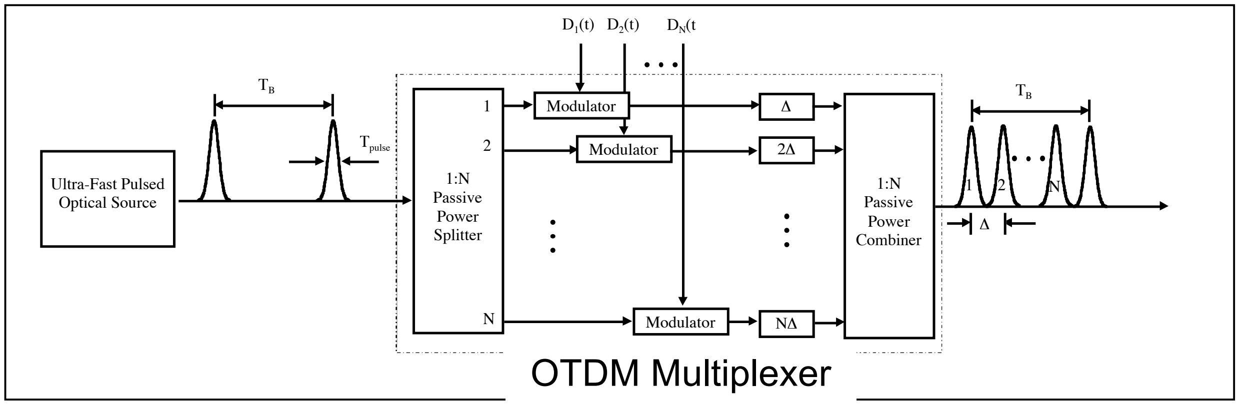
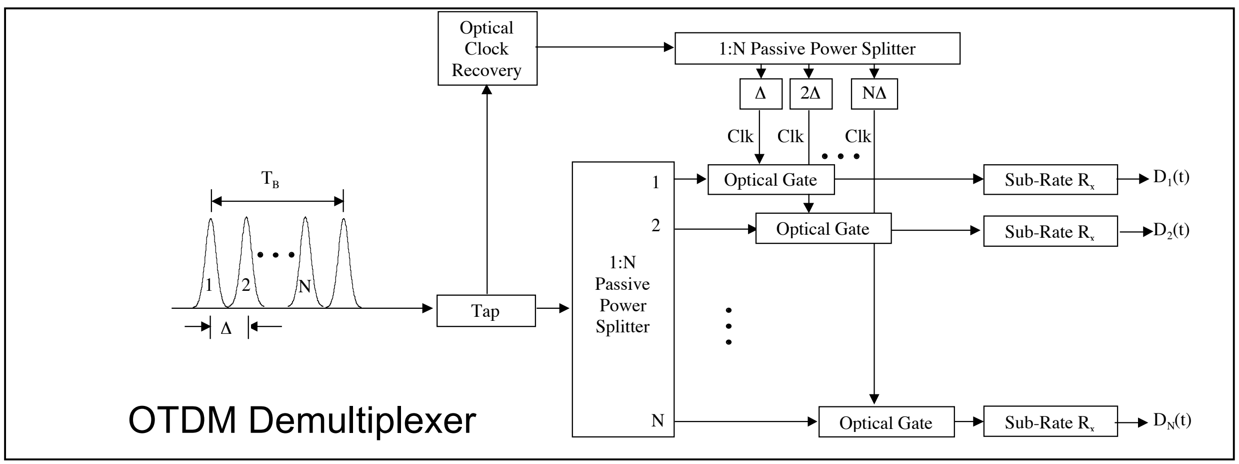
Lecture 14

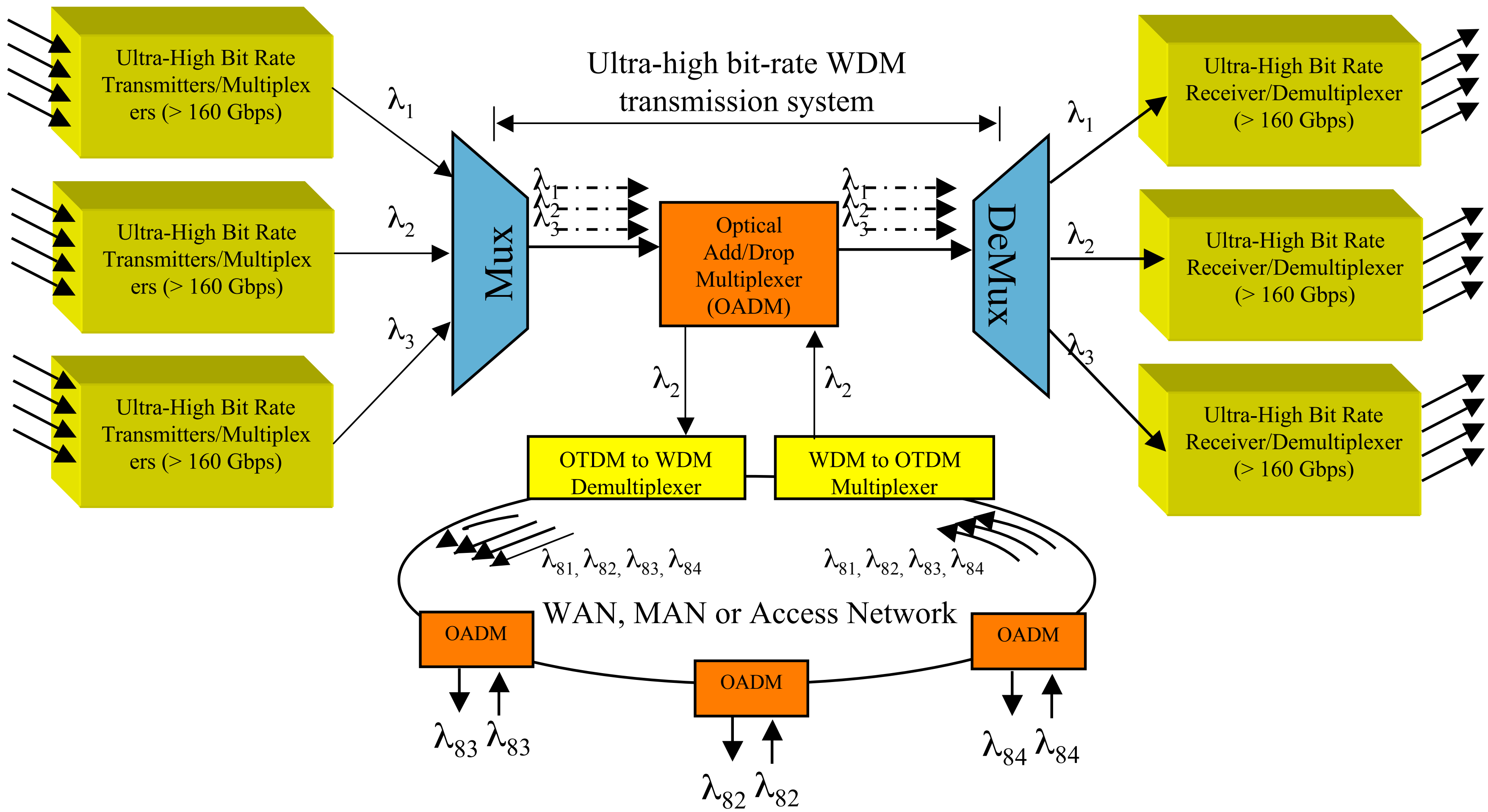
Optical Time Division Multiplexing (OTDM)

•Multiplexing factor (O:1) determined by pulse width, extinction ratio and source rep rate
•Data imprinted on pulses using optical modulators (e.g. EAMs)
•Passive optical splitters and delays used to multiplex and demultiplex
•Fast optical gates (e.g. EAM) used to convert OTDM data back to original data rate

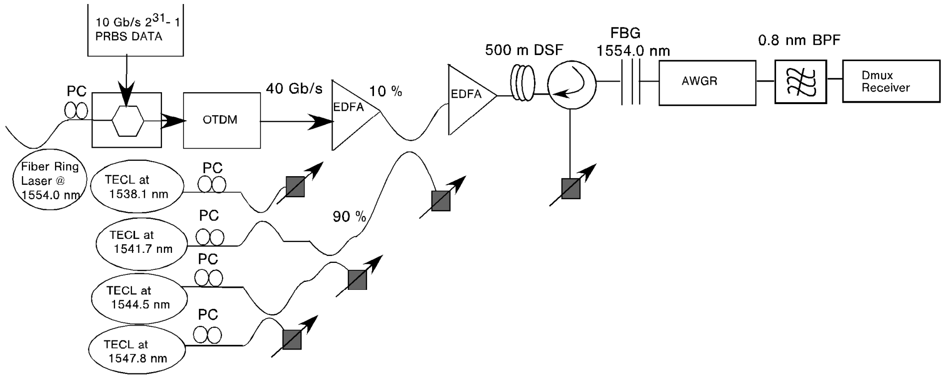


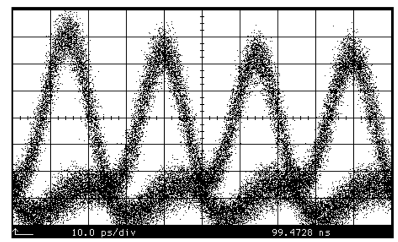


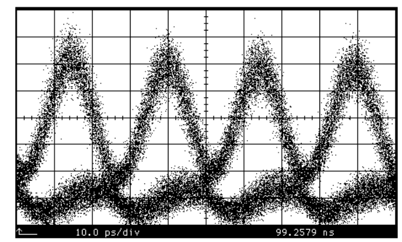
Agile-WDM/OTDM Network

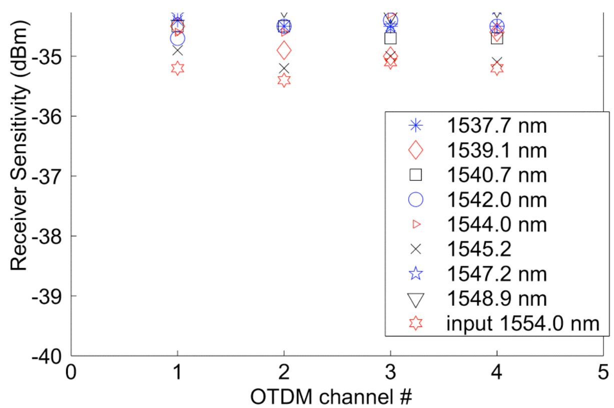


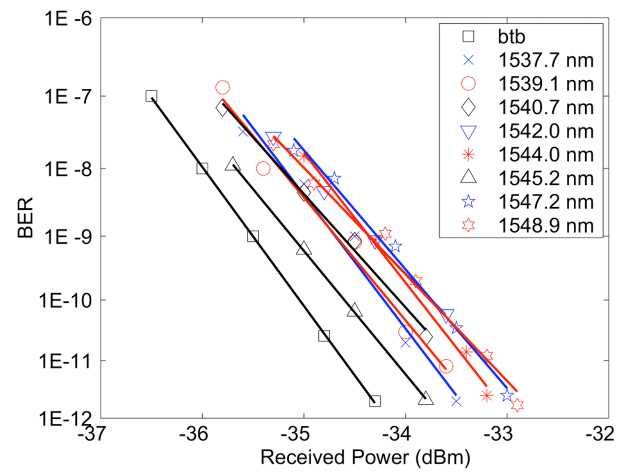
A Broadcast WDM-OTDM Technique based on 1 to 8 Multiple Wavelength Conversion with 2R Regeneration





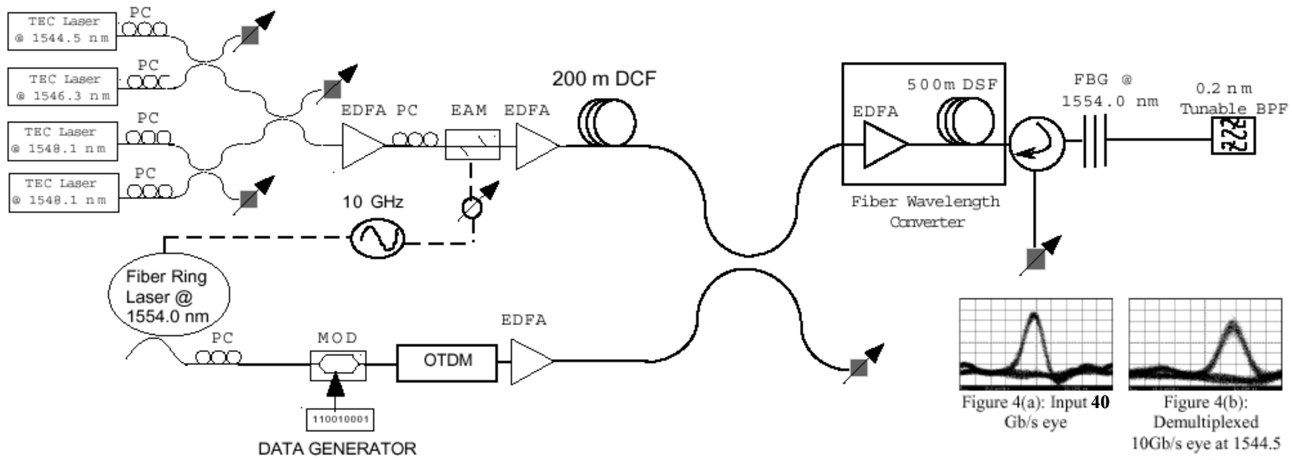






Lavanya Rau, Bengt-Erik Olsson and Daniel J. Blumenthal, OFC 2001.

OTDM to WDM Transmultiplexer



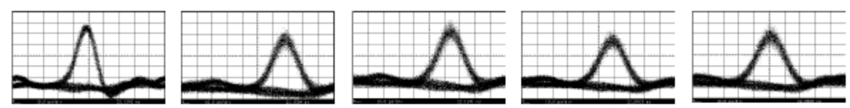


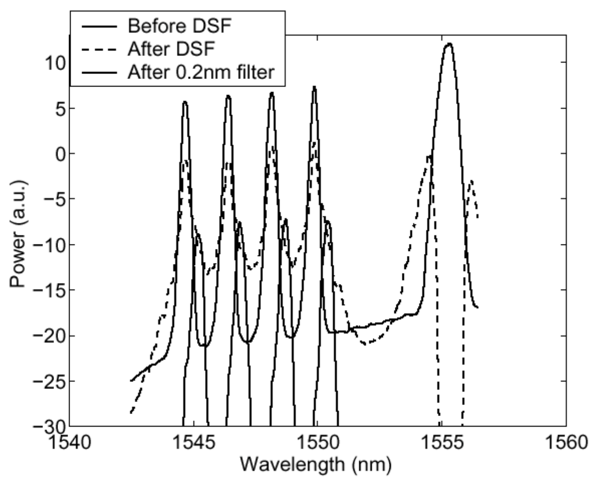
Figure 4(a): Input **40** Gb/s eye

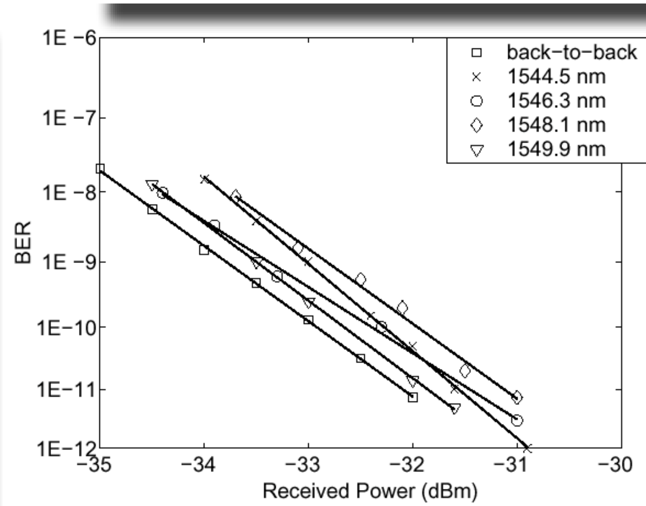
Figure 4(b): Demultiplexed 10Gb/s eye at 1544.5 nm

Figure 4(c): Demultiplexed 10Gb/s eye at 1546.3 nm

Figure 4(d): Demultiplexed 10Gb/s eye at 1548.1 nm

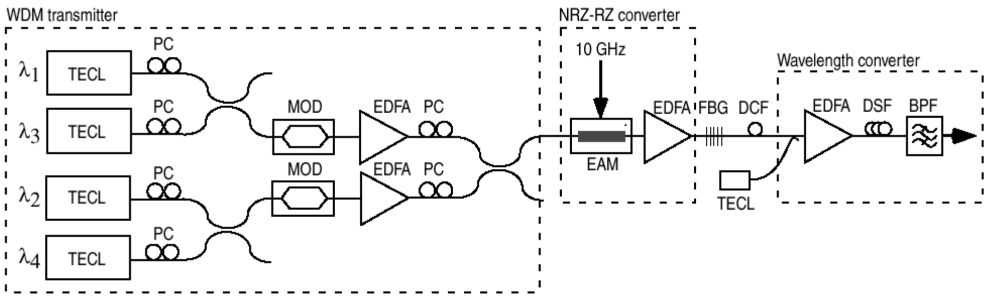
Figure 4(e): Demultiplexed 10Gb/s eye at 1549.9 nm



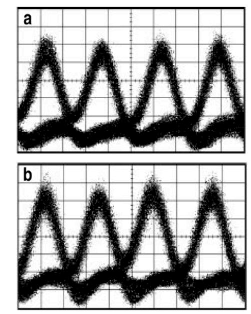


Lavanya Rau, Bengt-Erik Olsson and Daniel J. Blumenthal, Submitted to IEEE PTL, 2001

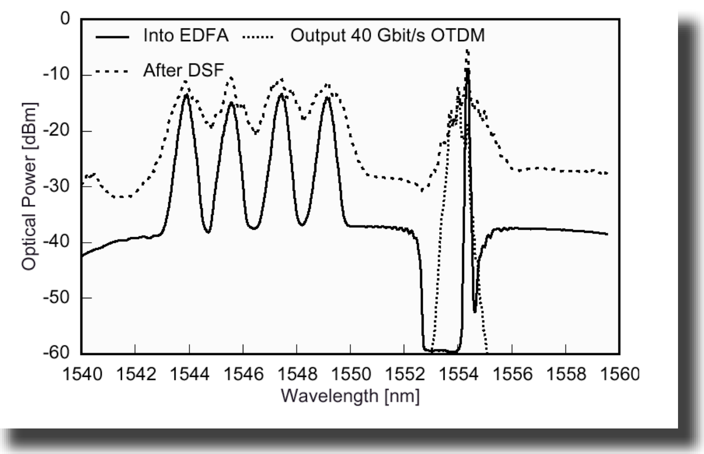
WDM to OTDM Transmultiplexer

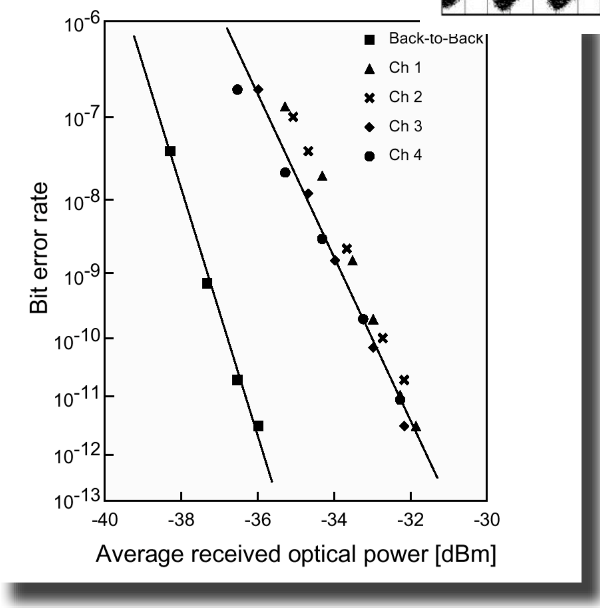


(4) 10 Gbps Channels



40 Gbps Channel





Bengt-Erik Olsson, Lavanya Rau and Daniel J. Blumenthal, IEEE PTL, September 2001

Optical Burst Switching (OBS)

- Network bandwidth access and switching on demand
  - Transmit at bit-rate only for as long as needed then release network resources
- Adaptation of ATM Block Transfer with (I) delayed transmission and (II) with immediate transmission
- Similar to fast circuit switched approaches
- Architectural examples include
  - Just-in-time switching (McFarland, Mellier-Smith)
  - Optical burst switching and Just-Enough-Time (JET) (Turner, Qiao)
- Issues
  - Limited flexibility and potential difficulties in scaling
  - Latency and collision window induced by common control channel
  - Blocking states and availability
  - Performance degradation with increase load and long bursts

Optical Burst and Packet Switching

OBS: Bandwidth is reserved in a one-way process such that a burst can be sent with acknowledgments as in circuit switching, leading to a potential reduction in latency

OBS: Transmit bursts through nodes without optical buffering.

OBS: Scheduling is performed at the edges

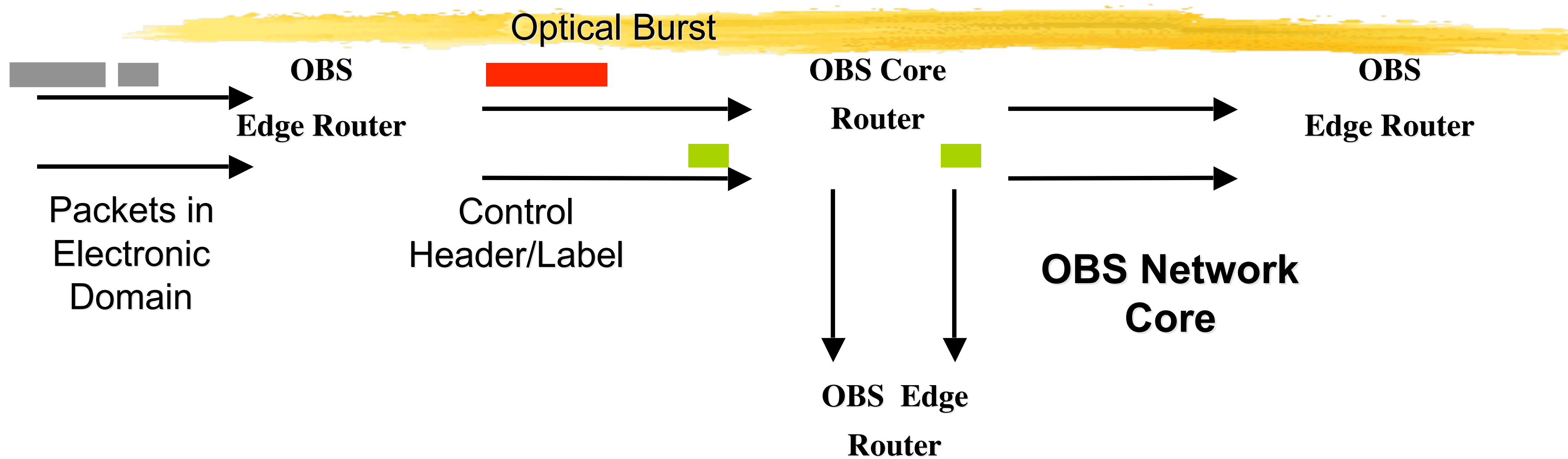
What is Optical Burst Switching (OBS)

- Packets are aggregated into a “optical burst” at the edge nodes of the network
  - Bursts are stored in electronic buffers at the edge of the network until ready for transmission
- A control header/label is sent on a separate out-of-band channel
  - Control is used to set up switch states in advance for bursts to minimize need for optical buffering.
  - Bursts are then sent without acknowledgement
- OBS offers
  - Reduction/elimination of optical buffering
  - Reduction of electronic processing bottleneck
  - Aggregation can reduce self-similarity
- OBS issues and challenges
  - Limited flexibility and potential difficulties in scaling
  - Latency and collision window induced by common control channel
  - Blocking states and availability
  - Performance degradation with increase load and long bursts

OBS Signaling Protocols and Classification

- Transmission techniques
  - Immediate: Control labels sent followed by data immediately afterwards
  - Delayed: Control labels are sent and resources established before data is sent
- Open-ended and close-ended resource allocation
  - Open-ended: Resources allocated till release signal is sent to stop allocation
  - Close-ended: Resources allocated for fixed duration
- Open-ended resource allocation techniques
  - TAG (Tell and go): release packet in control channel used to end allocation
  - IBT (In band terminator): release sent in data channel immediately after burst
- Close-ended resource allocation techniques
  - RLD (Reserve a limited duration) – Resources allocated for predicted length of burst
  - RFD (Reserve a fixed duration) – Duration of burst transmitted in control label
- Example signaling protocols
  - JIT (Just in time) switching: Delayed transmission technique with open ended resource allocation, using an IBT
  - JET (Just enough time) switching: Delayed transmission technique with close-ended resource allocation using RFD

Example OBS Network Architecture



Edge Router

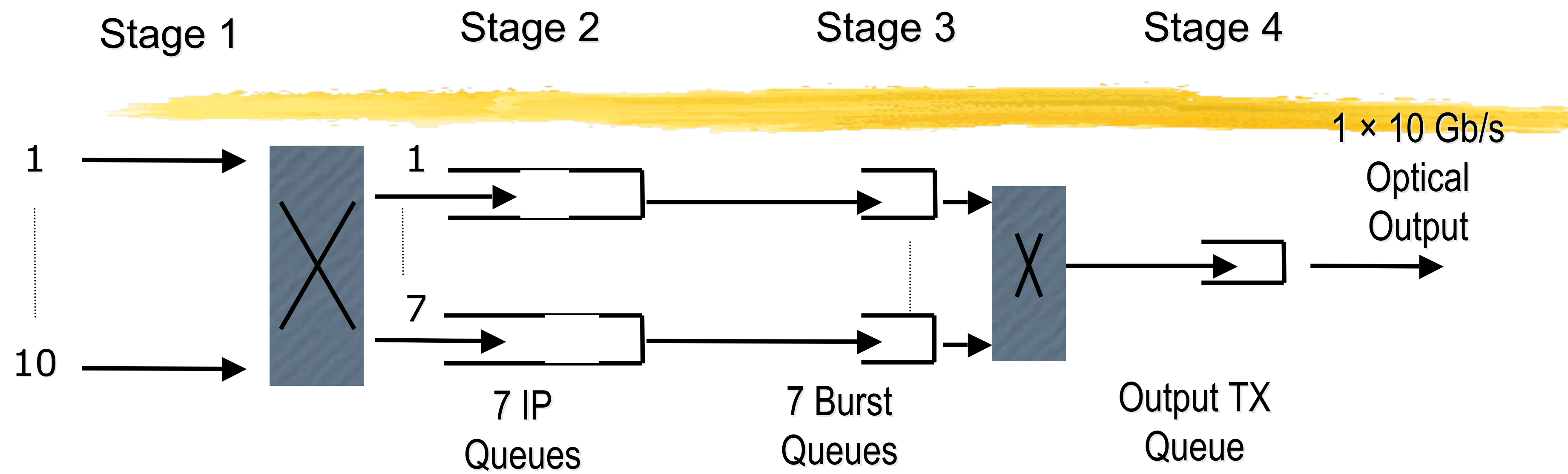
Sorts packets in electronic domain into classes and aggregates packets into optical bursts

Schedules optical burst transmission into OBS Network core as part of signaling protocol (e.g. Just-In-Time, Just-Enough-Time)

Core Router

Forwarding and routing of bursts from ingress edge router to egress edge router

Example OBS Edge Router



Stage 1: Variable length packets from 10 input channels (1 Gb/s) sorted and sent to 1 of 7 output channels (10 Gb/s) feeding IP queues

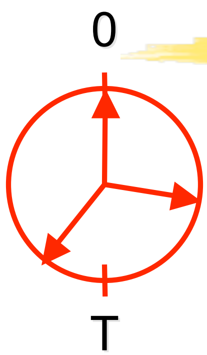
- **Stage 2:** Packets are assembled into bursts within each IP queue, and sent out
- **Stage 3:** Fully assembled bursts queued in burst queues and transmitted to output queue over switch fabric
- **Stage 4:** Bursts are transmitted to the network core

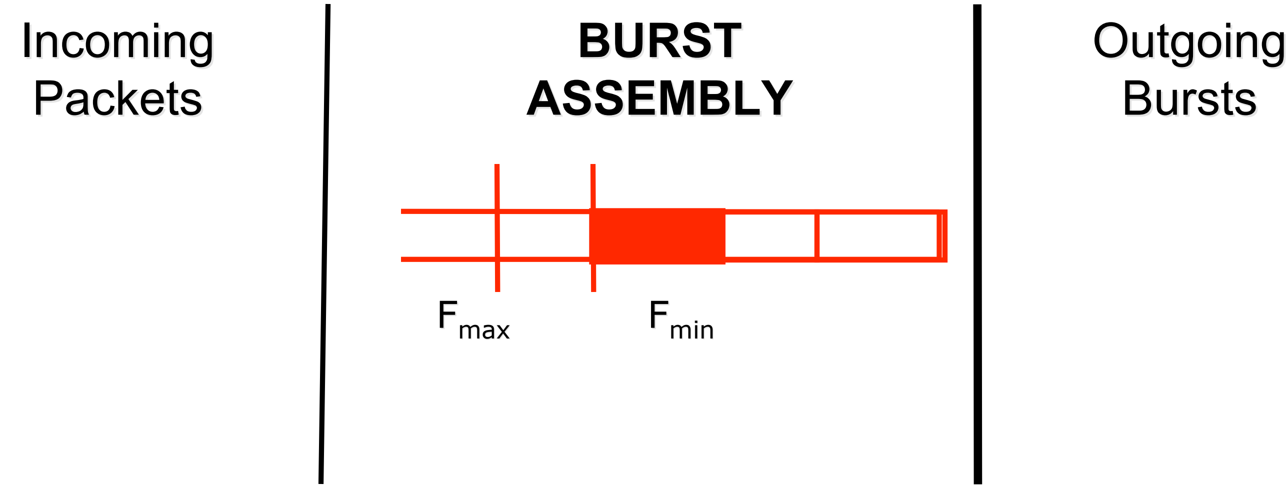
Burst Assembly Algorithms

- Definitions
  - Normalized burst size (B_n) = burst size/max data receivable in fixed assembly time T
  - Normalized burst assembly time (T_{BN}) = burst assembly time/T
  - Input Channel Utilization (ICU) = Proportion of time that an input channel to the sorting router of the LER is being used
  - Minimum fill factor (F_{min}) = Minimum burst size/max data receivable in fixed assembly time T
  - Maximum fill factor (F_{max}) = Maximum burst size/max data receivable in fixed assembly time T

Regions of Operation of Burst Assembly: Region 1

(R.Rajaduray, IEEE JLT Dec. 2004)





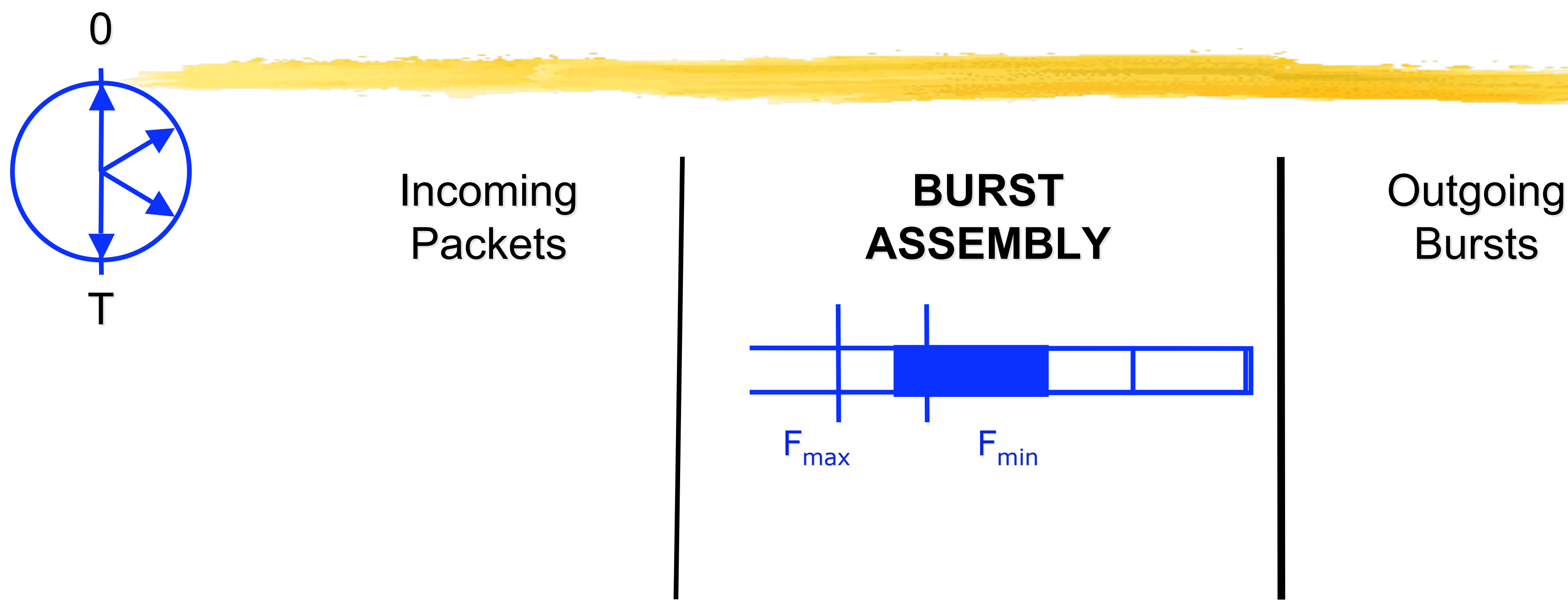
Most bursts do not reach F_{min} before T

Burst assembly process is dominated by burst filling to F_{min}

Normalized burst assembly time $T_{BN} > 1$

Normalized burst size $B_N = F_{min}$

Regions of Operation of Burst Assembly: Region 2

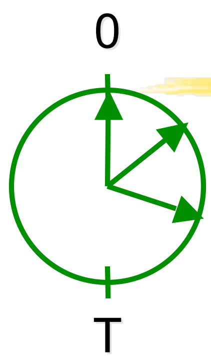


Most bursts exceed F_{min} before T, but do not reach F_{max}

Normalized burst assembly time T_{BN} = 1

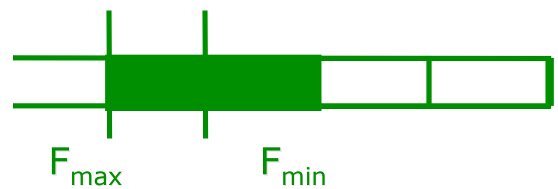
Normalized burst size B_N = ICU/7

Regions of Operation of Burst Assembly: Region 3



Incoming Packets

BURST ASSEMBLY

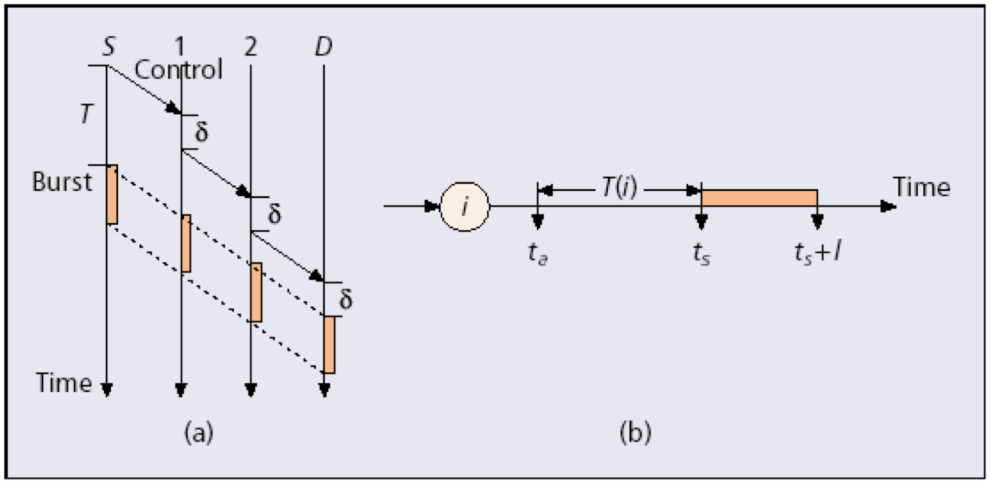


Outgoing Bursts

Most bursts reach F_{max} before T

- Burst assembly process is dominated by burst filling to F_{max}
- Normalized burst assembly time $T_{BN} < 1$
- Normalized burst size $B_N = F_{max}$

Just Enough Time (JET) Signaling Protocol



"Labeled Optical Burst Switching for IP-over-WDM Integration" pp. 104 - 114 C. Qiao, IEEE Comms. Mag.

Control header sent ahead of data burst by basic offset T

- Information about length of burst (l) and time of arrival at switching node t_s is contained in control packet arriving at time t_a

OBS Definitions

Derivative of ATM Block Transfer

With immediate transmission: Request are sent and data immediately sent afterwards.

With delayed transmission: Request are sent, resources established, then data is sent.

RFD: Reserve a fixed duration. Based on close ended resource allocation

TAG: Tell and go is a form of immediate transmission. Based on open ended resource allocation

IBT: In band terminator. Based on open ended resource allocation.

JIT: Just in time switching is an RFD form of TAG OBS. Uses offset time and close ended delayed reservation

JET: Just enough time switching is a form of delayed transmission. Can be modified to set resource allocation to packet arrival time.

IBT OBS

Control Information is sent followed by an IBT that signals the end of the burst.

Bandwidth is reserved and the switch configured as soon as control information is processed.

Bandwidth is released as soon as the IBT is detected.

The message does not need to be stored in the node before it can be switched to the output.

TAG OBS

Source node send setup packet to reserve bandwidth

Source node transmits corresponding message without waiting for an acknowledgment.

A release packet may be sent subsequently to release resources

A refresh packet may also be sent to maintain resources

RFD OBS

Bandwidth reservation is closed ended.

Bandwidth is reserved at each switch for a duration specified by the control packets.

Just-Enough-Time (JET) Switching

Example of RFD based OBS
Uses offset time and delayed reservation
Can lead to increased bandwidth utilization by reducing the burst drop probability

Motivation - Performance

- In 9 years traffic will grow at 4.5 times the capacity of individual routers
- Architecting electronic core routers with higher capacities will continue to burden all-aspects of system design and underlying technologies
  - Two-fold improvement in the electronic technology every 18 months
  - 0.2-fold performance increase from improvements in architectures, algorithms and packet-processing techniques
- Router capacity is often limited by the speed at which packets can be retrieved from memory.
  - Random access times improve only approximately 1.1-fold every eighteen months

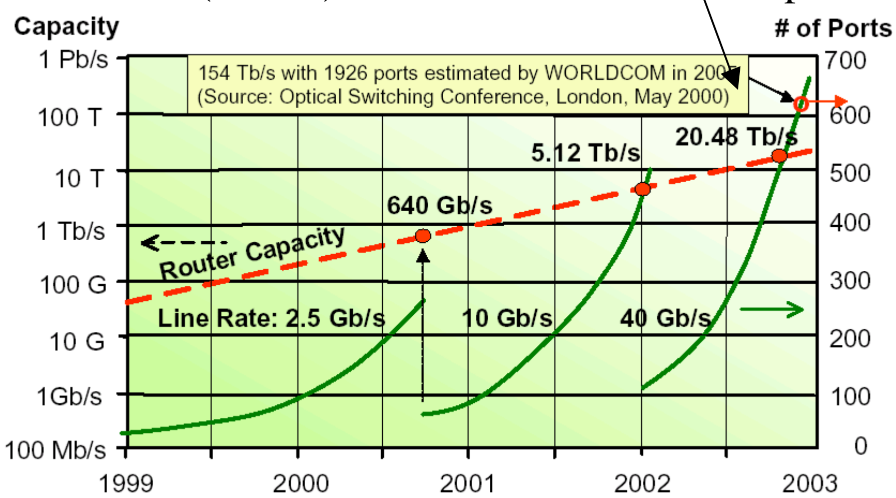
Motivation - Power/Footprint

- Commercial core routers currently handle, in a single rack, on the order of 1 Tbps.
  - Each generation of router consumes more power than the last.
  - Next generation core routers will utilize multi-rack designs in order to spread the system power over multiple racks, reducing the power density and push aggregate capacities to 20 Tbps.
- These systems require as many as 6 optoelectronic conversions per input/output.
  - For example a 1 Tbps router with 128 10Gbps I/O ports can require 768 10Gbps OE or EO conversions whose power dissipation and footprint goes up with increasing number of ports and increasing bit rate per port.

Scalability

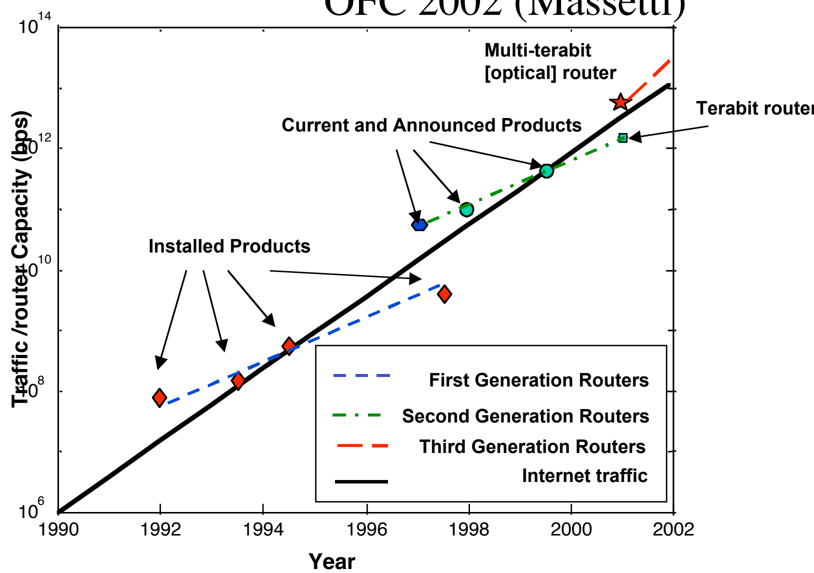
Predicted (Kaiser)

Still at 1-5 Tbps

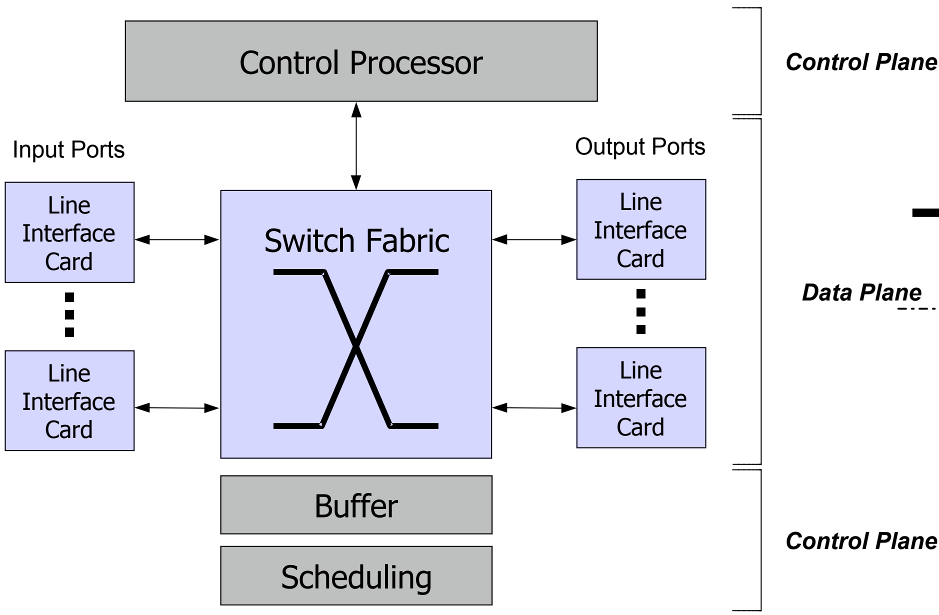


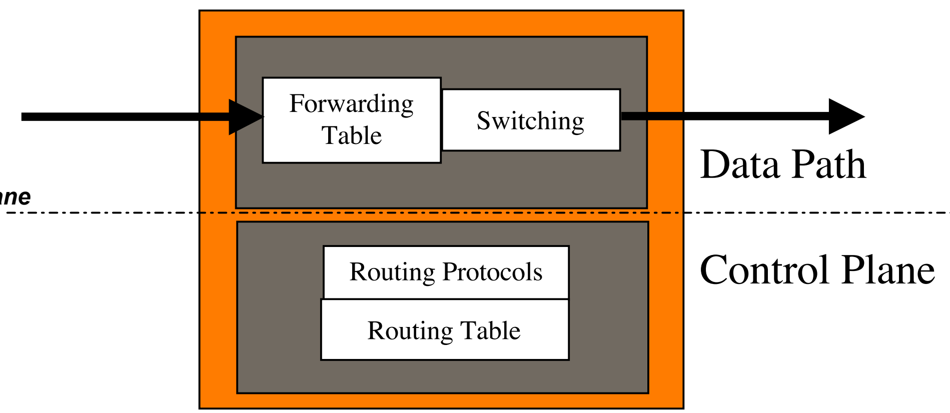
Adapted from Avici Systems, KMI Conf., Oct. '99

OFC 2002 (Massetti)



Basic Router Model





- **Line interface cards** to the incoming and outgoing links
- A **forwarding engine** that switches packets to the correct output port buffering modules
- A **backplane** that consists of either a bus or a switch fabric that connects input line interface cards to output interface cards
- Distributed and/or centralized **control processor** that handles route computation, scheduling (according to routing protocols) and management
- We can also classify the *functions* of a router into two *planes*:
  - **Control**: Performs functions related to routing protocols and route table lookup and manages the switching of packets from input to output
  - **Data**: Performs per-packet processing, including forwarding and switching

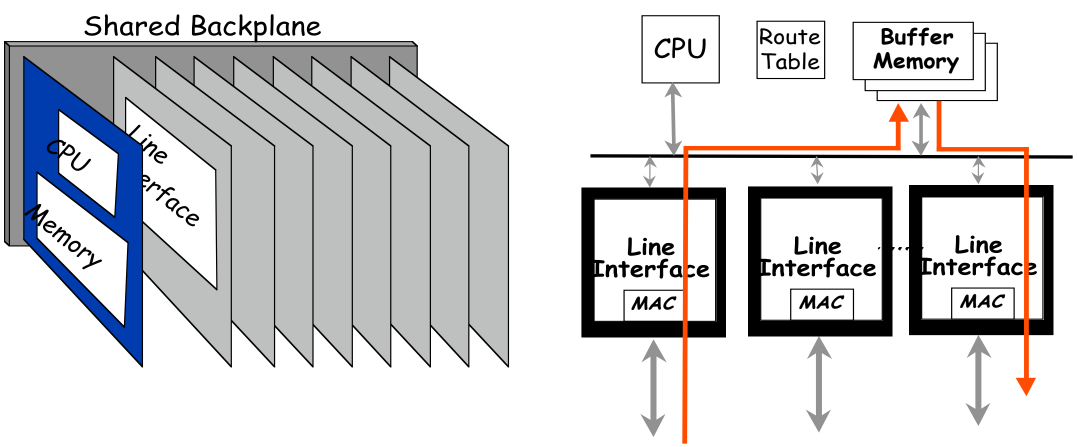
Router Classification

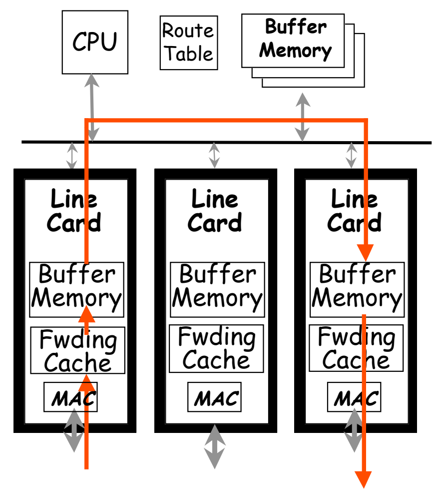
- **Electronic**
  - Fiber WDM transmission
  - All electronic line-cards, controller and switching fabric
  - All electronic packet handling and regeneration
- **Hybrid Optoelectronic**
  - Fiber WDM transmission
  - All-electronic line-cards and controller
  - Optical switching fabric
  - All electronic packet handling and regeneration
- **All-Optical**
  - Fiber WDM transmission
  - Optical packet switching plane
  - Optical packet handling and regeneration
  - Electronic or optical packet processing

Electronic Router Evolution

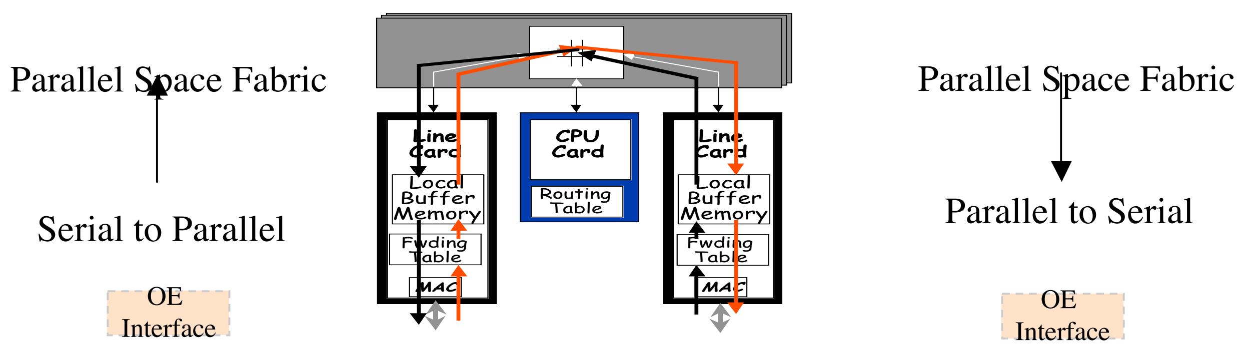
Single Processor Shared Bus

Multi-Processor Shared Bus



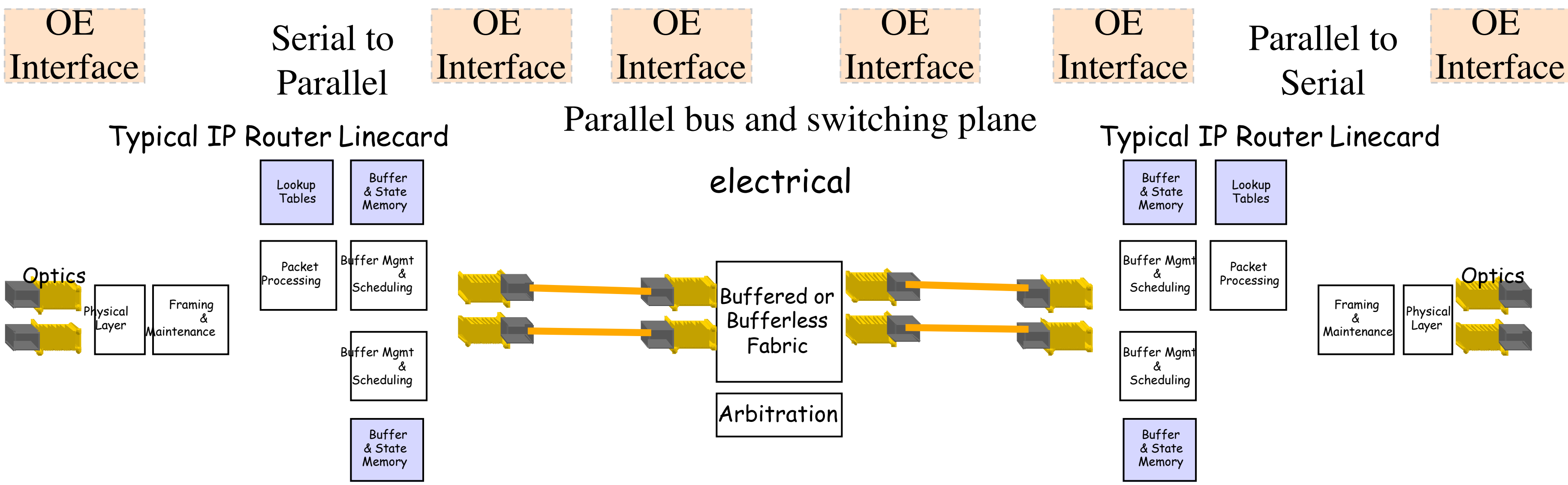


Multiple Processor Space Switching



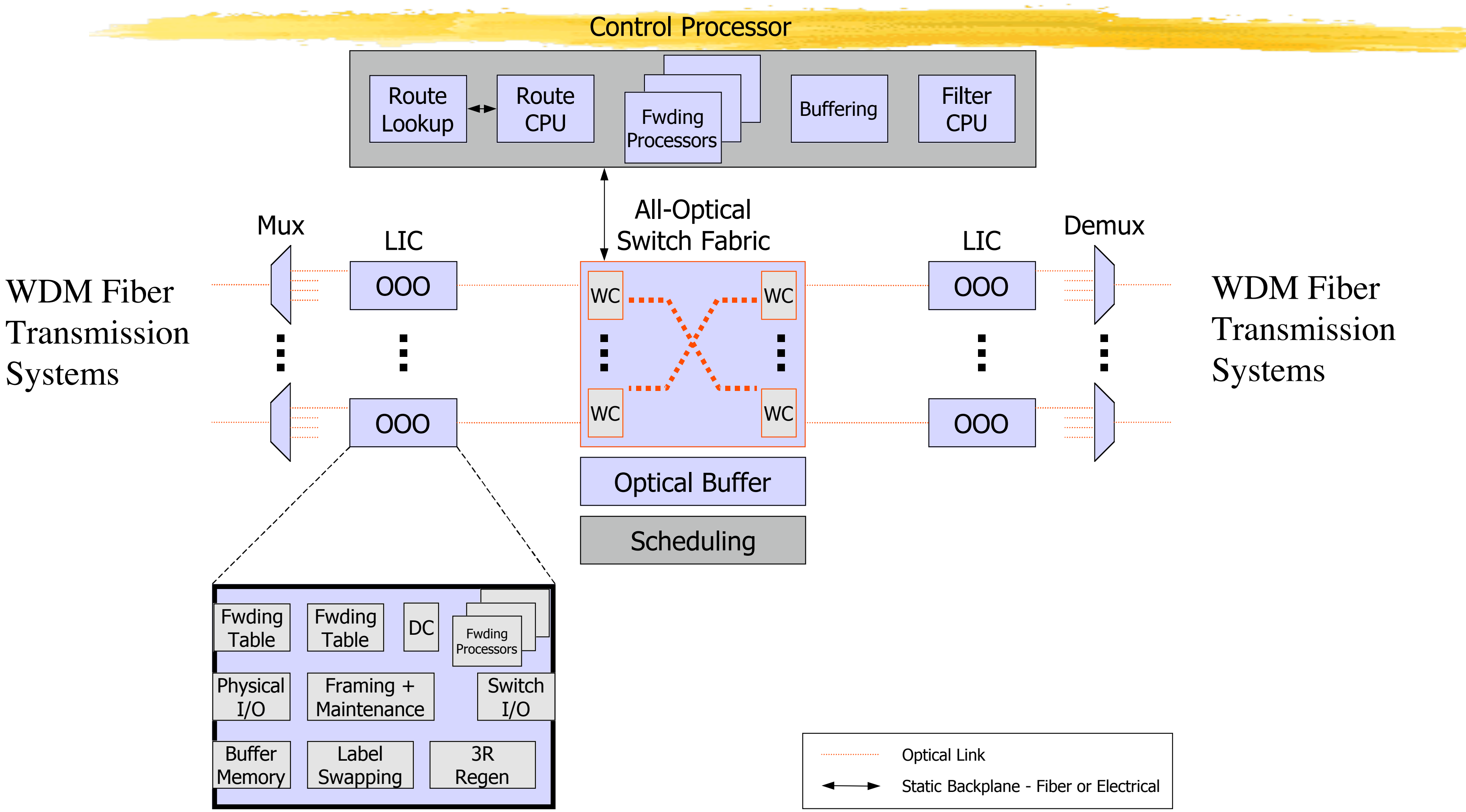
(McKeown)

4^{th} Generation Electronic: Shared Parallel Processor Space Switching



Adapted from McKeownn

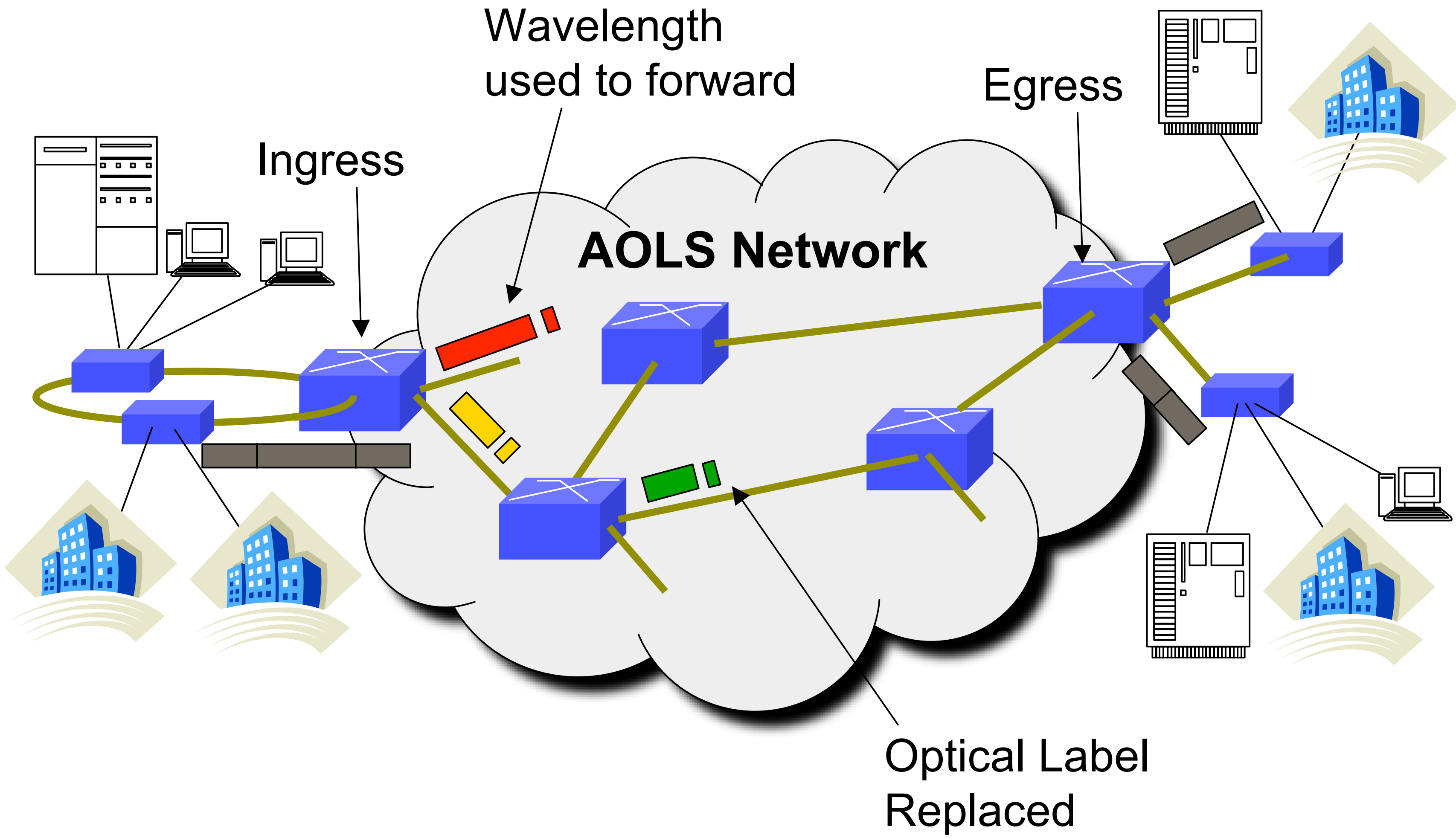
All-Optical Router Reference Model



Status of Optical Packet Switching

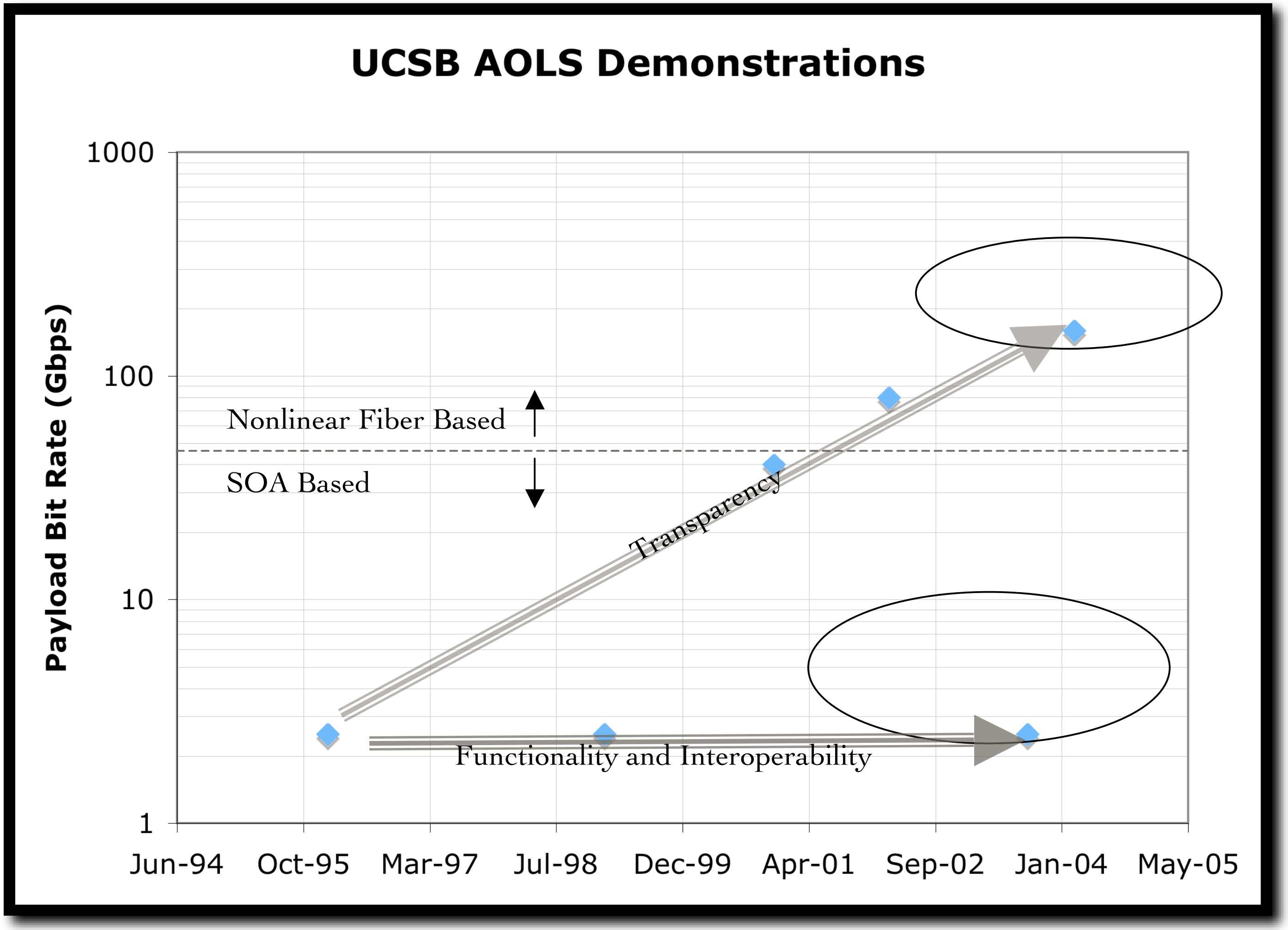
- Basic functions of optical packet switching have been demonstrated
  - Optical header/label recovery, removal, processing, reinsertion, packet routing and forwarding, limited packet buffering
  - Can do wavelength conversion and switching at packet line rates
- What are key scalable switching technologies
  - Rapid waveguide switches, fast wavelength tuning, wavelength routers, dispersive and switchable delay lines, photonic integration
- What are the most difficult issues
  - Variable Optical Delay Lines and Optical Buffers
  - Handling variable length packets
  - Functional high-density integration of photonic and optoelectronic circuits
  - Regeneration, network transmission engineering and interoperability
  - Ultra-high performance optical label recognition/lookup/routing engine

All-Optical Label Switching



AOLS Demonstrations

Institution	Date	Payload Bitrate [Gb/s]
Lucent	Jun-04	10
Lucent/Eindhoven/COM TUD	Nov-03	10
Chiao-Tung University Taiwan	Feb-04	10
Chiao-Tung University Taiwan/Telcord	Mar-00	2.5
Chiao-Tung University Taiwan/Telcord	Aug-00	2.5
Chinese University of Hong Kong	Nov-03	10
Chinese University of Hong Kong	Dec-03	10
Chinese University of Hong Kong	Feb-04	10
Chinese University of Hong Kong	Mar-04	10
Chinese University of Hong Kong	Apr-04	10
Chinese University of Hong Kong	Apr-04	10
Chunghwa Telecom Labs, Taiwan	Mar-01	10
COM TUD	Jul-01	10
COM TUD	Mar-03	10
COM TUD	May-03	10
COM TUD/Eindhoven	Apr-03	10
CRL Tokyo	Mar-02	40
NTT	Jan-03	20
Osaka University/CRL Tokyo	Dec-00	10
Stanford/USC	Nov-03	10
Tsinghua University	Nov-02	10
UC Davis	Jun-01	2.5
UC Davis	Aug-02	2.5
UC Davis	Mar-03	2.5
UC Davis	Mar-03	2.5
UC Davis	Nov-03	2.5
UC Davis	Dec-03	2.5
UC Davis	Jan-04	2.5
UCSB	Feb-96	2.5
UCSB	Feb-99	2.5
UCSB	Dec-00	40
UCSB	Mar-02	80
UCSB	Sep-03	2.5
UCSB	Mar-04	160
Univ. of Athens	Oct-02	10
Univ. of Essex	Jul-04	40
COM TUD	Nov-02	10
COM TUD	Aug-03	10
GaTech	Jan-04	10
GaTech	Jan-04	10
KDDI	Oct-01	10
KDDI	Dec-01	10
KDDI	Mar-03	10
STOLAS	Nov-03	10
Telcordia/Tellium/Chiao-Tung Univers	Nov-99	2.5
UC Davis	Mar-01	2.5
UC Davis	Mar-02	1.6
UC Davis	Mar-02	1.6
UC Davis	Sep-03	2.5
UCSB (ECOC 03)	Sep-03	2.5



Optical Packet Switching and Label Swapping Technology

- Where is it today
  - Basic functions of optical packet switching have been demonstrated: Optical header/label recovery, removal, processing, reinsertion, packet routing and forwarding, limited packet buffering
  - Packet rate wavelength conversion and switching
  - New techniques have been developed to make up for lack of optical random access and dynamic memory
  - Recent experimental work has started to address variable length packets
- What are technologies most likely to be used
  - Rapid waveguide switches, fast wavelength tuning, wavelength routers, fiber and dispersive delay lines
- What are the most difficult issues
  - Optical random access buffering
  - Handling variable length packets
  - Network transmission engineering and interoperability

Optical Packet Switching and Label Swapping Technology

- Where is it today
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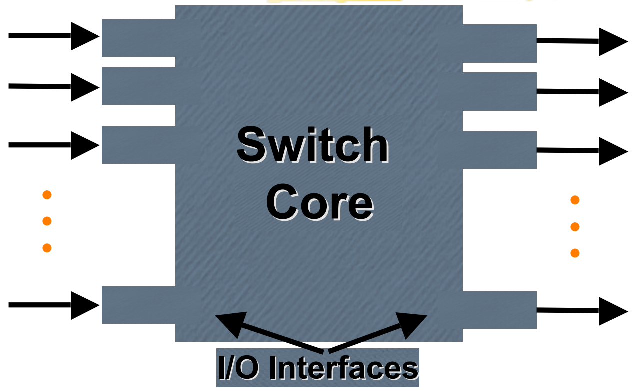
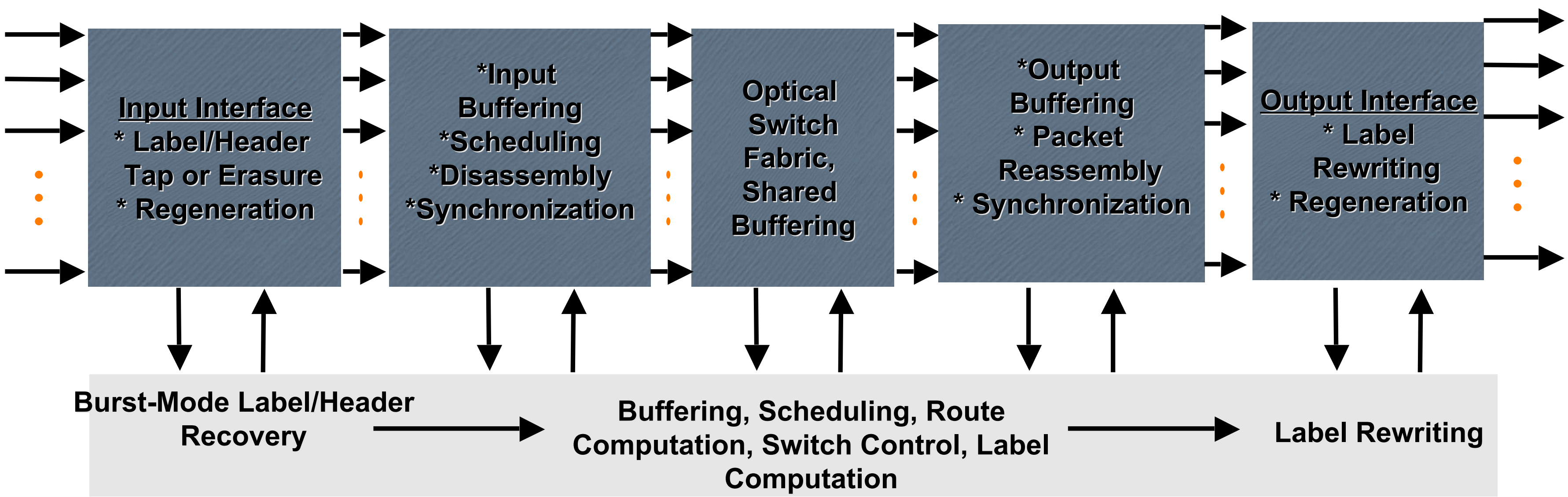
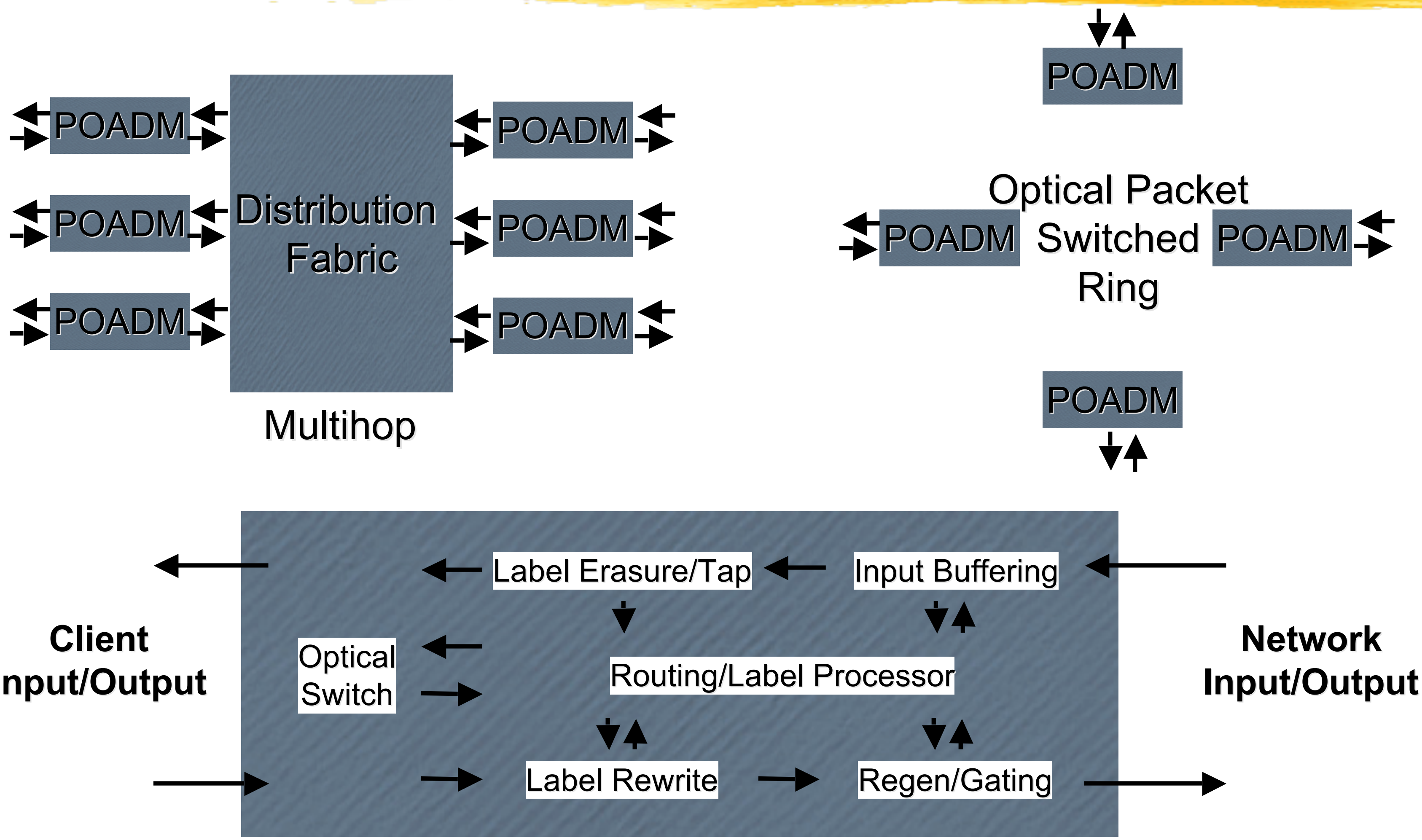
  - Recent experimental work has started to address variable length packets
- What are key scalable switching technologies
  - Rapid waveguide switches, fast wavelength tuning, wavelength routers, fiber and dispersive delay lines
- What are the most difficult issues
  - Optical random access buffering vs. optical FIFO. Also need elasticity.
  - Handling variable length packets
  - Functional integration
  - Network transmission engineering and interoperability

Centralized Packet Switch Architectures





Distributed Packet Switch Architectures (Packet OADMs)



Buffer Evolution

- No Optical Buffering
  - Employ all-optical regeneration (2R for transparency)
  - Wavelength conversion and wavelength switching
  - Optical burst switching, electronic header, signaling and switch control
  - Edge electronics used to aggregate, burst and schedule
- Limited Optical Buffering
  - Packet switched with scheduling at the switch
  - Fixed size optical buffers (e.g. fiber delays)
  - Wavelength conversion with wavelength switching
  - All-optical regeneration
  - Optical data plane/electronic header and signaling plane
- Limited Optical Buffering/Optical Logic
  - Limited optical packet bit-level processing
  - Optical header processing
  - Switched delay lines
- New Buffer Technology
  - Electromagnetic Induced Transparency (EIT)
  - Slow waveguides (e.g. PBGs)