relationship to MPLS
• Other Technology Approaches:
  – Pseudowire Emulation End-to-End (PWE3)
  – Provider Backbone Transport
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WHAT IS QUALITY OF SERVICE?

• Quality of Service is the Network’s Contribution to Quality of Experience
  – QoExperience (QoE) = QoApplication (QoA) + QoService (QoS)

  \[ QoE = QoA + QoS \]

Without Network-layer QoS, Exceptional QoE is Impossible

• QoS Metrics:
  – Minimize Delay (congestion-based)
  – Minimize Delay Variation (jitter)
  – Minimize Packet Loss
  – Minimize Packet Loss Variation
  – Security and reliability, though important, are not included

• Emphasis on “Real-Time Applications”
  – TCP/IP is inappropriate
WHAT IS QUALITY OF SERVICE?

...Network Issues

- **Utilization**
  - More is better
- **Convergence**
  - Application agnostic
  - Accommodate customers’ diverse and evolving applications
- **Scalable**
  - Lack of extensibility limits network value
- **Operation, Administration, Management and Provisioning (OAM&P)**
  - “Tis a gift to be simple”
- **Infrastructure**
  - Build on what you have – avoid expensive upgrades or change-outs
- **Standards Compliance**
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Voice over IP

- **Delay**
  - An Interactive Application…
    - ITU-T: ≤ 150 ms, one way delay
    - Bell Labs: < 100 ms

- **Delay Variation (Jitter)**
  - An acknowledged problem
    - A two-packet receiver jitter buffer

- **Packet Loss Rate (PLR)**
  - Tenths to a percent
    - Packet loss concealment (PLC) is possible

- **Packet Loss Variation**
  - An issue for low-rate-bit-rate predictive coding
Voice over IP - Overhead

- **G.711 Voice Packet = 238 Bytes**
  - 160-byte G.711-encoded payload
  - 12-byte Real Time Protocol (RTP)
  - 8-byte User Datagram Protocol (UDP)
  - 20-byte IP (OSI Layer-3) header
  - 38-byte Ethernet (OSI Layer-2) frame

- **160-Byte Payload → 238-Byte Packet !**
  - 64-kb/s TDM DS0 = 95-kb/s “IP-DS0”
  - 48% overhead
  - 24 DS0’s in a “T1” carrier frame reduced to 16 “IP-DS0s”

- **1536 kb/s → 1024 kb/s (67%)**
Voice over IP - Delay

• Requirement: 100 → 150 ms
• Delay Debits
  – G.711 packet creation = 20 ms
  – Jitter buffer (2 packets = 40 ms)
  – Transport @ 0.67 Speed-of-Light
    ▪ 3000 straight-line miles = 40 ms

• Leaving 0 → 50 ms for Queuing Delay
Voice over IP

• Packet Loss

– Relating packet loss to Mean Opinion Score (MOS):

  ▪ From the literature (Nortel Networks; Univ. Cal Berkeley):

    – 0.0 to 0.2% packet loss → Excellent quality (MOS = 5)
    – 0.2 to 0.5% packet loss → Good quality (MOS = 4)
    – 0.5 to 2.0% packet loss → Fair quality (MOS = 3)
    – 2.0 to 4.0% packet loss → Poor quality (MOS = 2)
    – Greater than 4.0% loss → Unacceptable (MOS = 1)

Voice over IP

Network Implications… An Example

• Assume a 15 node network
  – T-1 ingress and egress, with OC-3/-48 connectivity
  – 64-packet queue depth (standard router configuration)
    ▪ Greater queue depth increases delay
  – Packet Loss/MOS profile – as described
  – G.711 VoIP packetization + headers
  – Delay bound (in ms): 150 total – 20 packetization – 40 transport
    – 40 jitter buffer leaves
    ▪ 50 ms for queueing delay
Hop Distribution as measured by Cooperative Association for Internet Data Analysis (CAIDA)
VoIP MOS vs Network Utilization

VoIP Degrades Beyond 10-15% Network Utilization!

Service providers would likely overprovision the IP network by > X 6 → X 10
A Less-Constrained VoIP Network Scenario

- **Remove delay bound** from the analysis
- **Retain router queue depth and network topology**
  - T-1 ingress and egress, with intervening OC-3/-48 connectivity
  - 64-packet queue depth (standard router configuration)
    - Greater queue depth could increase delay while reducing loss
  - Packet Loss/MOS profile (as mentioned)
IDEAL: VoIP MOS vs Network Utilization

Performance “Improves” to ≈ 30 - 35% Network Utilization
Voice over IP – Concluding Observations

• QoS “Expectations” Have Been Reset
  – We Tolerate Dropped Calls, Longer Delay, and Poorer Voice Quality

• Broadband Access is Important
  – T-1 (1.544 Mb/s) is not enough
  – Link efficiency is reduced
  – Delay is increased
  – Audio quality is diminished
  – HOWEVER - The consumer accepts these for mobile voice, and will for wired telephony

• My Guess:
  – Mixing voice with other applications won’t work
    ▪ Video with voice is problematic: long video packets delay shorter voice packets
      – More delay and packet loss
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Video Conferencing over IP

• As Interactive as Speech
  – 100 → 150 ms one-way delay

• Delay Variation (Jitter) Requirements are Similar to Speech

• Packet Loss Ratio (PLR)
  – 0.1% to 1.0%, per ITU-T draft recommendation*
    ▪ Loss concealment difficult; subject of on-going study

• Packet Loss Variation Potentially a BIG Problem
  – Interframe coding

• No Industry-Wide Consensus on Performance Metrics

*“Multimedia QoS Service Classification,” ITU-T Temporary Document
  TD-31, Study Group 16, Q, D, F, G, 2-5/16 Rappoteur
  Meeting, October-November 2001
Packet Loss vs. Utilization for an Ideal Video Conferencing Network

- Assumptions
  - 15-hop path, as before
  - No network delay; no jitter buffer delay
  - 64-packet router queue; the only source of packet loss
  - Non-parametric queue (Multiscale Queue - Rice University)
  - Hour-long, million-packet traces from Lawrence Berkeley Laboratory*

*ACM Internet Traffic Archive: http://www.acm.org/sigs/sigcomm/ITA/
Measured traffic profile  Note bursty, unpredictable behavior

ACM Internet Archive: http://www.acm.org/sigs/sigcomm/ITA/

UDP packet arrivals at Lawrence Berkeley Laboratory
Packet Loss vs Network Utilization
(Superimposed 20 – 30% Anecdotal Experience)

No delay bound
~ 20 to almost 30% utilization
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Other “Real-Time” Applications

• **IPTV**
  – Interactivity becoming an issue…
  – Packet Loss Ratio (PLR): 0.0000001 (10 exp -7)
    - 10 exp -11 has been mentioned
    - Packet loss accentuates frame loss
    - FEC being considered
      - Adds additional overhead and delay
• **Broadcast**
  – Not interactive
  – Jitter is important
  – PLR similar to IPTV
• **Storage Networks**
  – Requires predictable delay for “back-ups”
    - TCP is *not* predictable
Other “Real-Time” Applications (Cont’d)

- **Private-Line Emulation (PLE)**
  - Same delay/jitter requirements as VoIP
  - PLR: $0.000001 \ (10 \ exp \ -6)$
  - Circuit emulation is not PLE
    - IETF PWE3 WG makes no assumptions about service quality

- **Network Games**
  - Very low delay
  - PLR - ?

- **Real-time Applications Use UDP – not TCP**
UDP vs TCP

- Data is invariably TCP/IP
  - Most Real-time IP applications use User Data Protocol

- UDP is NOT a TCP/IP Friendly Protocol!

“New trends in communications, in particular the deployment of multicast and real-time audio-video applications, are likely to increase the percentage of non-TCP traffic in the internet...The Internet community strongly fears that the current evolution could lead to collapse and starvation of TCP traffic.”

UDP Erodes TCP Goodput

A Personal Perspective on CONVERGENCE

• CONVERGENCE
  – “The ability to accommodate a full breadth of important user applications on a single IP Internetwork”
    ▪ Heterogeneous applications
    ▪ Widely differing performance requirements
    ▪ One network

• Without Convergence…
  – An overlay network for every individual application?
    ▪ If not VoIP in a converged environment, then PSTN
    ▪ If not Video Conferencing via IP, then use ISDN
    ▪ If not IP VPNs, then Private Lines with TDM Leased Lines
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ACHIEVING QUALITY OF SERVICE

• Over Provisioning
  – Estimates range as high as 12X (8% utilization)
    • How much depends on application or mix
    • No one knows precisely how much is enough – performance is probabilistic
  – Expensive – doesn’t scale – no service guarantees

• Nearly All Other Methods Involve:
  – Queue Management with Prioritization
    • DiffServ is one example
    • Numerous other methods are the subject of on-going research…

• Time-based Resource Reservation (TbRR)
  – Akin to TDMuxing of IP Packets
  – Ideally suited for critical flows
    • Especially delay- and packet-loss-sensitive applications
  – Not limited to real-time applications
    • E.g., storage data
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Over-Provisioning

Additional bandwidth reduces the possibility of packet contention...

Over-Provisioned Flows

Additional bandwidth spaces out packets to avoid contention
“AVerAGE” UTILIZATION

ACM Internet Archive
# How Much Over Provisioning is Enough?

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<td>8% VoIP Link Utilization; (Overprovision X 12)</td>
<td>Sevcik, “The Pitfalls of Scaling VoIP, Business Communications Review, March 2002 (Analytic simulation)</td>
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<td>20 - 30% Data Link Utilization (Overprovision X 3 – 5)</td>
<td>Anecdotal; reported here</td>
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<td>10% Link Utilization (Overprovision X 10)</td>
<td>IETF: draft-baker-tsvwg-mlpp-that-works-01.txt (February 2004); Cisco Systems</td>
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### Conclusion: Use < 30% - - - and Waste >70% 😞 ?
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Prioritization?  

Is Prioritization the answer? 

Does it work today?

Will it work in IP networks?
WHAT WE KNOW ABOUT PRIORITIZATION

• “When Everyone has Priority – No One has Priority”
  – I.e., Doesn’t scale to high levels of utilization
    • Degrades to “best effort”
• Highest Priority Starves Lower-Priority Traffic
• Impossible to Provide Multiple, Ordered, Service Classes (Gold, Silver, and Bronze) that Include:
  – Packet loss, jitter, and queuing delay
• Lacks QoS Guarantees
  – Probabilistic
• Organizational Barriers Impede Multiple Applications on a Single Network
  – IT concern that heterogeneous applications will contend
  – Paraphrasing George Orwell in Animal Farm: “All applications are equal, but some applications are more equal than others.”
• IETF DiffServ: Structured Approach to Classify Packets for Prioritization
Prioritization

Does not work when traffic flows are of equal priority (i.e., prioritization does not scale)

Contending traffic causes delay and packet loss
Prioritization

Prioritization may allow traffic flows to move through the network with quality, but low priority traffic is not protected…

Prioritized Flows

<table>
<thead>
<tr>
<th>Green</th>
<th>Red</th>
</tr>
</thead>
<tbody>
<tr>
<td>= High Priority</td>
<td>= Low Priority</td>
</tr>
</tbody>
</table>

Prioritized traffic
• Incidentally…
  – There is a service ordering problem across multiple QoS metrics:

“In particular, considering QoS vectors comprised of mean packet loss, packet loss variance, mean queueing delay, and queueing delay variance, independent of whether network contention is high or not, it is impossible for a service class to deliver better quality of service in each of the measures over some other service class.”

Delay and Jitter QoS Classes with Diff-Serv

• Moreover…
  – Difficult to deliver delay and jitter QoS
    relative services using Diff-Serv

“…under bursty traffic conditions, it is intrinsically difficult for one service
class to deliver quality of service superior in both mean – and business-
related QoS measures – delay and jitter – over another when [Diff-Serv]
is employed by routers.”

Expected Performance of Differentiated Services

Actual Performance of Differentiated Services

Measurements on a major US carrier across 16 city pairs
DOES PRIORITIZATION WORK?
DOES PRIORITIZATION WORK?

- When everyone has priority, no one has priority

Starved packets
DOES PRIORITIZATION WORK?

- Absence of QoS Guarantees
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WHAT IS DiffServ?

- **DiffServ** = Differentiated Services
- **A Means to Classify** IP Packets
  - An extension of the old Type of Service (ToS) bits
  - Alone, classifying IP packets does not provide QoS
  - Packet classification must be *coupled* to policies and queuing behavior
- **DiffServ Code Points (DSCPs)** are a 6-bit Field in the IP Packet Header
  - $2^{6} = 64$ possibilities
- **Coupled** DSCPs and Queues are Summarized in the Next Slide…
DSCPs and ROUTER QUEUES

DSCP 101 110 Corresponds to Expedited Forwarding, EF. EF uses low latency queues for critical, highest-priority data flows (“real time”)

The following DSCPs are Allocated for Assured Forwarding, AF. AF uses less-robust queuing policies, e.g., Weighted Random Early Detection and Weighted Round Robin

<table>
<thead>
<tr>
<th>Drop Precedence</th>
<th>Class 1</th>
<th>Class 2</th>
<th>Class 3</th>
<th>Class 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Drop</td>
<td>AF11 = 001010</td>
<td>AF21 = 010 010</td>
<td>AF31 = 011 010</td>
<td>AF41 = 100 110</td>
</tr>
<tr>
<td>Medium Drop</td>
<td>AF12 = 001 100</td>
<td>AF22 = 010 100</td>
<td>AF32 = 011 100</td>
<td>AF42 = 100 100</td>
</tr>
<tr>
<td>High Drop</td>
<td>AF13 = 001 110</td>
<td>AF23 = 010 110</td>
<td>AF33 = 011 110</td>
<td>AF43 = 100 110</td>
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DSCP 000 000 is Default (e.g., Best Effort)

Other DSCPs might be used for infrequent, internal, network messages, e.g., alarms, routing-table updates, etc.
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GENERIC TIME-BASED RESOURCE RESERVATION TECHNIQUES

- Reserve IP “Resources” for Most-Critical Traffic on the Basis of Time
  - Link throughput is reserved before flow initiation, rather than sharing/contention.
  - Eliminates need for complex packet buffer management
  - Requires synchronization (widely available GPS, BITS, CDMA, PCR)

- Implications:
  - Significantly reduces delay
    - Analysis shows that time spent in a queue is a major source of packet delay
    - Minimal to no jitter
  - Without contention, there is no layer-3 packet loss
    - Loss concealment techniques are unneeded
  - QoS guarantees, rather than statistical
  - High level of network utilization

- Leaves Open the Possibility of Prioritization – for Less Important Applications

- A Variety of Techniques (“Time-driven Priority”; “Layer-1 Switching”; “Sequencing”; and “Autonomous Flow Scheduling”)
  - Not all comply with communications standards
  - Most require specialized routers or switches
    - Limited to fork-lift or green-field networks
• Synchronized Sources
• **Time**-based, Centralized Reservations
• Centrally Determined, Connection-Oriented Paths
• Requires Precise Knowledge of Link and Switch-Fabric Delays
NETWORK ARCHITECTURE – SEQUENCING

Time Reference e.g., GPS

Sequence Agent
Connection Setup: Computes End-to-End Itineraries and Downloads Local “State” Information to every SSR

Endpoint Application

Scheduled Switch/Routers (SSRs)

Scheduled Switch/Router with Local or Distributed Timing; Stores Local “State” Information

Application-dependent Timing at endpoints, and/or master nodes, and/or every node
TRADITIONAL “FIFO” QUEUE MANAGEMENT

Simple queue management: FIFO

Delay- or loss-sensitive packet

Future - Time - Present

Present - Time - Future
CONTRASTING FIFO AND SEQUENCING QUEUE MANAGEMENT

Simple queue management: FIFO

Time-based switch/routing – “Sequencing”

Delay- or loss-sensitive packet

Future - Time - Present

Present - Time - Future
Flow Alignment

Sequencing aligns multiple IP flows – packets arrive in a precise sequence – eliminating contention

*Sequenced Flows*

*No impairment of IP traffic*
- No packet loss
- No delay
- No jitter
SEQUENCING: TYPICAL FRAME STRUCTURE

Heartbeat: Path Delay and Timing

Guard Band

Appointment

Sequenced Packet

Schedule Period

EXAMPLE:

100 Mb/s Link; 20-ms Schedule Period; 250-byte Appointment; → 1000 Appointments, at 20 μs each

G.711 Ethernet Voice Packet:

- 160-byte payload, 12-byte RTP header, 8-byte UDP header, 20-byte IP header,
- 38-byte Ethernet frame = 250 bytes = 1 Appointment

With a 50-byte Appointment, G.711 Ethernet Voice Packet = 5 Appointments
<table>
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Schedule Period

SSR 3

SSR 2

Buffered Itinerary Delay

Path Propagation Delay

Scheduled Endpoint

Schedule Period

Appointment
Attributes

• **Zero** Packet Loss
• **Zero** Packet Loss Variance
• **No or Minimal** Congestion-based Queueing Delay and Jitter
• **Guaranteed** Throughput
• **Perfect** Flow Isolation
  – Immune to TCP-UDP interaction
Storage Attached Networks are not “real-time”, however

They require:

- Deterministic behavior
- Immunity to traffic load
- Geographical extensibility
  (IP in the WAN)

Open Issues

• Centralized versus Distributed Path Determination
  – Distributed route determination widely used
    ▪ Little question about scalability
    ▪ Internet traffic is not quiescent – flows come and go
  – Centralized network knowledge assures “Network Busy”
    ▪ Facilitates policy management…
    ▪ But is it scalable?

• Node (Switches and Routers) Technology
  – Special-purpose devices
    ▪ Fork-lift or green-field applications
  – Legacy devices

Moore, “Packet Sequencing: A Deterministic Protocol for QoS in IP Networks”,
IEEE Communications Magazine, October 2003
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• AUTONOMOUS FLOW
• SCHEDULING

Also Known As...

• AUTONOMOUSLY
• SCHEDULED FLOWS
THE “HOW” OF AUTONOMOUS FLOW SCHEDULING

• Uses DiffServ (In a Novel Way!)
  • Commercial, standards-compliant routers; customary routing protocols; easily configured priority or low-latency queuing

• Hierarchically Ordered Traffic
  1. Critical Traffic (Highest Priority Traffic Uses Expedited Forwarding, EF (DSCP 101110))

  No resource contention among real-time flows, because…

  2. Discovery Finds and Reserves “Time Slots” (2nd Priority; Assured Forwarding AF)

  3. Other Traffic Receives Lower Priority (Lesser AF classes, and Default – “Best Effort”)

    • Use with traditional prioritization techniques
NETWORK ARCHITECTURE

– Simple!
– DiffServ-Enabled Routers
– Synchronized End-Points

Time Reference e.g., GPS, CDMA...

Access Edge Device (AED)

Endpoint Application

DiffServ-Enabled Edge, Access, and Core Routers

Customary Network (Routers/Protocols)

AED:
• Interfaces to application and network
• Administers admission control, and
• Synchronizes packets for network ingress.
ESTABLISHING THE FIRST AUTONOMOUSLY SCHEDULED FLOW

Common Time Interval (CTI)

(a) Common Time Interval (User Traffic Not Shown)
ESTABLISHING THE FIRST AUTONOMOUSLY SCHEDULED FLOW

(a) Common Time Interval (User Traffic Not Shown)

(b) Discovery Flows
ESTABLISHING THE FIRST AUTONOMOUSLY SCHEDULED FLOW

(a) Common Time Interval (User Traffic Not Shown)

(b) Discovery Flows

(c) Establishment of First ASF; Less-Critical Traffic Not Shown
ESTABLISHING A SUBSEQUENT ASF

(a) Introducing Discovery Flows, in the Presence of an ASF
ESTABLISHING A SUBSEQUENT ASF

(a) Introducing Discovery Flows, in the Presence of an ASF

(b) Two ASFs; Non-ASF Traffic Not Shown
ESTABLISHING A SUBSEQUENT ASF

(a) Introducing Discovery Flows, in the Presence of an ASF

(b) Two ASFs; Non-ASF Traffic Not Shown

(c) Two ASFs, with Non-ASF Traffic (on the link and queued)
PICTORIAL CAPTURE OF LINK UTILIZATION

CTI: 10 milliseconds, 1 GigE link

Transmitter
Receiver
PICTORIAL CAPTURE OF LINK UTILIZATION

Transmitter
10% Utilization

Receiver

CTI: 10 milliseconds, 1 GigE link

Three 33-Mb/s Flows
PICTORIAL CAPTURE OF LINK UTILIZATION

Transmitter
Six 33-Mb/s & Two 4-Mb/s Flows
CTI: 10 milliseconds, 1 GigE link

Added at Transmitter

Receiver
Two 33-Mb/s & Two 4-Mb/s Flows

21% Utilization
AUTONOMOUS FLOW SCHEDULING

• QoS for Any Application
  – Application Agnostic: Audio, Video, other real-time or non-real-time applications)
    • No packet loss
    • Minimal jitter
    • Low delay

• High Network Utilization
  – With guaranteed throughput

• Scalable
  – Existing Internet routing protocols
  – No “state machines”

• Easily Managed

• Conventional Switching/Routing Technology
  – Existing, standards-compliant DiffServ-enabled routers
  – Interoperable with MPLS

• Synchronization
  – Readily available sources
    • GPS, CDMA, BITS, Primary Clock Oscillators
CASE STUDIES – MAJOR MEDICAL CENTERS IN NEW YORK CITY
TWO CASE STUDIES – MAJOR MEDICAL CENTERS IN NEW YORK CITY

• New York University Medical Center, New York City
  – Multi-facility environment
  – Converged IP network supporting: data, voice, medical information, videoconferencing, and video, with upgrade to high definition (HD)
Real-time ASF Video in a Converged IP Network

Operating Room
- Patient Monitoring
- Cameras

ASF Video Playback Software on PCs

Conference Room #2
- AED
- Projector
- AED and SAN
- ASF Management

Conference Room #1
- Projector
- Lecture Hall
- Projector

Converged IP Network

- AFS Real-time IP Video
- Analog Video
- XGA
- GigE
END-USER ASSESSMENT

“New York University joins the very small group of elite institutions moving toward video on a fully converged network. The technical and operational quality on display today was apparent to every conference attendee, and underscores the importance of your work to the Medical center. You have ushered in a new era of digital media facilities on campus.”

Assistant Dean of Advanced Applications, New York University School of Medicine
SECOND CASE STUDY – MAJOR MEDICAL CENTERS IN NEW YORK CITY

• Memorial Sloan-Kettering Cancer Center
  – Upgrade to existing IP LAN
    • Unsatisfactory video performance (packet loss) at <10% utilization
      – With AFS, tested to ≈ 90%
    – 21 Operating Rooms
    – Video, voice, and archival storage
Hospital Campus-Wide Video Distribution

Operating Room
- Nurse’s Station
- Data Monitoring
- Touch Panel
- AV Switch
- Legacy Image Device

Hospital-wide Offices with Video Endpoints
- AED
- Image Device
- AV Switch
- Nurse’s Station

Existing IP LAN Network
- AED
- Monitor
- SAN with integrated AED
- AFS Management
- Hospital Databases and Infrastructure

Control Room
- AED
- Projector
- Lecture Hall

Pathology Lab
- AED
- Microscope
- AED

AFS Real-time IP Video
- Analog Video
- RS-232 Control
- GigE
END USER ASSESSMENT

“After months of operation, hundreds of hours of video flows, not a single lost packet.”*

“…The best news is, since we went live, I haven’t heard from the IT guys.”

Engineering Specialist, Memorial Sloan-Kettering Cancer Center

* Service turned up May 1, 2006; thousands of surgeries; no packet loss
Presentation Outline

• What is “Quality of Service” (QoS)?
  – IP Protocol and Network Issues
• Applications…and Associated QoS Requirements
  – VoIP
  – Video Conferencing over IP
  – Other Applications ….

• **QoS Approaches**
  – Over Provisioning
  – Prioritization (i.e., queue management) and DiffServ
  – **Time-based Resource Reservation (TbRR)**
    • Sequencing
    • Autonomous Flow Scheduling
    • **Relationship to MPLS**

• Other Technology Approaches:
  – Pseudowire Emulation End-to-End (PWE3)
  – Provider Backbone Transport

• Summary
Multiprotocol Label Switching

• A Technology Going Back Over 10 Years
  – Immediate need: *Speed* - circumvent slow (software-based) *routing* with faster *switching*
    • Routing requires examining Layer 3 packet address
    • Switching is simpler: Layer “2½” addressing (“labels”)
    • No longer a compelling need
      – Software-based routers since replaced by (terra-bit) hardware-based routers
  – Additional Attribute: Multiprotocol
    • IP, Frame Relay, and ATM
      – MPLS makes possible a common switching platform
        » ATM is dead
        » Frame relay generally deployed at < DS-3 (45 Mb/s) speeds
        » IP emerging as the preeminent protocol
  – Basis for carrier Virtual Private Network (VPN) Services
    • Labels can intrinsically aggregate individuals flows for a customer
      – “Siller” → Curtis, Patsy, Deborah, Freddy

• What Doesn’t MPLS Have? Answer: An Intrinsic QoS Capability
MPLS Network Topology

After W. Stallings, “MPLS”, The Internet Protocol Journal, vol. 4.no.3
**MPLS SHIM HEADER**

- Between Layer 2 (Data Link) and Layer 3 (Network Layer) IP Packet

<table>
<thead>
<tr>
<th>Layer 2 (e.g., Ethernet)</th>
<th>MPLS Label Value (20 bits)</th>
<th>Experimental Use (EXP) Field (3 bits)</th>
<th>Time-to-Live (8 bits)</th>
<th>Layer 3 (e.g., IP Packet)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Used by local LSR</td>
<td>Bottom-of-Label Stack, S (1 bit)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

MPLS “Shim Header”
Tracking a Packet from Ingress to Egress

- LER Adds MPLS Shim Header Packet Upon Ingress
  - `ip2mpls`, label is added (push)
- MPLS-Labeled IP Packets Traverse the MPLS Domain, LSRs Can Do the Following:
  - `mpls2mpls`, labels are added (pushed), manipulated (swapped), or removed (popped)
  - Note that the EXP value from an underlying label is copied to the EXP field of the newly imposed label
- Egress LER removes the MPLS Shim Header
  - `mpls2ip`, label is removed (popped)
  - IP DSCP field is re-exposed
    - Consonant with EXP field while in the MPLS network
- By Default, the IP Class Bits are Propagated Unchanged Through the MPLS Network
MULTIPROTOCOL LABEL SWITCHING (MPLS)

• Deployed in the Backbone (“Core”) of Carrier Networks
  – The “average” packet traverses 10 – 12 nodes
    • Typically 3 → 5 nodes in the core
      – High speed routers/switches; “fat pipes”; little or no packet loss or jitter
    • QoS problems arise in the edge/access
      – Slower, smaller routers; “thin pipes”; lots of congestion;
      – Substantial packet loss, jitter, and queuing delay

• Lacks Explicit QoS
  – Requires router interpretation of DSCP in 3-bit EXP-field of “shim header”
  – Potentially augmented with complex/expensive traffic engineering (TE)

• Scaling MPLS to Include Access/Edges Routers:
  – Labels must be intelligently applied
    • The larger the network, the greater the challenge
Understanding core versus edge IP Networks

**Network Core**
- Few hops
- Generally over provisioned
- Little packet loss, delay
- Uses MPLS-TE with DiffServ

**Network Edge**
- Many hops
- Congested
- Major source of packet loss, delay
ASF NETWORK ARCHITECTURE WITH MPLS
– Assume DiffServ Throughout
– Synchronized Endpoints
– ASF and MPLS Readily Meld

Customary Network (Routers/Protocols)
MPLS - DiffServ and ASF

- IETF RFC 3270, “Multi-protocol Label Switching (MPLS) Support of Differentiated Services”
  - Provides for a “Uniform Mode” of Tunnel Operation
  - As MPLS packets move through an MPLS domain, labels can be added, removed and manipulated
  - However, the 3-bit EXP field does not change.
  - The 3 most-significant EF, AFXy (Class), and Default bits in the IP packet header are directly mapped to EXP in the MPLS Shim Header
    - EF 101 – EXP 101
    - AF4 100 – EXP 100
    - AF3 011 – EXP 011
    - AF2 010 – EXP 010
    - AF1 001 – EXP 001
    - DF 000 – EXP 000

- Hierarchical Use of AF (e.g., 4) for Discovery, EF for ASF, and Lower Priority Levels (AF3, AF2, AF1, DF) for All Other Traffic is Preserved through MPLS
DSCP-to-MPLS EXP MAPPING

- **IP L3 Header**
  - **Type of Service Byte**
  - **Class Selector**
  - **DSCP Codepoint Field**
  - **Explicit Congestion Notification**

- **L3 Codepoint copied from DSCP to MPLS EXP bits**

- **MPLS Header**
  - **MSBit**
  - **MPLS EXP**
  - **Explicit Congestion Notification**
MultiProtocol Label Switching

• Traffic engineering is *always* prudent
• Traffic engineering is *exceedingly* complex – and expen$sive*
  – Collection and interpretation of traffic statistics
  – Use of historical data
  – Maintain data concurrency with actual network environment?
  – Development and/or purchase of network optimization tools

• **Diff-Serv = Prioritization**
  – With all its limitations: Effectiveness and Scalability

* Draft-liljenstolpe-tewg-cwbcp-02.txt
# RANK ORDERING QoS for DIFFERENT IP/MPLS TECHNOLOGY ALTERNATIVES

<table>
<thead>
<tr>
<th>Approach</th>
<th>Rank</th>
<th>Issue(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>IP Environment</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IP – Best Effort</td>
<td>0</td>
<td>The “original” internet without any QoS mechanisms</td>
</tr>
<tr>
<td>IP – DiffServ</td>
<td>1</td>
<td>Standards-based prioritization; potential for packet contention (jitter, delay, and loss) remains</td>
</tr>
<tr>
<td>Autonomous Flow Scheduling (AFS)</td>
<td>3</td>
<td>Unique use of DiffServ: no packet loss, low delay, little or no jitter</td>
</tr>
<tr>
<td><strong>MPLS Environment</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MPLS</td>
<td>0</td>
<td>Adding labels are basis for VPNs, but no explicit improvement in QoS</td>
</tr>
<tr>
<td>MPLS – DiffServ</td>
<td>1</td>
<td>QoS generally equivalent to IP – DiffServ; MPLS supports backbone switching</td>
</tr>
<tr>
<td>MPLS – DiffServ – TE</td>
<td>2</td>
<td>Potentially superior to MPLS-IP-DiffServ; requires traffic engineering</td>
</tr>
<tr>
<td>MPLS – AFS</td>
<td>3</td>
<td>Equivalent to AFS; fully interoperable with MPLS-DiffServ or MPLS-DiffServ-TE</td>
</tr>
</tbody>
</table>
## Comparing/Contrasting Sequencing and Autonomous Flow Scheduling

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<tr>
<th>ISSUE</th>
<th>SEQUENCING</th>
<th>AFS</th>
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<tr>
<td>QoS</td>
<td>Guaranteed zero packet loss, minimal delay, no jitter</td>
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</tr>
<tr>
<td>Synchronization</td>
<td>Potentially needed at endpoints and switch/routers</td>
<td>Only needed at Access Edge Device (AED) real-time traffic aggregators</td>
</tr>
<tr>
<td>Switching/Routing Technology</td>
<td>Non-standard SSRs required at every node</td>
<td>Customary, standards-compliant DiffServ-enabled routers</td>
</tr>
<tr>
<td>Scalability</td>
<td>Limited by per-flow computation and availability of itineraries</td>
<td>Uses existing Internet routing protocols</td>
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PSEUDOWIRE EMULATION END-to-END (PWE3)

• Basis for Migrating Traditional Public-Switched-Network (PSN) Communications to IP or MPLS-Enabled Packet Networks
  – Time Division Multiplexed (TDM), including Structure-Agnostic T/E-1 and T/E-3 (SAToP)
  – Synchronous Optical Network/Synchronous Digital Hierarchy (SONET/SDH)
  – Ethernet, Frame Relay and PPP/HDLC via Ethernet
  – ATM

• Provides for Encapsulation, Transport, Control, Management, Internetworking, and Security for IETF-Specified PSNs

• Founded on Extensive (and On-Going) Work in the IETF

• Uses “Existing” QoS Mechanisms
  – Over provisioning, DiffServ, Traffic engineering, 802.1Q PRI-to-MPLS EXP bit mappings, etc.
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As an Alternative - TbRR Works Within the PWE3 Framework and Offers Superior QoS Performance
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• Summary
PROVIDER BACKBONE TRANSPORT (PBT)

- Service-Provider-Domain Technology to Support Native Ethernet and Ethernet-via-MPLS Transport
  - Envisioned as an alternative to Ethernet-over-SONET/SDH, Layer-3 IP and IP-MPLS
- Technical Dimensions:
  - Address Scalability
    - Logical partitioning (VLAN stacking) for service provider use (IEEE 802.1ad)
    - Provider Backbone Bridging extends addressability (IEEE 802.1ah)
  - Service Management
    - First-mile Ethernet OAM (IEEE 802.3ah)
    - Ethernet Fault Management (IEEE 802.1ag)
    - Ethernet OAM and Performance Management (ITU T.1731)
  - Quality of Service
    - Point-by-point path specification, with traffic-engineered trunks
    - Bandwidth reservation and DiffServ
PROVIDER BACKBONE TRANSPORT Cont’d

ISSUES

• A “Provider-to-Provider Edge Solution” that does not include Customer Networks
• Requires Switch-by-Switch Network Management and Provisioning
• Concerns: Scalability and “State” Maintenance
  – Scalability is about more than address space
• Uncertain QoS

• Does PBT Fulfill the Simplicity and Economy of Ethernet as a Layer-2 Technology?
PROVIDER BACKBONE TRANSPORT Cont’d

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• Does PBT Fulfill the Simplicity and Economy of Ethernet as a Layer-2 Technology?

AFS is Interoperable with PBT, but PBT’s Lack of an End-to-End “Solution”, Uncertain Scalability, and Lack of Deterministic QoS Invite Concern
AN IP-PROTOCOL IMPOSES QoS REQUIREMENTS

- IP Increasingly Called on to Support “Real-time Applications”
  - In addition to everything else (best effort)
- Real-Time Applications Vary in Terms of QoS Requirements
- In a Converged Network, a Real-Time Protocol Must be Robust Enough to Handle the Most Demanding Application
- A Suitable Real-Time IP Protocol:
  - Conforms to existing standards
  - Provides connection-oriented (“circuit-like”) paths
  - Eliminates managing already-queued packets
  - Draws upon widely available synchronization
## Technology Attributes

<table>
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<tr>
<th>Superior QoS Metrics</th>
<th>Network Utilization</th>
<th>End-to-End Solution</th>
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<th>Simple OAM&amp;P</th>
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<th>Standards Compliance</th>
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### Technology Alternatives

- **AFS**
  - Over Provisioning
  - Prioritization

- **MPLS**
  - MPLS-DiffServ
  - MPLS-DiffServ-TE

- **PWE3 (DiffServ-TE)**
- **MPLS with PWE3**
- **PBT (DiffServ-TE)**

### LEGEND
- **Excellent**
- **Satisfactory**
- **Neutral**
- **Unsatisfactory**
- **Poor**
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**LEGEND**

- ![Excellent](images/excellent.png): Excellent
- ![Satisfactory](images/satisfactory.png): Satisfactory
- ![Neutral](images/neutral.png): Neutral
- ![Unsatisfactory](images/unsatisfactory.png): Unsatisfactory
- ![Poor](images/poor.png): Poor
### Technology Attributes

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<tr>
<th>Technology Alternatives</th>
<th>Superior QoS Metrics</th>
<th>Network Utilization</th>
<th>End-to-End Solution</th>
<th>Application Agnostic</th>
<th>Scalability</th>
<th>Simple OAM&amp;P</th>
<th>Existing Infrastructure</th>
<th>Standards Compliance</th>
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REFERENCES FOR FURTHER READING

-Thank You!
-& Q&A