Labeled Optical Burst Switching and IP/WDM Integration

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OVERVIEW

– Introduction to IP/WDM
– Optical Switching Paradigms
  Circuit or Packet Switching?
– Optical Burst Switching (OBS)
Just In Case ...

- IP: Internet Protocol
  - not *Intellectual Property*
- ATM: Asynchronous Transfer Mode
  - not *Automatic Teller Machine*
- SONET: Synchronous Optical NETwork
  - not as in *son et (lumiere)*
- WDM: Wavelength Division Multiplexing
  - or *Wha’Daya Mean?*
Network Architectures

- today: IP over (ATM/SONET) over WDM
- trend: Integrated IP/WDM (with optical switching)
- goal: ubiquitous, scalable and future-proof
IP / ATM / SONET / WDM
SONET/SDH

• standard for TDM transmissions over fibers
  – basic rate of OC-3 (155 Mbps) based on 64 kbps PCM channels (primarily voice traffic)
  – expensive electronic Add-Drop Muxers (ADM) @ OC-192 (or 10 Gbps) and above
  – many functions *not* necessary/meaningful for data traffic (e.g., bidirectional/symmetric links)
  – use predominantly rings: not BW efficient, but quick protection/restoration (<= 50 ms)
Internet Protocol (IP)

• main functions
  – break data (email, file) into (IP) packets
  – add network (IP) addresses to each packet
  – figure out the (current) topology and maintains a routing table at each router
  – find a match for the destination address of a packet, and forward it to the next hop
    • a link to a popular server site may be congested
Asynchronous Transfer Mode

- break data (e.g., an IP packet) into smaller ATM cells, each having $48+5 = 53$ bytes
- a route from point A to point B needs be pre-established before sending cells.
- support Quality-of-Service (QoS), e.g., bounded delay, jitter and cell loss rate
- basic rate: between 155 and 622 Mbps
  - just start to talk 10 Gbps (too late?)
Data Traffic Growth

• double every 4 (up to 12) months or so, and will increase by 1,000 times in 5 years
  – at least 10 x increase in users, and uses per user
  – at least 100 x increase in BW per use:
    • current web pages contain 10 KB each
    • MP3 & MPEG files are 5 & 40 MB each, resp.

• beat Moore’s Law (growth rate in electronic processing power)
  – electronic processing, switching, and transmission cannot and will not keep up
  – need WDM transmissions and switching
Wavelength Division Multiplex

- up to 50 THz (or about 50 Tbps) per fiber (low loss range is now 1335nm to 1625nm)
- mature WDM components
  - mux/demux, amplifier (EDFA), transceiver (fixed-tuned), add-drop mux, static λ-router,
- still developing
  - tunable transceiver, all-optical λ-conversion and cross-connect/switches, Raman amplifiers
WDM Pt-2-Pt Transmission

MUX

fiber

EDFA

DMUX

\(\lambda_1\)

\(\lambda_2\)

\(\ldots\)

\(\lambda_n\)
Advance in WDM Networking

- Transmission (long haul)
  - 80 λs (1530nm to 1565nm) now, and additional 80 λs (1570nm to 1610nm) soon
  - OC-48 (2.5 Gbps) per λ (separated by 0.4 nm) and OC-192 (separated by 0.8 nm)
  - 40 Gbps per λ also coming (>1 Tbps per fiber)

- Cross-connecting and Switching
  - Up to 1000 x 1000 optical cross-connects (MEMS)
  - 64 x 64 packet-switches (switching time < 1 ns)
ATM and SONET: Legacy

- interest in ATM diminished
  - a high cell tax, and segmentation/re-assembly and signaling overhead
  - failed to reach desktops (& take over the world)
  - on-going effort in providing QoS by IP (e.g., IPv6 & Multi-protocol Label Switching or MPLS)

- SONET/SDH more expensive than WDM
  - & IP & WDM can jointly provide satisfactory protection/restoration (< 99.999% reliability?)
**Datagram (IP) or VC (ATM)**

- *datagram*-based packet switching
  - next-hop determined for each packet based on *destination* address and *(current)* routing table
    - IP finds a longest sub-string match (a complex op)
- *virtual circuit* (VC)-based packet-switching
  - determines the path (VC) to take before-hand
    - entry at each node: [VCI-*in*, next-hop, VCI-*out*]
  - assigns packets a VCI (e.g., Rt. 66)
**Benefit of VC (as in ATM)**

- faster and more efficient forwarding
  - an exact match is quicker to find than a longest sub-string match
- facilitates traffic engineering
  - paths can be explicitly specified for achieving e.g., network-wide load-balance
  - packets with the same destination address (but different VCI’s) can now be treated differently
**IP-over-ATM**

- IP routers interconnected via ATM switches
- breaks each packet into cells for switching
- a flow: consecutive packets with the same source/destination (domain/host/TCP conn.)
- Multi-protocol over ATM (MPOA)
  - ATM-specific signaling to establish an ATM VC between source/destination IP routers
  - segmentation and re-assembly overhead
**IP-centric Control**

- **Tag Switching** (centralized, control-driven)
  - the network sets up end-to-end VC’s
  - each packet carries a tag (e.g., VCI)

- **IP Switching** (distributed, data-driven)
  - first few packets are routed at every IP router
    - up to a threshold value to filter out short “flows”
  - following packets bypass intermediate routers via a VC (established in a hop-by-hop fashion).
MPLS (Overview)

- A control plane integrating network-layer (routing) and data-link layer (switching)
  - packet-switched networks with VC’s
- LSP: label switched path (VC’s)
  - identified with a sequence of labels (tag/VCI)
  - set up between label switched routers (LSRs)
- Each packet is augmented with a shim containing a label, and switched over a LSP
**IP over WDM Architectures**

- IP routers interconnected with WDM links
  - with or without built-in WDM transceivers
- An optical cloud (core) accessed by IP routers at the edge
  - pros: provide fat and easy-to-provision pipes
  - either transparent (i.e., OOO) or opaque (i.e., O-E-O) cross-connects (circuit-switches)
  - proprietary control and non-IP based routing
Optical/Photonic (OOO) Switching

• Pros:
  – can handle a huge amount of *through*-traffic
  – synergetic to optical transmission (no O/E/O)
  – transparency (bit-rate, format, protocol)

• caveats
  – optical 3R/performance monitoring are hard
  – more mature/reliable opaque (OEO) switches
  – SONET or GbE like framing still useful
Emerging Integrated IP/WDM

- IP and MPLS on top of every optical circuit or packet switch:
  - IP-based addressing/routing (electronics), but data is optically switched (circuit or packet)
  - MPLS-based provisioning, traffic engineering and protection/restoration
  - Internetworking of optical WDM subnets
    - with interior and exterior (border) gateway routing
Why IP over WDM

- IP: the unifying/convergence network layer
- IP traffic is (& will remain) *predominant*
  - annual % increase in voice traffic is in the teens
- IP/WDM the choice if start from scratch
  - ATM/SONET were primarily for voice traffic
  - should optimize for pre-dominant IP traffic
- IP routers’ port speed reaches OC-48
  - no need for multiplexing by ATM/SONET
Why IP/WDM (continued)

- IP is resilient (albeit rerouting may be slow)
- a WDM layer (with optical switches)
  - provides fast restoration (not just WDM links for transmission only)
- Why Integrated IP/WDM
  - no need to re-invent routing and signaling protocols for the WDM layers and corresponding interfaces
  - facilitates traffic engineering and inter-operability
MPLS-variants: $MP\lambda S$ and LOBS

- optical core: circuit- or packet-switched?
- circuit-switched WDM layer
  - OXC’s (e.g., wavelength routers) can be controlled by $MPLambda S$ (or $MP\lambda S$)
- packet-switched or burst-switched (a burst = several packets) WDM layer
  - optical switches controlled by *Labeled Optical Burst Switching* (LOBS) or other MPLS variants.
Labeled Optical Burst Switching

• similar to MPLS  
  (e.g., different LOBS  
  paths can share  
  the same \( \lambda \))

• control packets  
  carry labels as well  
  as other burst info

• unique LOBS issues:  
  assembly (offset time),  
  contention resolution,  
  light-spitting (for WDM  
  mcast), \( \lambda \) conversion...
Observation

• IP over WDM has evolved:
  – from WDM links, to WDM clouds (with static virtual topology and then dynamic λ services),
  – and now integrated IP/WDM with MPλS

• to be truly ubiquitous, scalable and future-proof, a WDM optical core should also be
  – capable of OOO packet/burst-switching, and basic QoS support (e.g., with LOBS control)
Optical Switching Techniques

historically, circuit-switching is for voice and packet-switching is for data
Optical Core: Circuit or Packet?

- five src/dest pairs
  - circuit-switching (wavelength routing)
    - 3 λs if without λ–conversion
    - only 2 λs otherwise
  - if data is sporadic
    - packet-switching
      - only 1 λ needed with statistical muxing
      λ conversion helps too
Impacts on Components

(a) Cross-Connect (1000 by 1000, ms switching time)

(b) Packet-Switch (64x64, with ns switching time)
Packet Core: A Historical View (hints from electronic networks)

- optical access/metro networks (LAN/MAN)
  - optical buses, passive star couplers (Ethernet)
  - SONET/WDM rings (token rings)
  - switched networks? (Gigabit Ethernet)

- optical core (WAN)
  - $\lambda$-routed virtual topology (circuits/leased lines)
  - dynamic $\lambda$ provisioning (circuits on-demand)
  - optical burst (packet/flow) switching (IP)
Packet Core: Technology Drivers

- explosive traffic growth
- bursty traffic pattern
- to increase bandwidth efficiency
- to make the core more flexible
- to simplify network control & management by making the core more intelligent
Circuit Switching

- long circuit set-up (a 2-way process with Req and Ack): \( RTT = \text{tens of } ms \)
- pros: good for smooth traffic and QoS guarantee due to fixed BW reservation;
- cons: BW inefficient for bursty (data) traffic
  - either wasted BW during off/low-traffic periods
  - or too much overhead (e.g., delay) due to frequent set-up/release (for every burst)
Wavelength Routing

- setting up a lightpath (or \( \lambda \) path) is like setting up a circuit (same pros and cons)
- \( \lambda \)-path specific pros and cons:
  - very coarse granularity (OC-48 and above)
  - limited # of wavelengths (thus # of lightpaths)
  - no aggregation (merge of \( \lambda \)s) inside the core
    - traffic grooming at edge can be complex/inflexible
  - mature OXC technology (\( msec \) switching time)
Self-Similar (or Bursty) Traffic

- Left:
  - *Poisson* traffic (voice)
  - smooth at large time scales and mux degrees

- Right:
  - data (IP) traffic
  - bursty at all time scales and large mux degrees
  - circuit-switching not efficient (*max >> avg*)
To Be or Not to Be BW Efficient?
(don’t we have enough BW to throw at problems?)

• users’ point of view:
  – with more available BW, new BW intensive (or hungry) applications will be introduced
    • high BW is an addictive drug, can’t have too much!

• carriers’ and venders’ point of view:
  – expenditure rate higher than revenue growth
  – longer term, equipment investment cannot keep up with the traffic explosion
  – need BW-efficient solutions to be competitive
Packet (Cell) Switching

• A packet contains a header (e.g., addresses) and the payload (variable or fixed length)
  – can be sent without circuit set-up delay
  – statistic sharing of link BW among packets with different source/destination

• store-and-forward at each node
  – buffers a packet, processes its header, and sends it to the next hop
Optical Packet Switching: Holy Grail

- No.1 problem: lack of optical buffer (RAM)
- fiber delay lines (FDLs) are bulky and provide only limited & deterministic delays
  - store-n-forward (with feed-back FDLs) leads to fixed packet length and synchronous switching
- tight coupling of header and payload
  - requires stringent synchronization, and fast processing and switching (ns or less)
Optical Burst Switching (OBS)

- a burst has a long, variable length payload
  - low amortized overhead, no fragmentation
- a control packet is sent out-of-band ($\lambda_{\text{control}}$)
  - reserves BW ($\lambda_{\text{data}}$) and configures switches
- a burst is sent after an offset time $T > 0$ (loose coupling), but $T << RTT$ (1-way process)
  - uses asynchronous, cut-through switching (no delay via FDLs needed)
Packet (a) vs. Burst (b) Switching
Optical Packet or Burst Switching?

- OBS = optical packet switching with:
  - variable-length, super (or multiple) packets
  - asynchronous switching with switch *cut-through* (i.e., no store-and-forward)
    - a packet is switched before its last bit arrives
  - out-of-band control using e.g., dedicated λs or sub-carrier multiplexing (SCM)
    - electronically processed or optically processed (with limited capability and difficult implementation)
OBS Protocols

• based on Reserve-Fixed-Duration (RFD)
  – $T \geq \Sigma$ (processing delay of the control packet)
    • eliminate the need for FDLs at intermediate nodes
  – same end-to-end latency as in packet-switching
    • bursts delayed (electronically) at sources only
    • use 100% of FDL capacity for contention resolution
  – auto BW release after a fixed duration (= burst length) specified by the control packet (YQ97)
Just-Enough-Time (JET)

- combined use of offset time and delayed reservation (DR) to facilitate intelligent allocation of BW (and FDLs if any)
TAG-based Burst Switching

- BW reserved from the time control packet is processed, and released with: (Turner’97)
  - an explicit *release* packet (problematic if lost)
  - or frequent *refresh* with time-out (overhead)

- **T = 0** (or negligible)
  - without *DR*, using \( T > 0 \) wastes BW
  - FDLs per node \( \geq \) max \{proc. + switch time\}
Burst Switching Variations

- based on Tell-And-Go (TAG)
  - BW reserved from the time control packet is processed, and released with: (Turner97)
    - either an explicit release packet (problematic if lost)
    - or frequent refresh packets with time-out (overhead)

- based on In-Band-Terminator (IBT)
  - BW released when an IBT (e.g., a period of silence in voice communications) is detected
  - optical implementation is difficult
More on Offset Time

- TAG and IBT: $T = 0$ (or negligible)
  - without $DR$, using $T > 0$ wastes BW
  - FDLs per node $\geq$ max. (proc. + switch) time
- $JET$ buffers bursts for $T > \Sigma$ ($\Delta$: proc. delay)
  - a plenty of electronic buffer at source
  - no mandatory FDLs to delay payload
  - can also take advantage of FDLs (buffer)
    - 100% used for (burst) contention resolution
Tolerate Switching Delay

- control packet can leave right after $\delta = \Delta - s$
  - where $s$ is the switch setting time
FDLs for Contention Resolution

- shared (a) or dedicated (b) structure with max delay time = $B$
OBS Nodes with FDL
**BW and FDL Allocation**

- intelligent BW scheduling (known durations)
- no wasted FDL capacity (known blocking time)
  - max. delay time $0 < d_{\text{max}} \leq B$
Performance Evaluation

- metrics: link utilization vs. latency
- a 16-node mesh network (with OC-192 links)
- ave. burst length \((L)\): \(0.1\) msec \((1\) Mbits\)
- relative FDL capacity \(b = B/L\) is 0 or 1
- also found performance improvement of JET over other protocols scale with
  - # of \(\lambda\)s \((k)\) & relative processing speed \(c = \Delta/L\)
BW Utilization vs Latency

- JET as good as NoDR with FDLs
- JET with FDLs 50% better NoDR with FDLs.
## Why OBS? A Comparison

<table>
<thead>
<tr>
<th>Optical switching paradigms</th>
<th>Bandwidth Utilization</th>
<th>Latency (setup)</th>
<th>Optical Buffer</th>
<th>Proc./Sync. Overhead (per unit data)</th>
<th>Adaptivity (traffic &amp; fault)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circuit</td>
<td>Low</td>
<td>High</td>
<td>Not required</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Packet/Cell</td>
<td>High</td>
<td>Low</td>
<td>Required</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>OBS</td>
<td>High</td>
<td>Low</td>
<td>Not required</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>

OBS combines the best of coarse-grained circuit-switching with fine-grained packet-switching
Switching Paradigms (Summary)

<table>
<thead>
<tr>
<th>Circuit-Switching</th>
<th>Burst-Switching</th>
<th>Packet-Switching</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength-routing</td>
<td>Optical burst switching</td>
<td>Optical packet switching</td>
</tr>
</tbody>
</table>

- fast circuit-switching
- TAG
- IBT
- RFD
- message switching
- datagram
- MPLS
- VC-based

<table>
<thead>
<tr>
<th>two-way reservation</th>
<th>one-way reservation</th>
</tr>
</thead>
<tbody>
<tr>
<td>switch cut-through</td>
<td>store-and-forward</td>
</tr>
<tr>
<td>variable-length</td>
<td>fixed-length</td>
</tr>
<tr>
<td>out-of-band control</td>
<td>in-band control</td>
</tr>
<tr>
<td>large granularity</td>
<td>medium granularity</td>
</tr>
<tr>
<td></td>
<td>small granularity</td>
</tr>
</tbody>
</table>
Support QoS Using OBS
QoS schemes

- current IP: single class, best-effort service
  - *Apps*, users and ISPs need *differentiated service*
- existing schemes (e.g., WFQ) require buffer
  - so to have different queues and, service a higher priority queue more frequently
  - not suitable for WDM networks
    - no optical RAM available (FDLs not applicable)
    - using electronic buffers means E/O/E conversions
Why QoS at WDM layer?

- a WDM layer supporting basic QoS will
  - support legacy/new protocols incapable of QoS and thus making the network truly ubiquitous
  - facilitate/complement future QoS-enhanced IP
  - handle mission-critical traffic at the WDM layer for signaling, and restoration
Prioritized OBS Protocol

- extend \textit{JET} (which has a base \( t > 0 \)) by using an \textit{extra} offset time \( T \) to isolate classes
- example:
  - two classes (class 1 has priority over class 0)
  - class 1 assigned an \textit{extra} \( T \), but not class 0
Prioritized OBS (continued)

- no buffer (not even FDLs) needed, suitable for all-optical WDM networks
- can take advantage of FDLs to improve QoS performance (e.g., a higher isolation degree)
- the extra $T$ does introduces additional latency
  - but, only insignificantly (e.g., $\leq$ a few $ms$)
Why *Extra Offset Time* $\Rightarrow$ *Priority*?

- assumptions:
  - a link having one available $\lambda$ and no FDLs
  - two classes (class 1 has priority over class 0)
    - lost class 0 (best-effort class) bursts retransmitted
    - class 1 (critical) bursts need low blocking prob.
  - class 1 assigned an *extra* $T$, but not class 0
  - the difference in their base $t$’s is *negligible*
Class Isolation: Example

\[ t_a^1 \quad t_a^0 (= t_s^0) \quad t_s^1 \quad t_s^1 + l_1 \]

- a class 0 burst won’t block a class 1 burst
  - class 1 control packet arrives first (a)
  - class 0 control packet arrives first (b)
- extra \( T \) = right to reserve BW in advance
(Extra) Offset Time Required

- extra T assigned to class 1: \( t_1 \)
- class 0 burst length: \( l_0 \)
  - expected ave: 10 Mbits or 1 ms @ OC-192
- completely isolated classes if \( t_1 \geq \text{max.}\{l_0\} \)
- let \( p = \text{prob}\ \{l_0 \leq t_1\} \), that is, \( p\% \) of class 0 bursts are no longer than \( t_1 \)
  - partially isolated (with a degree of \( p \))
  - e.g., 95% isolation when \( t_1 = 3 \) times of ave\(\{l_0\}\)
When Number of Classes \((n) > 2\)

- \(L_i\): class \(i\)’s mean burst length
- \(t_{i,i-1}\): difference in \(T\) between classes \(i\) & \(i-1\)
- \(R_{i,i-1}\): (adjacent) class isolation degree
  - \(\text{prob. \{class } i \text{ will not be blocked by class } i-1\}\)
- \(R_{i,i-1}\) = PDF\{class \(i-1\) bursts shorter than \(t_{i,i-1}\}\)
  - with exponential distribution

\[
PDF = 1 - e^{-u_{i-1} t_{i,i-1}}, \quad u_{i-1} = 1 / L_{i-1}
\]
Isolation Degree Achieved

<table>
<thead>
<tr>
<th>offset time difference</th>
<th>$0.4 \ L_{i-1}$</th>
<th>$L_{i-1}$</th>
<th>$3 \ L_{i-1}$</th>
<th>$5 \ L_{i-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolation degree</td>
<td>0.3296</td>
<td>0.6321</td>
<td>0.9502</td>
<td>0.9932</td>
</tr>
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</table>

- more isolated from lower priority classes
  - class $i$ is isolated from class $i - 1$ with $R_{i,i-1}$
  - class $i$ is isolated from class $i - 2$ with $R_{i,i-2} > R_{i,i-1}$ (since $t_{i,i-2} = t_i - t_{i-2} > t_{i,i-1} = t_i - t_{i-1}$)
  - similarly, class $i$ is isolated from all lower classes with at least $R_{i,i-1}$
Analysis of Blocking Probability

- single node with $k \lambda$'s and $\lambda$–conversions
- the classless OBS (for comparison)
  - blocking probability: $B(k, \rho)$ using Erlang's loss formula ($M/M/k/k$) (bufferless)
- the prioritized OBS
  - $B(k, \rho) = \text{ave. blocking probability over all classes (the conservation law)}$
  - assume complete (100%) class isolation
Analysis (II)

- block prob. of class $n - 1$ (highest priority)
  - $pb_{n-1} = B(k, \rho_{n-1})$ because of its complete isolation from all lower priority classes
- blocking prob. of bursts in classes $j$ to $n - 1$:
  - calculated as one super class isolated from all lower classes: $PB_{n-1,j} = B(k, \rho_{n-1,j})$  
  - where the combined load is $\rho_{n-1,j} = \sum_{i=j}^{n-1} \rho_i$
Analysis (III)

• blocking prob. of bursts in classes $j$ to $n - 1$
  – when calculated as a weighted sum:

$$PB_{n-1, j} = \sum_{i=j}^{n-1} c_i \times Pb_i \quad where \quad c_i = \rho_i / \rho$$ (2)

• given blocking prob of classes $j+1$ to $n - 1$

$$pb_{j} = (B(k, \rho_{n-1, j}) - \sum_{i=j+1}^{n-1} c_i \times pb_i) / c_j$$
  – e.g., blocking prob. of class $n - 1$

$$pb_{n-2} = (B(k, \rho_{n-1,n-2}) - c_{n-1} \times pb_{n-1}) / c_{n-2}$$
Loss Probability vs. Load

- by default: \( n = 4, k = 8, L_i = L \), and \( t_{i,i-1} = 3L \)

Class Isolation

Average (Conversation Law)
**Differentiated Burst Service**

- same average over all classes (conservation law)
- FDLs (if any) improve performance of all classes
- class isolation increases with # of $\lambda$s, classes and FDLs (if any)
- bounded E2E delay of high priority class

**Loss Prob vs. Load**
(four classes, 8 $\lambda$s)
Scalability

Loss prob vs. $k$

Loss prob vs. $n$
Some Practical Considerations

Loss prob. saturation when offset time difference = 3L

Loss prob under self-similar traffic
Application to FDLs

- to isolate two classes for FDL reservation
  - extra offset time to class 1 > \( \max\{ l_0 \} \)
- for \( \lambda \) reservation: \( \text{extra } t > B + \max\{ l_0 \} \)
  - class 0 may be delayed for up to \( B \) units
- isolation degree differs for a given \( t \)

<table>
<thead>
<tr>
<th>FDL (buffer)</th>
<th>0.4 ( L_0 )</th>
<th>( L_0 )</th>
<th>3 ( L_0 )</th>
<th>5 ( L_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>0.4 ( L_0 + B )</td>
<td>( L_0 + B )</td>
<td>3 ( L_0 + B )</td>
<td>5 ( L_0 + B )</td>
</tr>
<tr>
<td>Isolation degree (R)</td>
<td>0.3296</td>
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FDLs vs Queue

- FDLs only store bursts with blocking time $< B$
- a queue can store any burst indefinitely
- queueing analysis (M/M/k/D) generally yields a lower bound on the loss probability
  - except when number of FDLs and B are large
Effect of Max Delay Time

Loss Prob.

Queueing Delay

![Graphs showing the effect of maximum delay time on loss probability and queuing delay for different classes. Each graph has multiple curves representing different classes.]
Other Topics in OBS (I)

- burst assembly
  - based on fixed time, min. length, or burst detection heuristics

- offset time value
  - priority vs additional pre-transmission delay

- burst route determination
  - shortest (in hop count) or least loaded
  - alternate routes & adaptive routing
Other Topics in OBS (II)

- WDM multicasting
  - constrained multicast routing (e.g., multicast forests to get around mcast-incapable switches)
  - IP/WDM multicast interworking
- contention resolution & fault recovery
  - drop, re-transmission (WDM layer), buffering (via FDLs), deflection (in both space and wavelength), or pre-emption
End of Part I