Photonics in switching

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The aim of this lecture

- To show principles for optical circuit switching, packet switching and burst switching
- To highlight the main technological problems
- To give an overview of the optical switching node architectures

Photonics in switching

- Introduction
- Optical circuit switching (OCS)
- Optical packet switching (OPS)
  - Functions of an optical router
  - Contention resolution
  - OPS architectures
- Optical burst switching (OBS)
- Summary

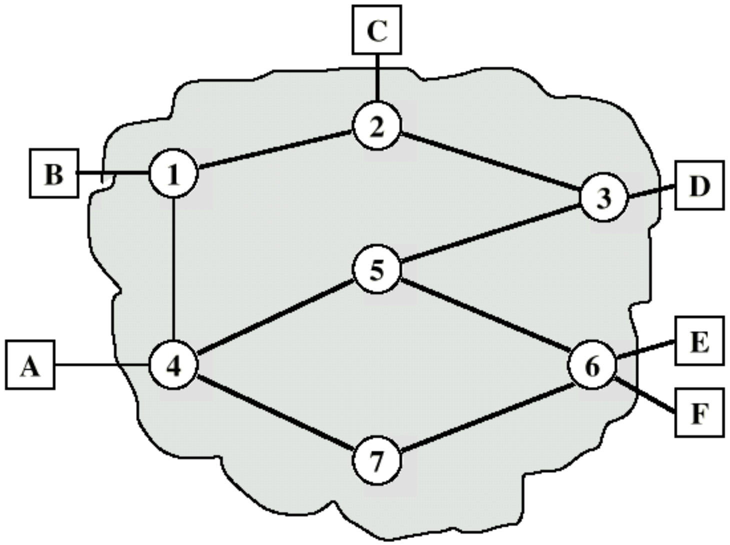
Switching

- Need for efficient utilization of network resources
- Full mesh connectivity vs. switched connectivity
- Resource sharing

Switching paradigms

- Circuit Switching
- Packet switching
- Cell switching
  - a kind of packet switching
  - fixed packet size (e.g. ATM cells)
  - uses virtual circuits (VCS), routing decisions - during virtual circuit setup.

Switched networks



Switching nodes

- not concerned with contents of data
- purpose: provide switching facility
- in general not fully connected

End nodes

- provides data to transfer
- connected via switching nodes

Links

- physical connections between nodes

Advantages of Optics

- Fantastic for transmission
  - Optical amplifier can simultaneously amplify all of the signals on all channels (~160) on a single fiber
- Huge bandwidth: 50 Tbps on single fiber
  - Compare it to electronic data rates of few Gbps
- Low signal attenuation
- Low signal distortion
- Low power requirement
- Low cost

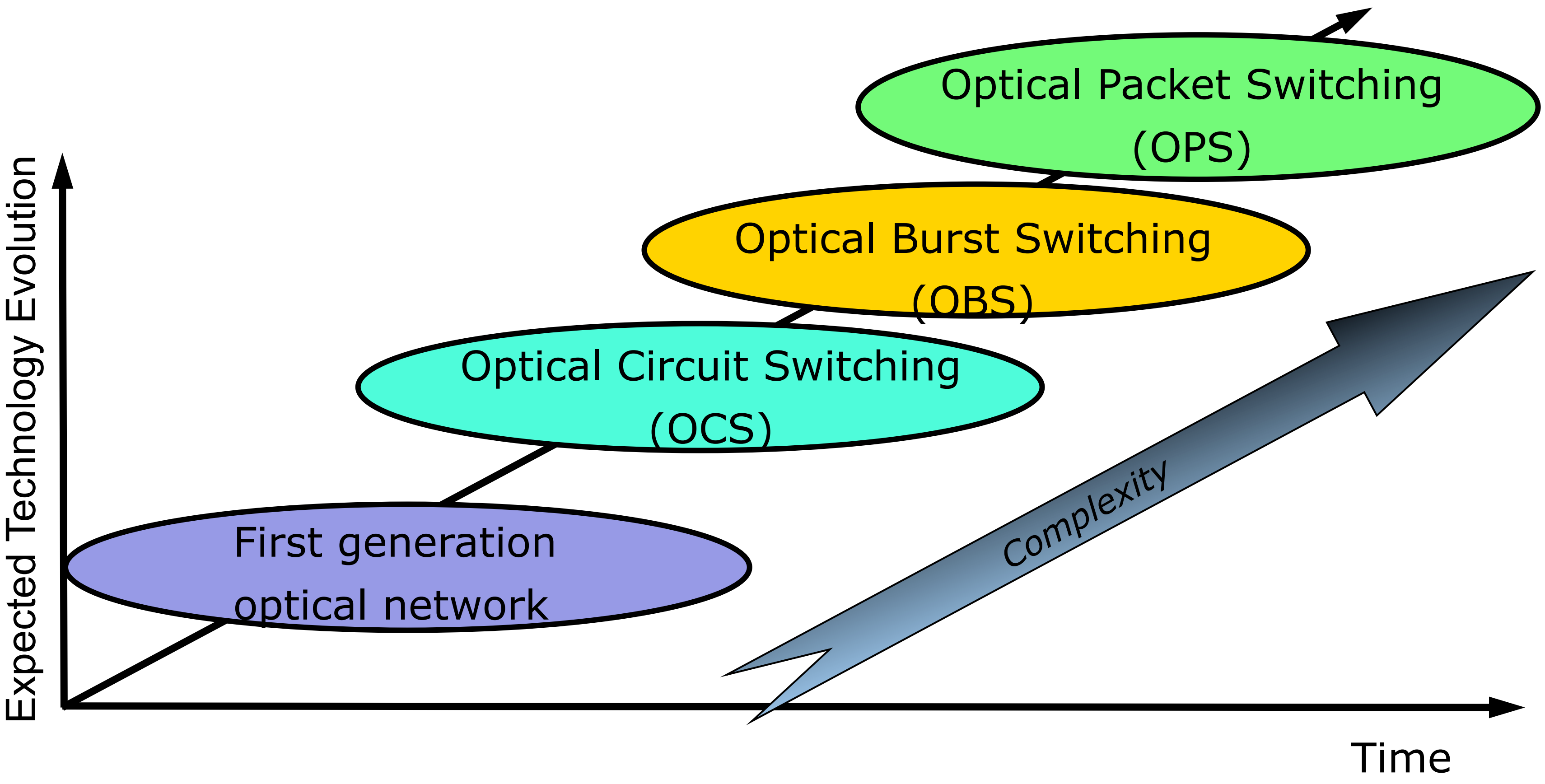
Optics-Electronics Mismatch

- 50 Tbps vs. 10 Gbps
- How to exploit the fiber's huge capacity?
  - Introduce concurrency among multiple users
  - Wavelength division multiplexing: WDM
- WDM: multiplexing technology for optical networks
  - The optical transmission spectrum is divided into a number of non-overlapping frequency bands (wavelengths)
  - Client interface (e.g., IP router port) needs to operate at the bitrate of the WDM channel
  - Channel bitrate: e.g., peak electronic bitrate.
  - Challenge is to design and develop appropriate network architectures, protocols, and algorithms

Photonics in switching

- Optical circuit switching (OCS)
  - Wavelength-routed networks
  - Relatively mature technology today
  - Providing lightpaths
  - WDM network elements: OLT, OADM, OXC
- Optical packet switching (OPS)
  - Not available today due to some technological problems
    - Controllable optical memory for optical buffering
    - Control functions in the optical domain
    - Synchronization, etc
- Optical burst switching (OBS)
  - Hybrid packet switching: a feasible solution?

Optical Networks



Optical circuit switching

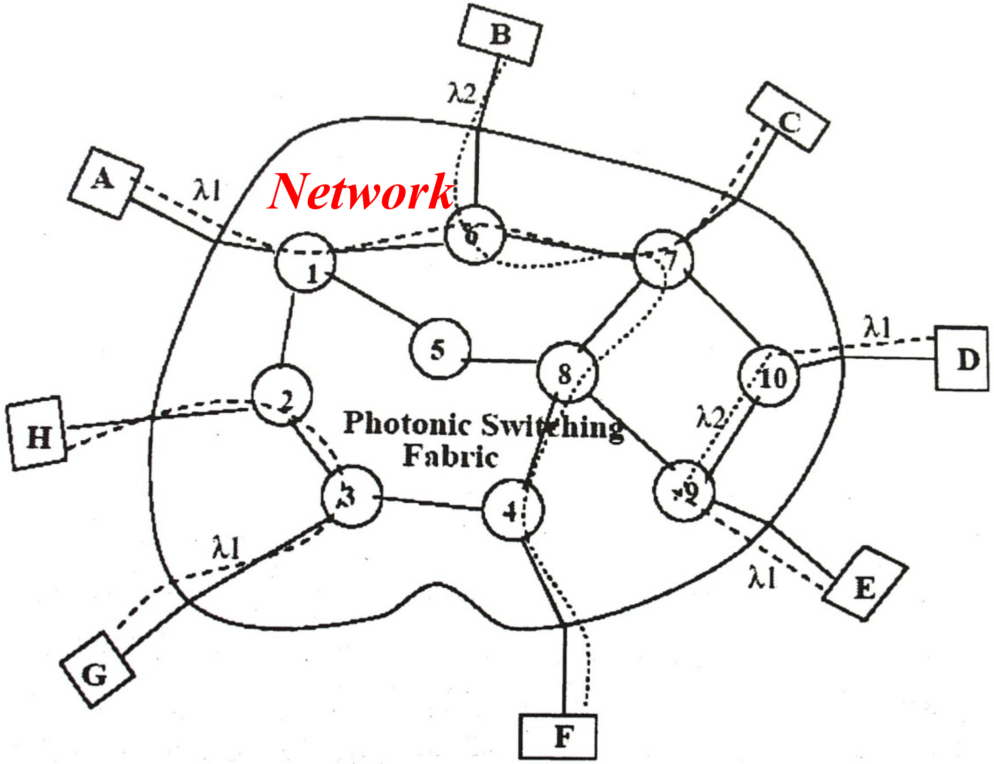
Wavelength-Routed Networks

Wavelength-Routed Networks

- W-R switches
- Provide lightpaths

Problems:

- Low bandwidth efficiency
- Large granularity



1 Wavelength-routing switch

A Access (client) node (e.g., IP router): contains (tunable) transmitters and receivers

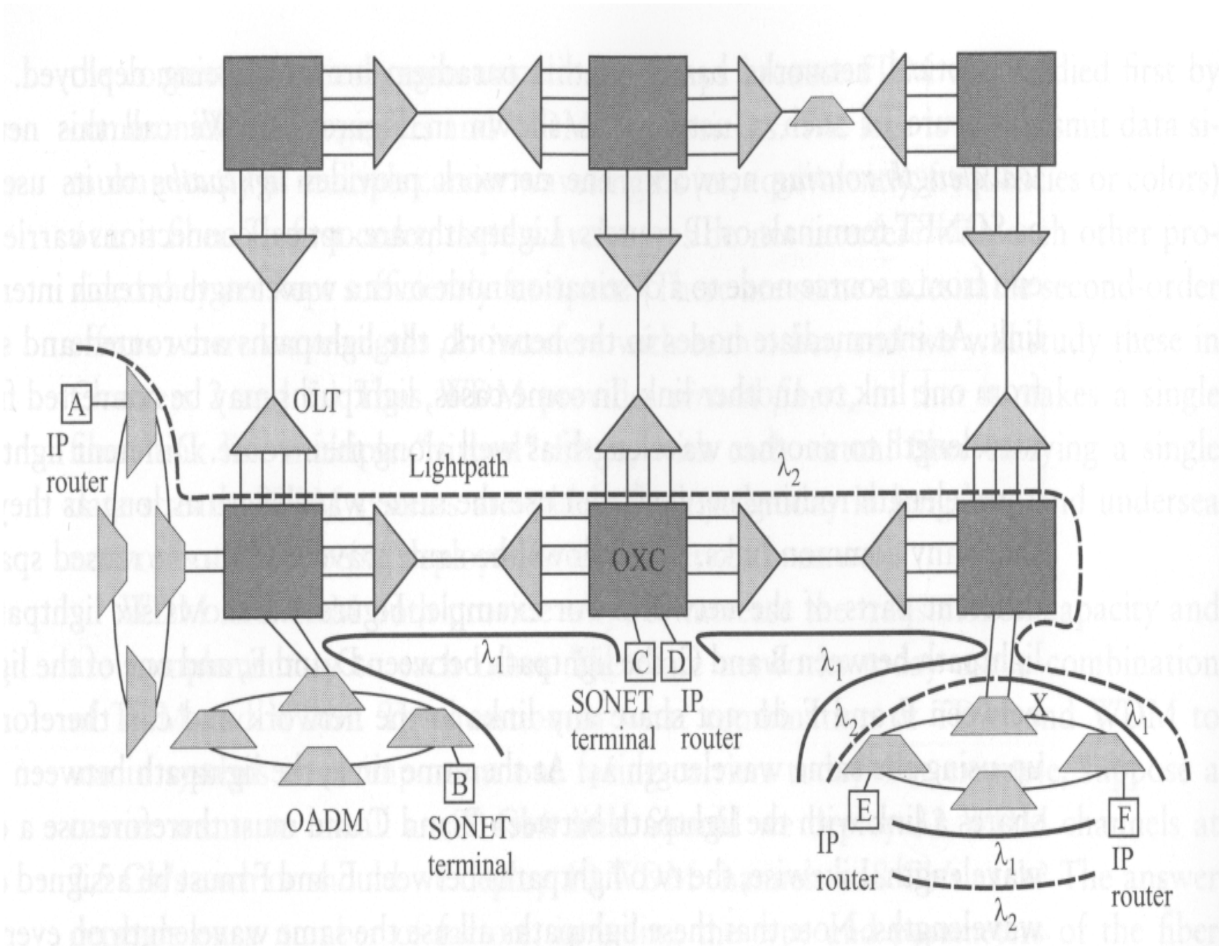
Optical circuit switching

- Solving LTD and RWA problems
- A lightpath corresponds to a circuit
  - Set-up a lightpath
  - The whole lightpath is available during the connection
  - Disconnect
- Network elements
  - Fiber
  - Optical line amplifier (OLA)
  - Optical line terminal (OLT)
  - Optical add-drop multiplexer (OADM)
  - Optical cross-connect (OXC)

WDM network elements

- Optical line terminals (OLTs)
- Optical add-drop multiplexers (OADMs)
- Optical cross-connects (OXCs)
- Optical line amplifiers

WDM network example



Architecture Features

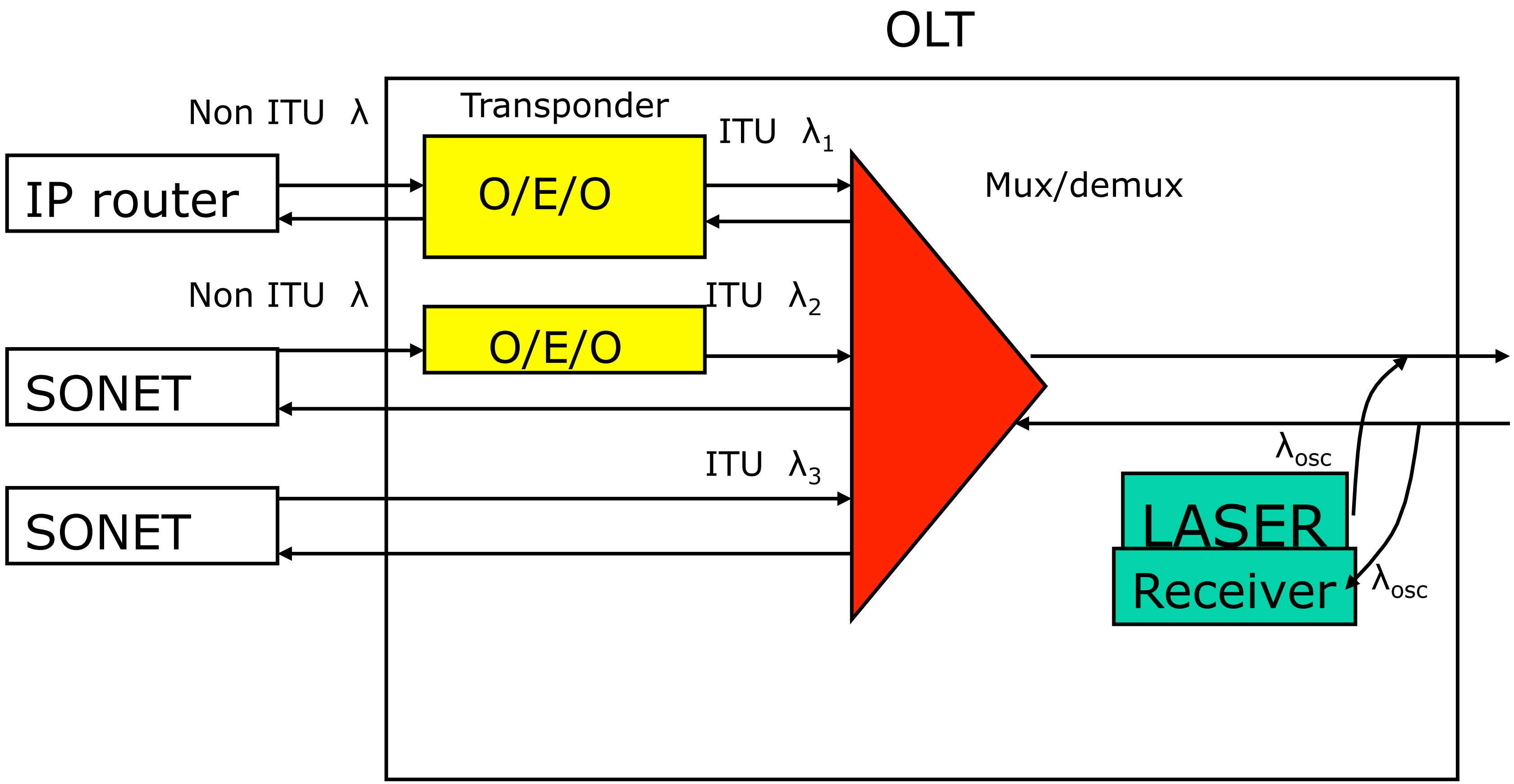
- Wavelength reuse
- Wavelength conversion
- Transparency
- Survivability
- Lightpath topology

Optical Line Terminal (OLT)

Three functional elements

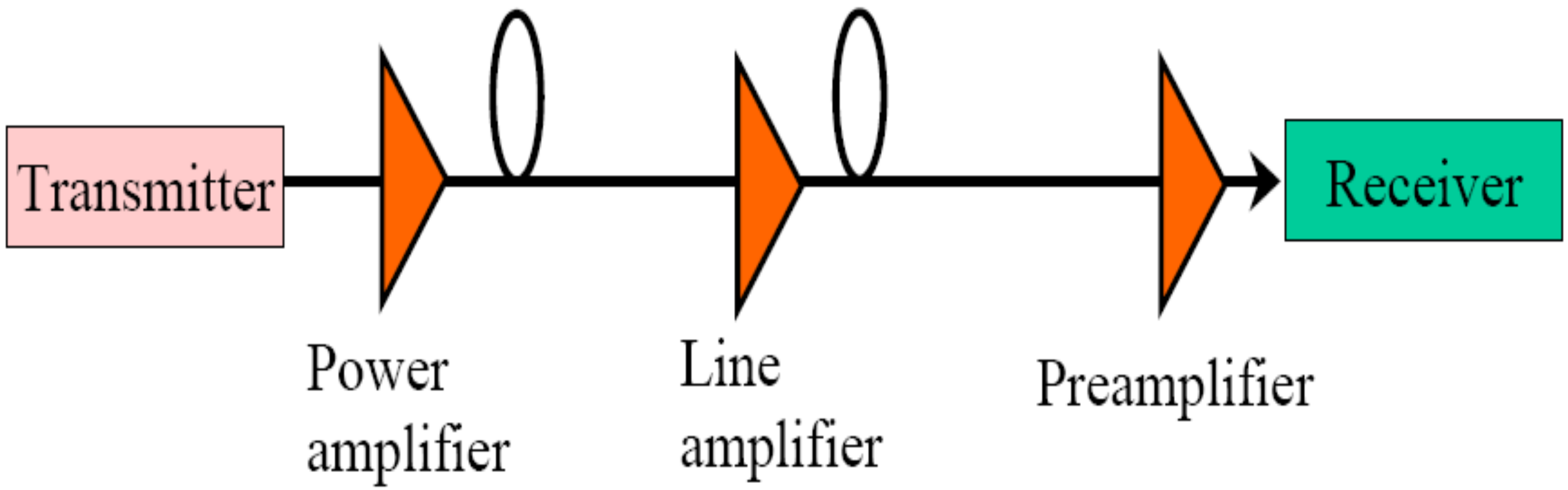
- Transponders (transmitters, receivers)
  determine cost, footprint, power consumption
- Wavelength multiplexers
  AWG (arrayed waveguide grating), FBG (fiber Bragg grating), thin-film filers
- Optical amplifiers (optional)

Block diagram of an OLT

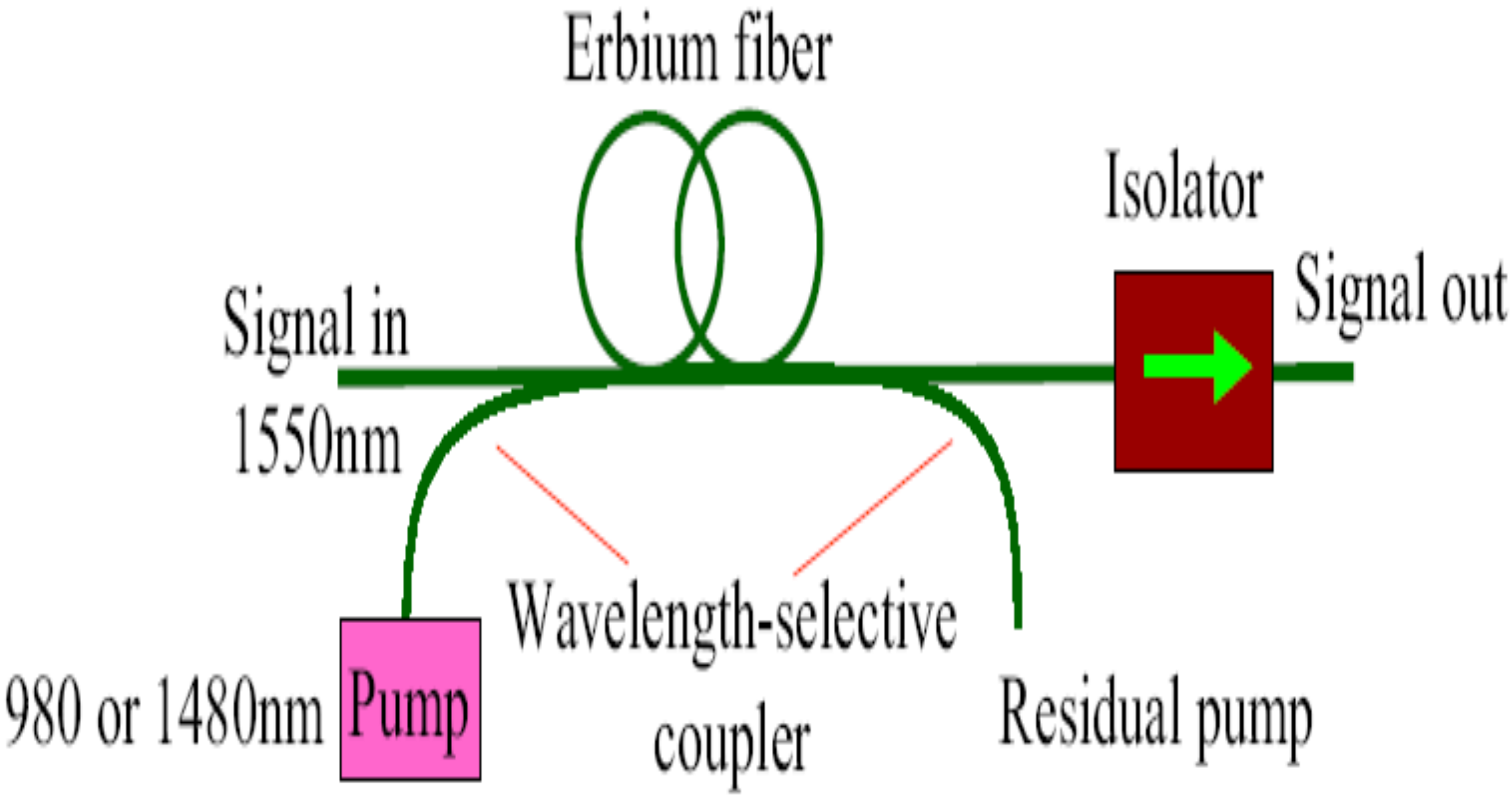


Optical Supervisory Channel

Optical line amplifier



Erbium Doped Fiber Amplifier (EDFA)



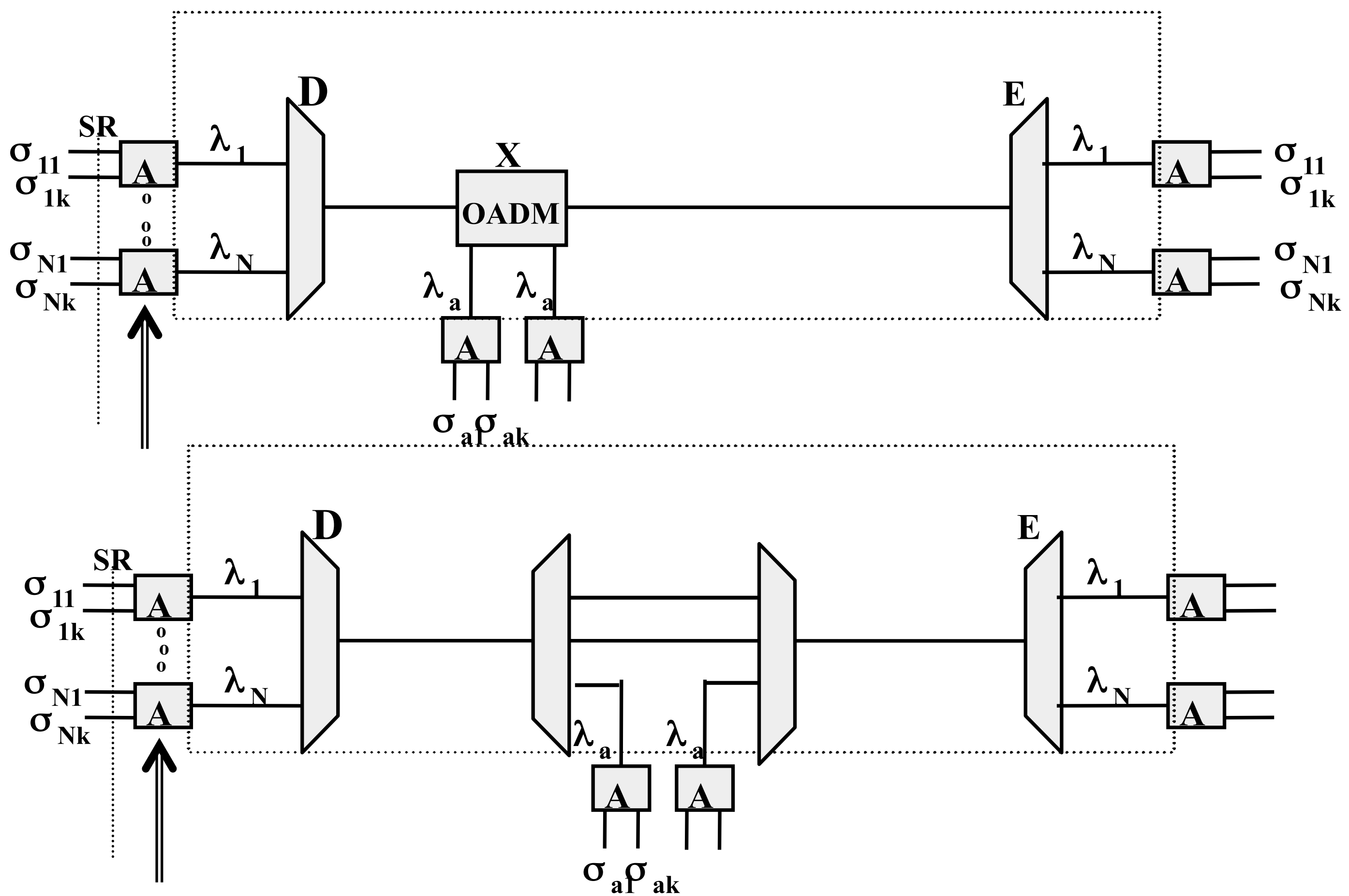
Optical add/drop multiplexer (OADM)

- **Drop and add one or more wavelength channel**
  - To and from equipment at local node
  - Remaining channels pass transparently
- **Channel selection**
  - Any channel or only some
  - Static ➔ Requires careful planning
  - Reconfigurable: software configurable remotely
  - One, a few or any number of channels
    - Modularity
    - Loss dependence on number of dropped channels

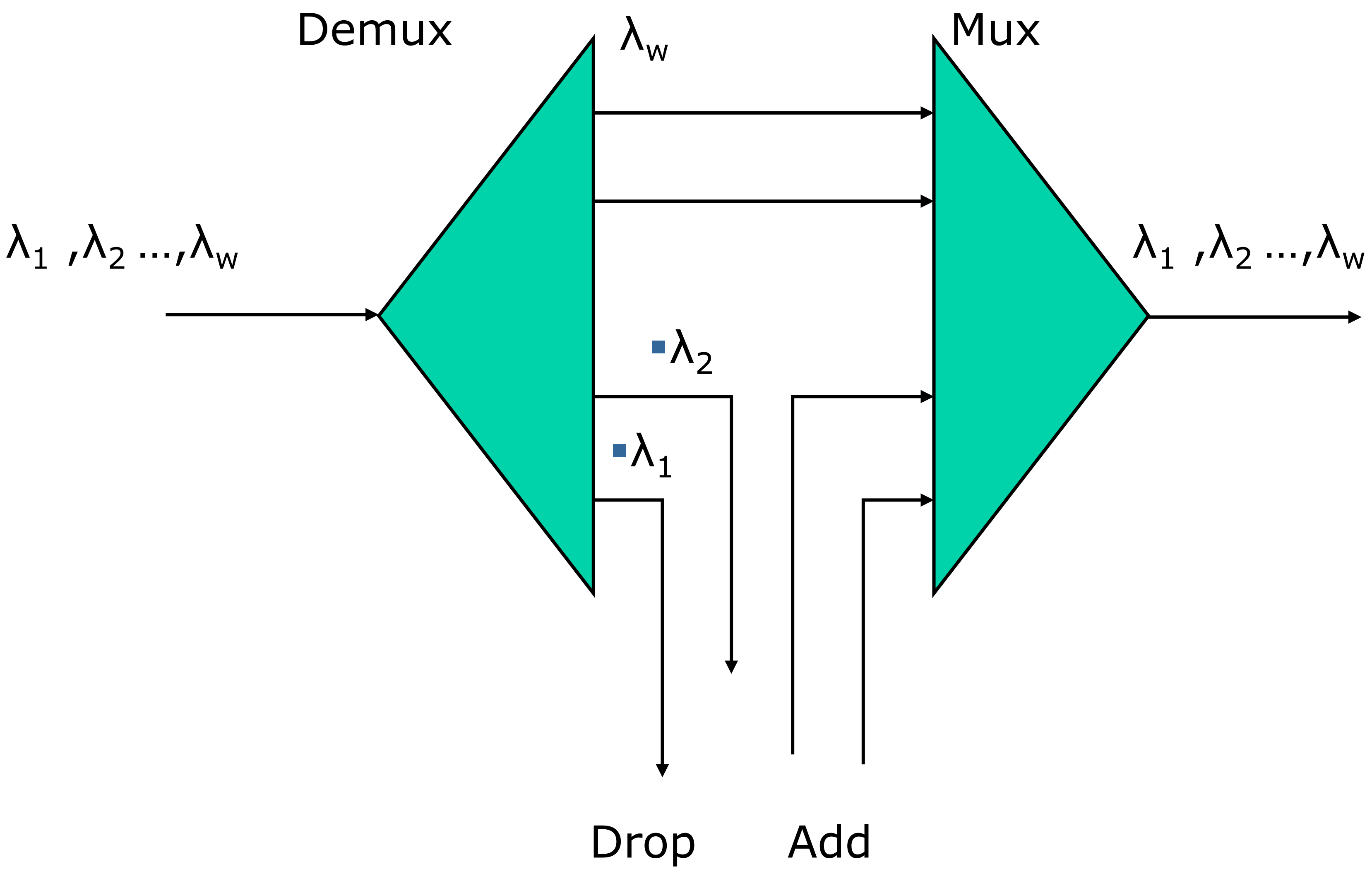
Ideal OADM

- Would drop and add any channel
  - And any number of channels
- Remotely controlled
  - Reconfiguration without disturbance to unaffected channels
  - No plan-ahead needed
- Low and fixed loss
  - Independent of set of wavelengths dropped

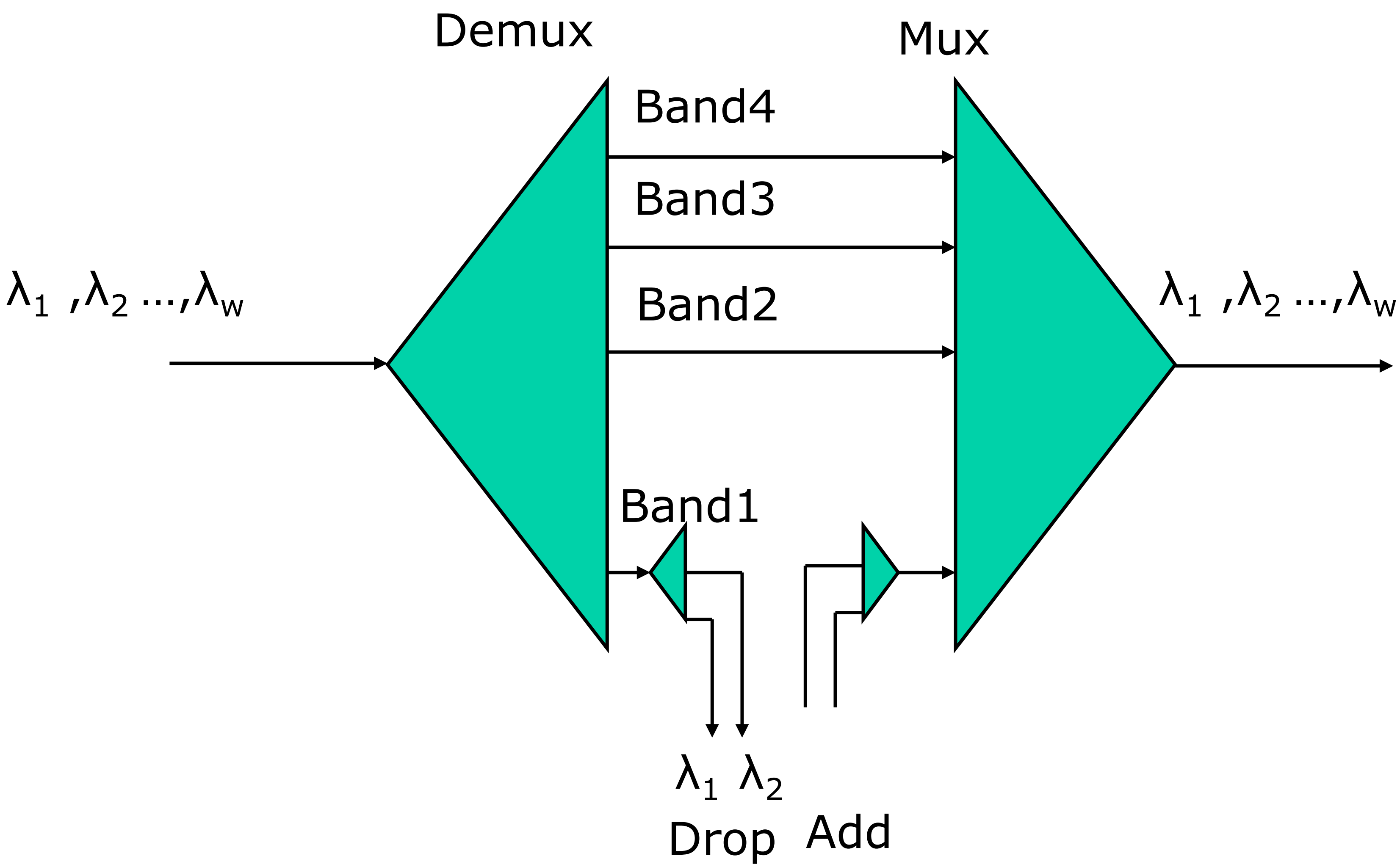
OADM example



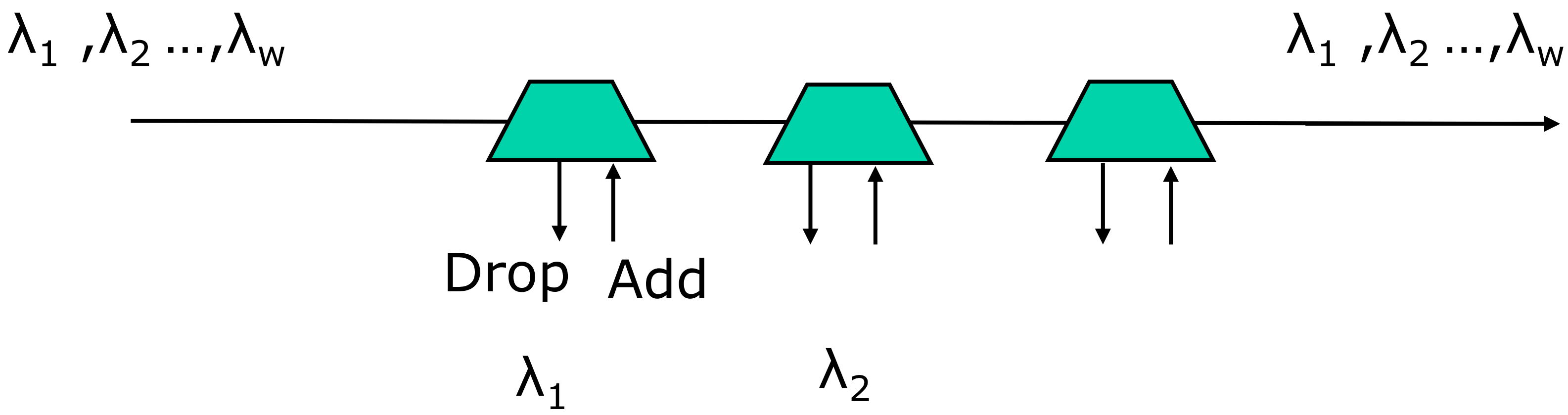
OADM: Parallel Architecture



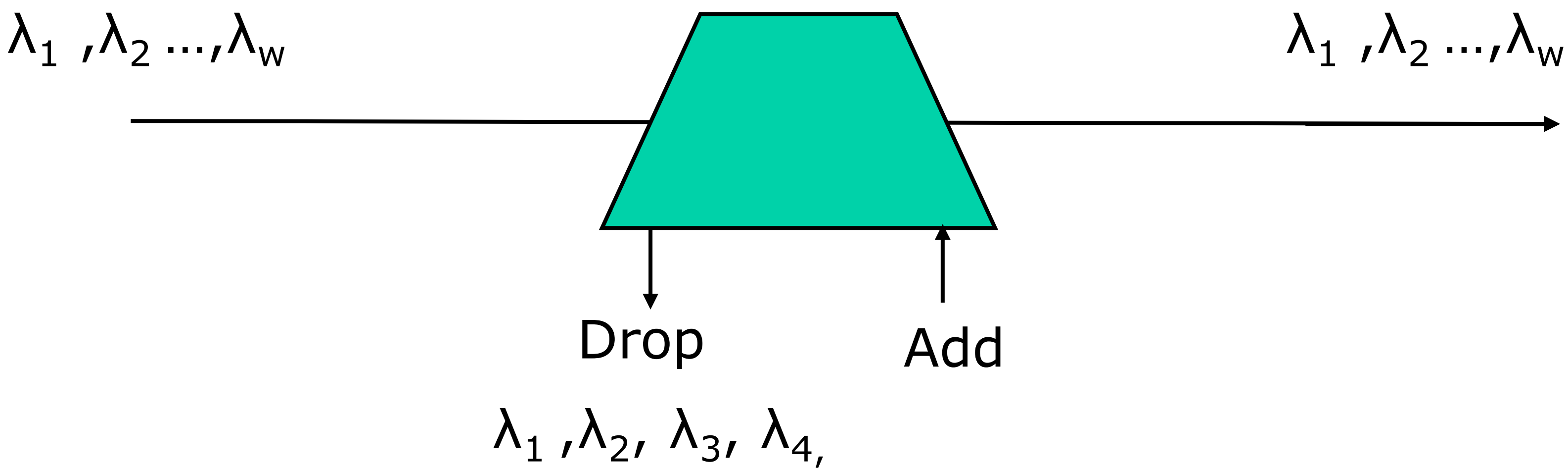
OADM: Modular version



OADM: Serial Architecture



OADM: Band drop



Optical Cross-connects (OXC)

- Switching of wavelengths channels
  - From input to output ports
  - From input to output wavelengths
- Functions
  - Provide lightpaths
  - Protection switching (rerouting)
  - Performance monitoring
  - Wavelength conversion

All-Optical OXC

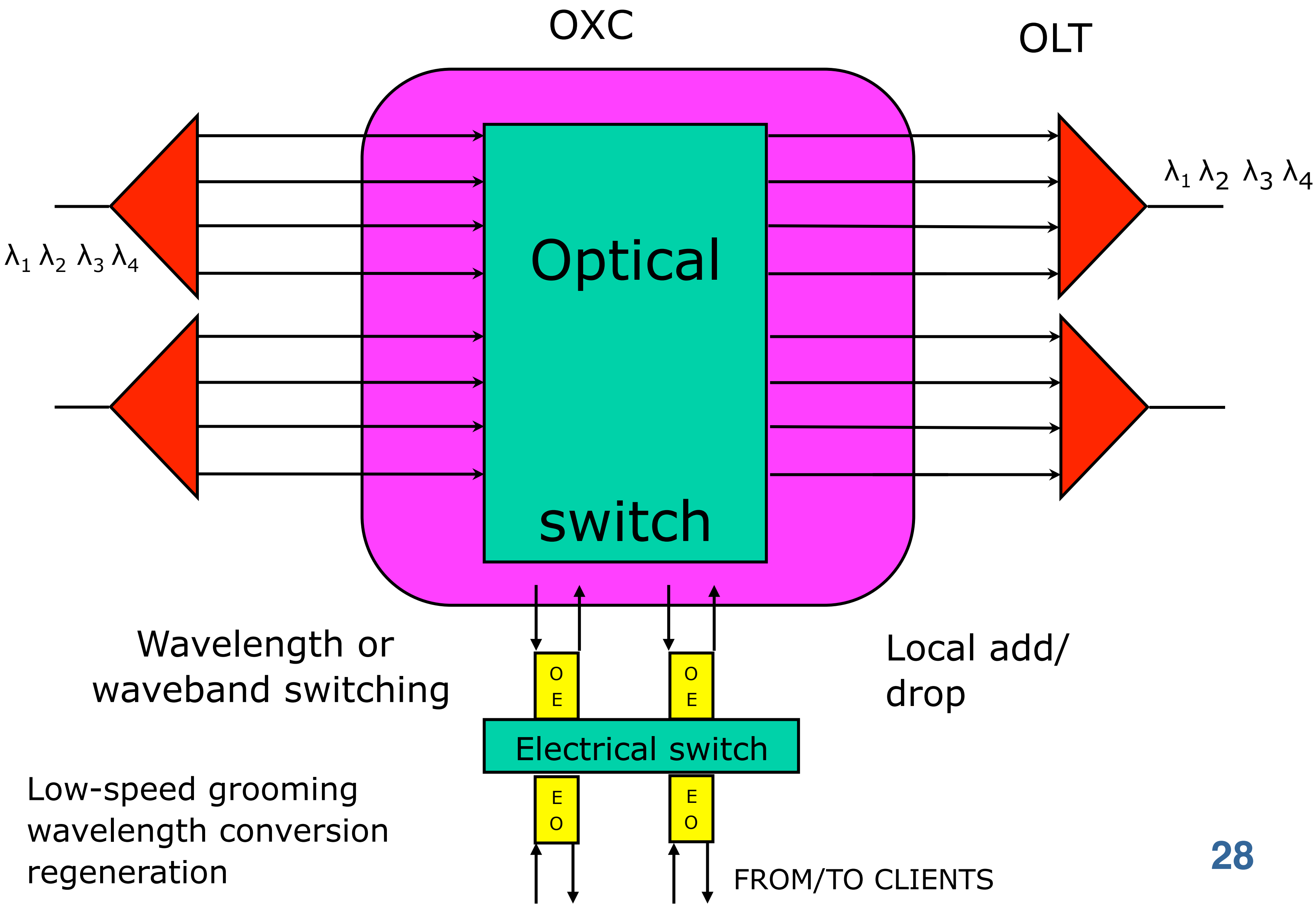
Disadvantages

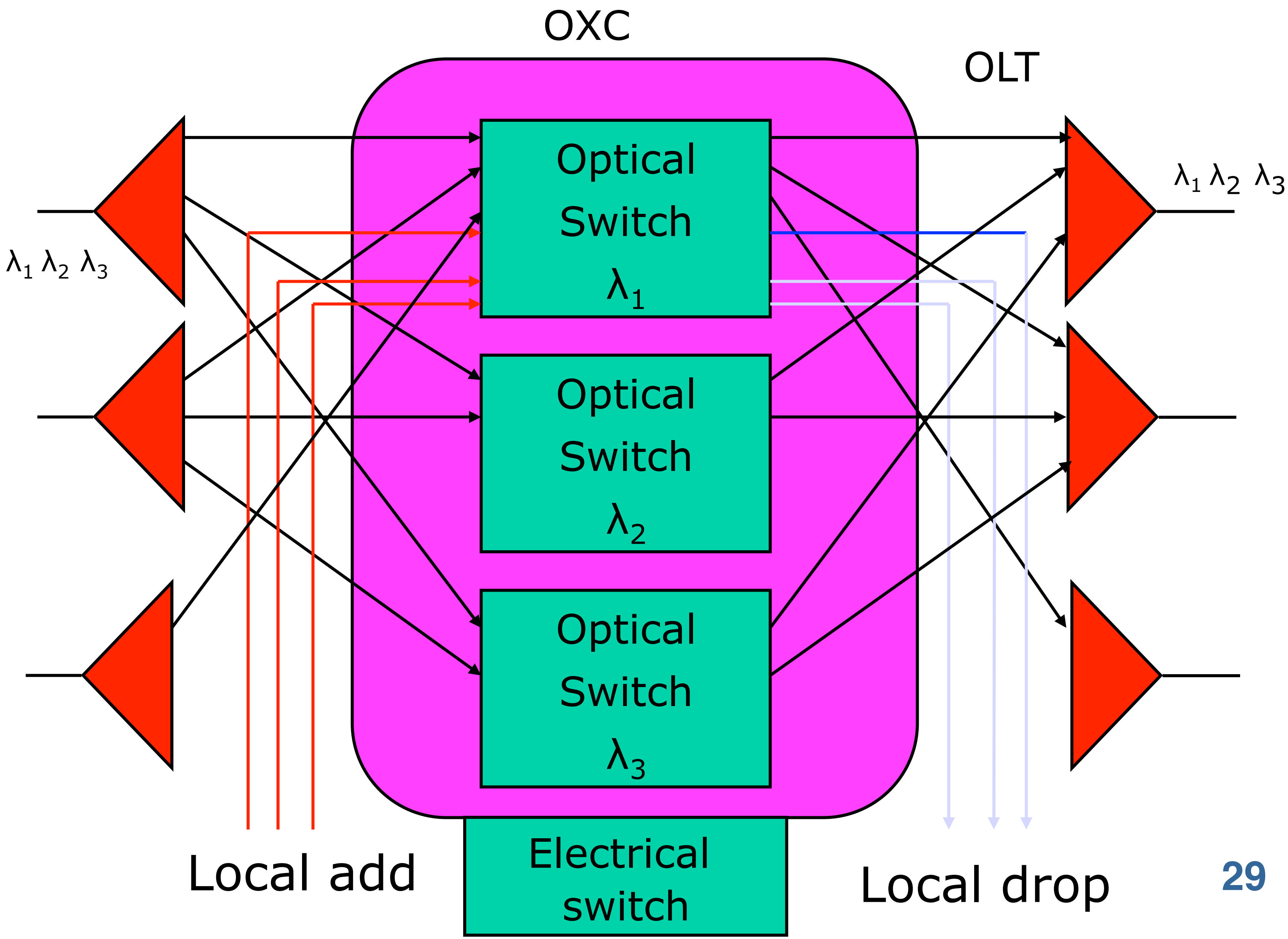
Lack of functionality for:

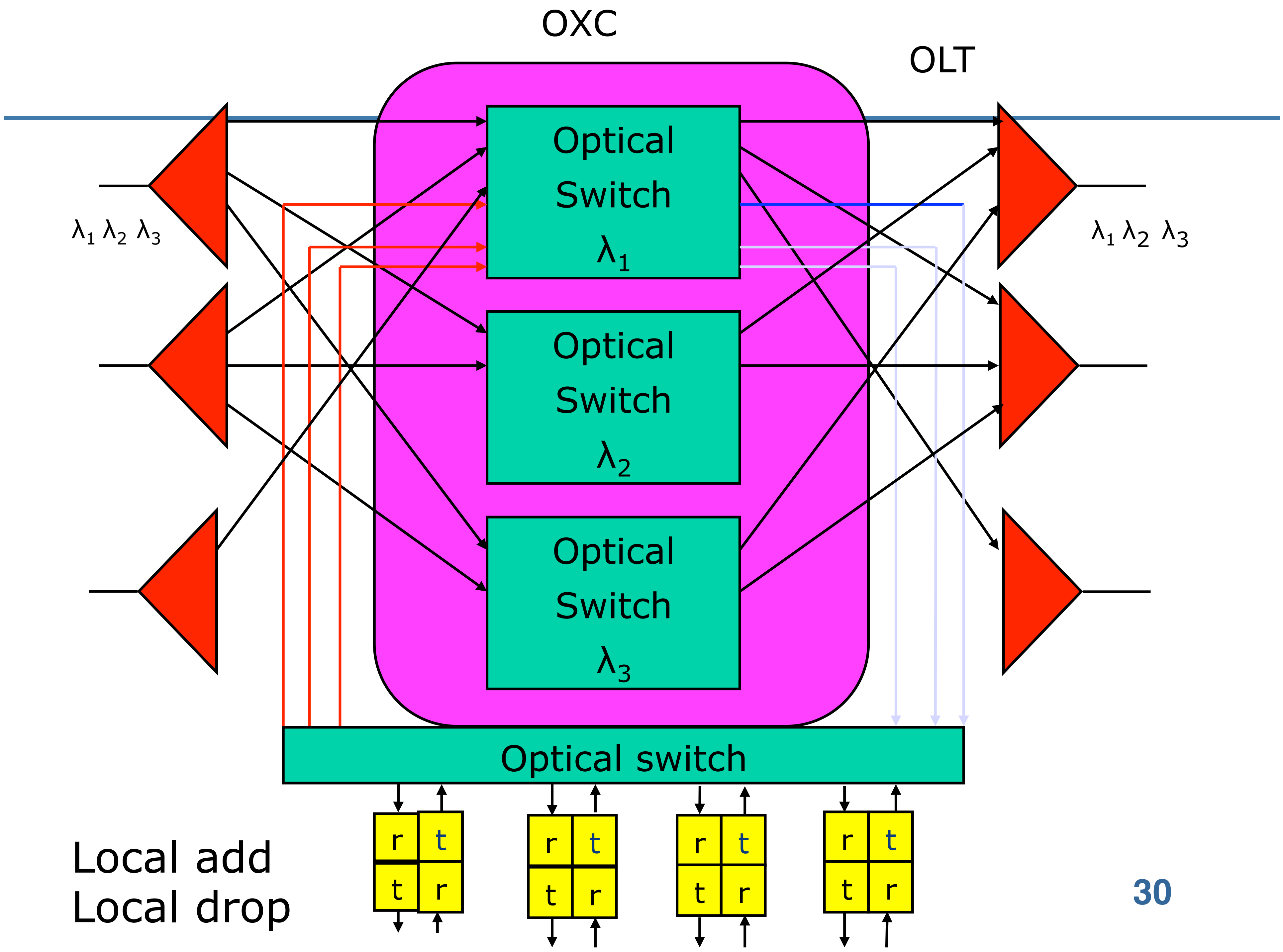
- Low-speed grooming
- Wavelength conversion
- Signal regeneration

Solution

- Use electrical switch or tunable transponder


OXC
OLT
λ1 λ2 λ3 λ4
Optical
switch
λ1 λ2 λ3 λ4
Wavelength or
waveband switching
O
E
O
E
Local add/
drop
Electrical switch
E
O
E
O
Low-speed grooming
wavelength conversion
regeneration
FROM/TO CLIENTS


OXC
OLT
Optical Switch λ_1
Optical Switch λ_2
Optical Switch λ_3
$\lambda_1\ \lambda_2\ \lambda_3$
$\lambda_1\ \lambda_2\ \lambda_3$
Local add
Electrical switch
Local drop

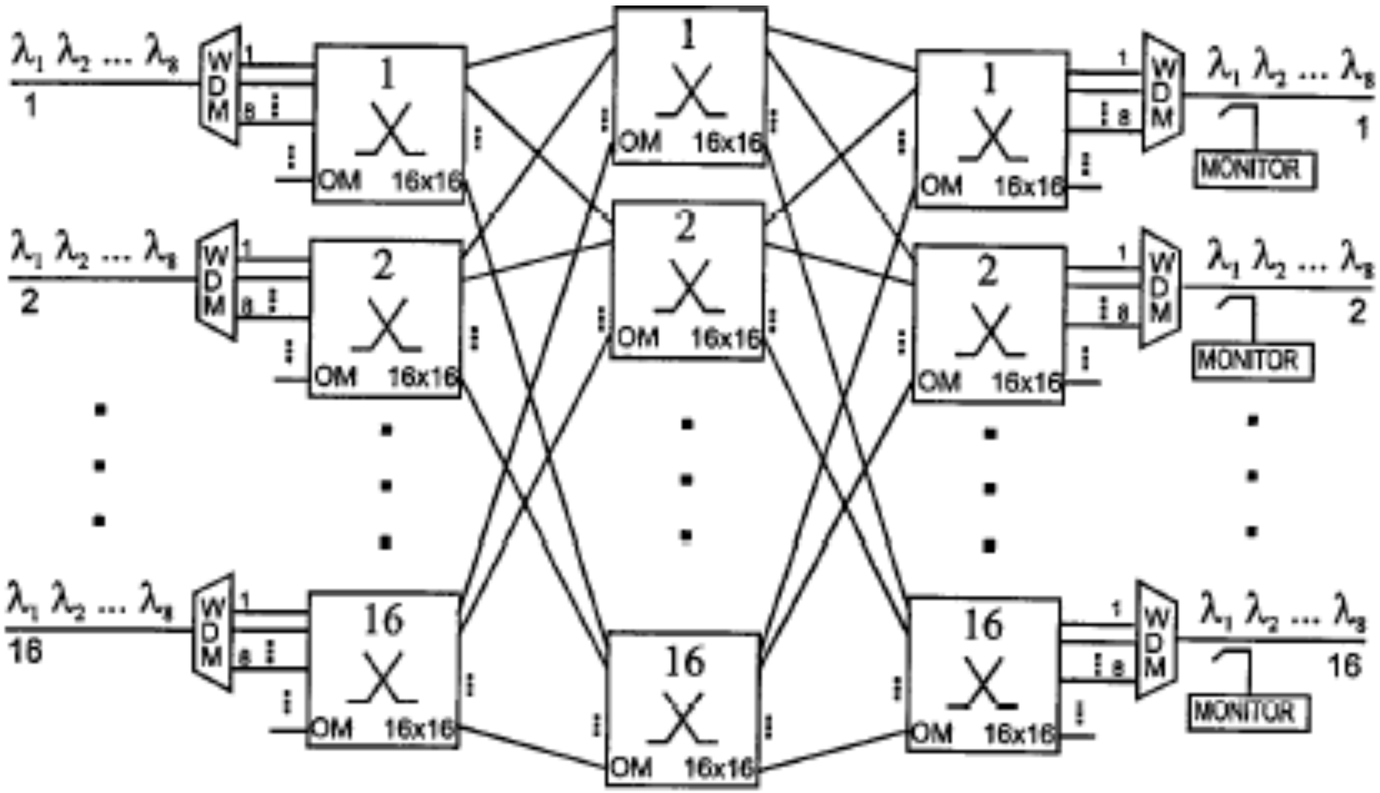

OXC
OLT
Optical
Switch
λ1
Optical
Switch
λ2
Optical
Switch
λ3
λ1 λ2 λ3
λ1 λ2 λ3
Optical switch
r t
t r
r t
t r
r t
t r
r t
t r
Local add
Local drop

All-optical OXCs

Transparency at the cost of:

- Grooming
  - Higher demand for lightpaths
    - —No aggregation of low bitrate demands
- Wavelength conversion
  - Higher blocking of lightpath demands
- Signal regeneration
  - More constrained routing of lightpaths

Ex. 1: All-optical OXC. Clos architecture

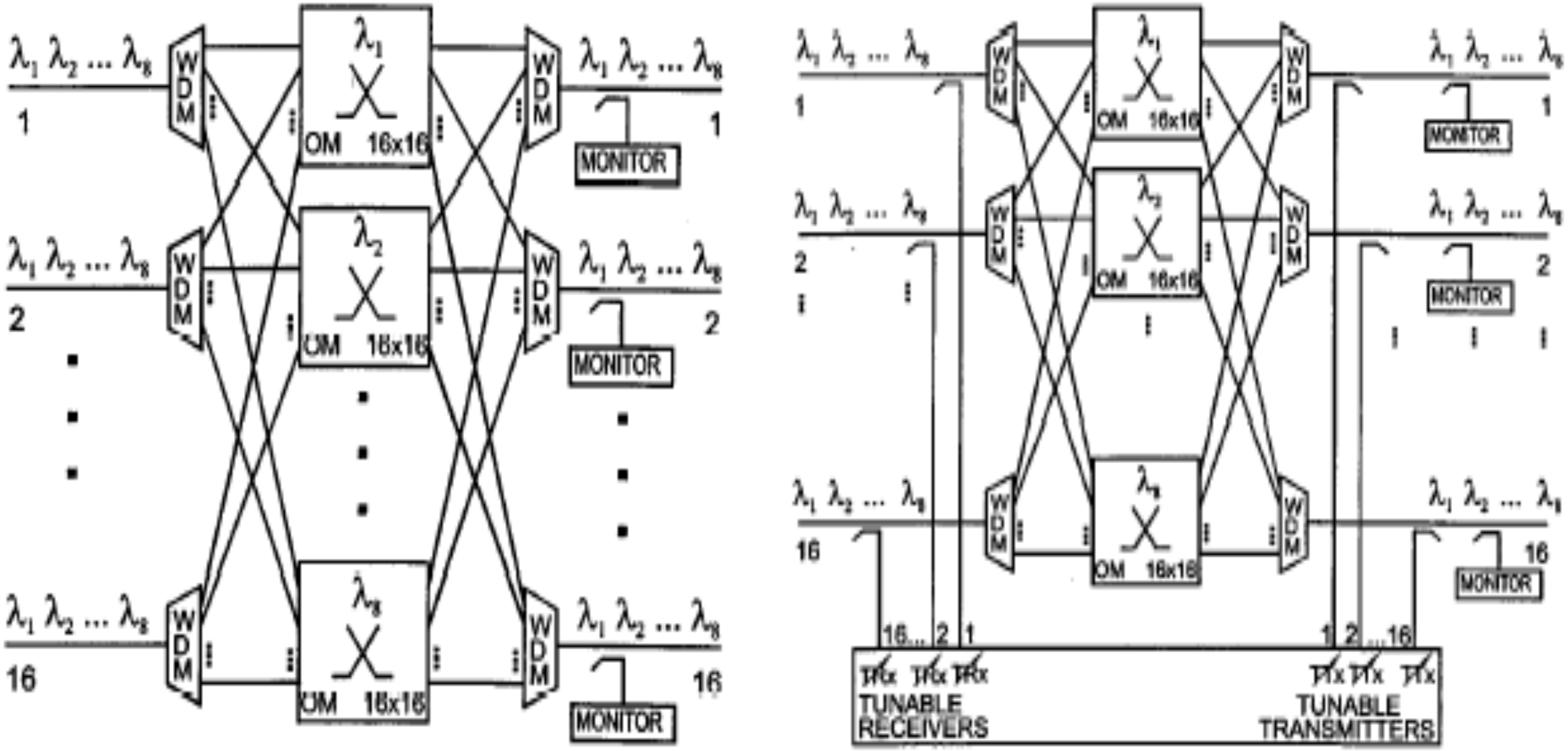


Three stage strict internal non-blocking Clos architecture.

Size: 128x128

L. Wosinska et al.: "Large Capacity Strictly Non-Blocking OXCs Based on MEOMS Switch Matrices. Reliability Performance analysis," IEEE/OSA JLT, Vol.19, No.8, Aug. 2001

Ex. 2: All-optical OXCs. WR architecture.

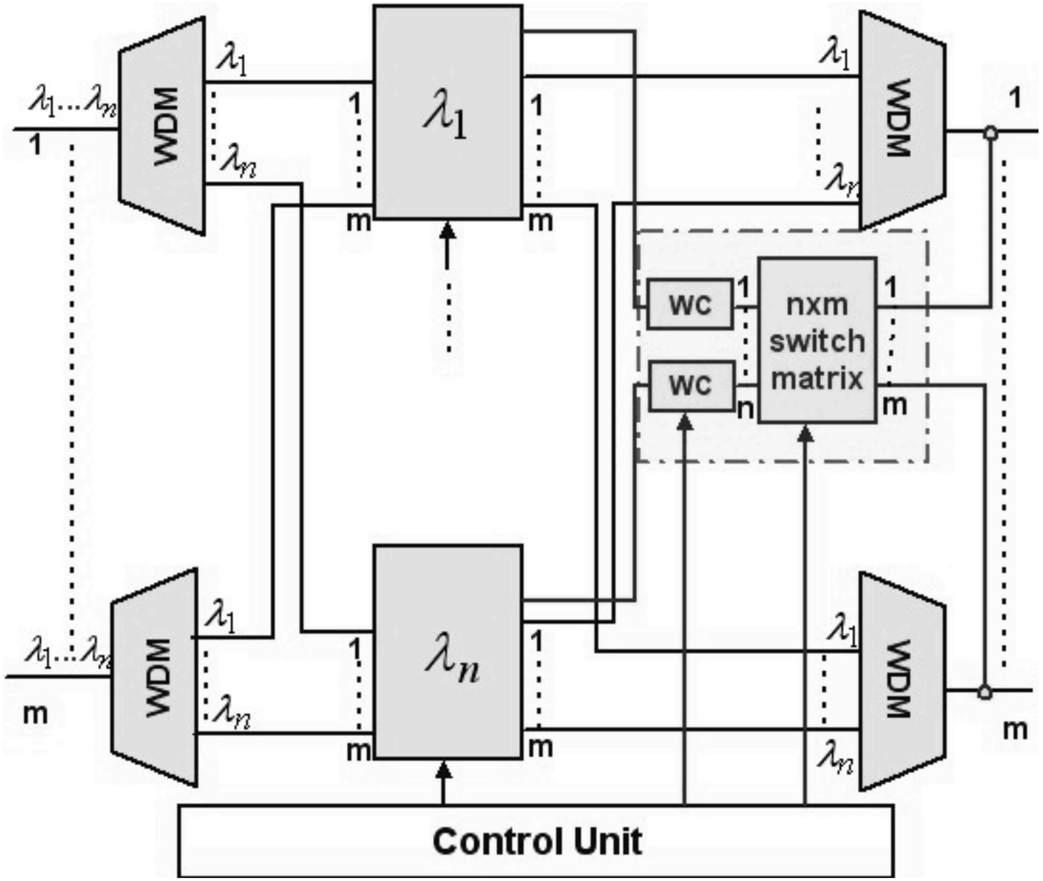


Strict internal non-blocking wavelength routing architecture.

Size 128x128

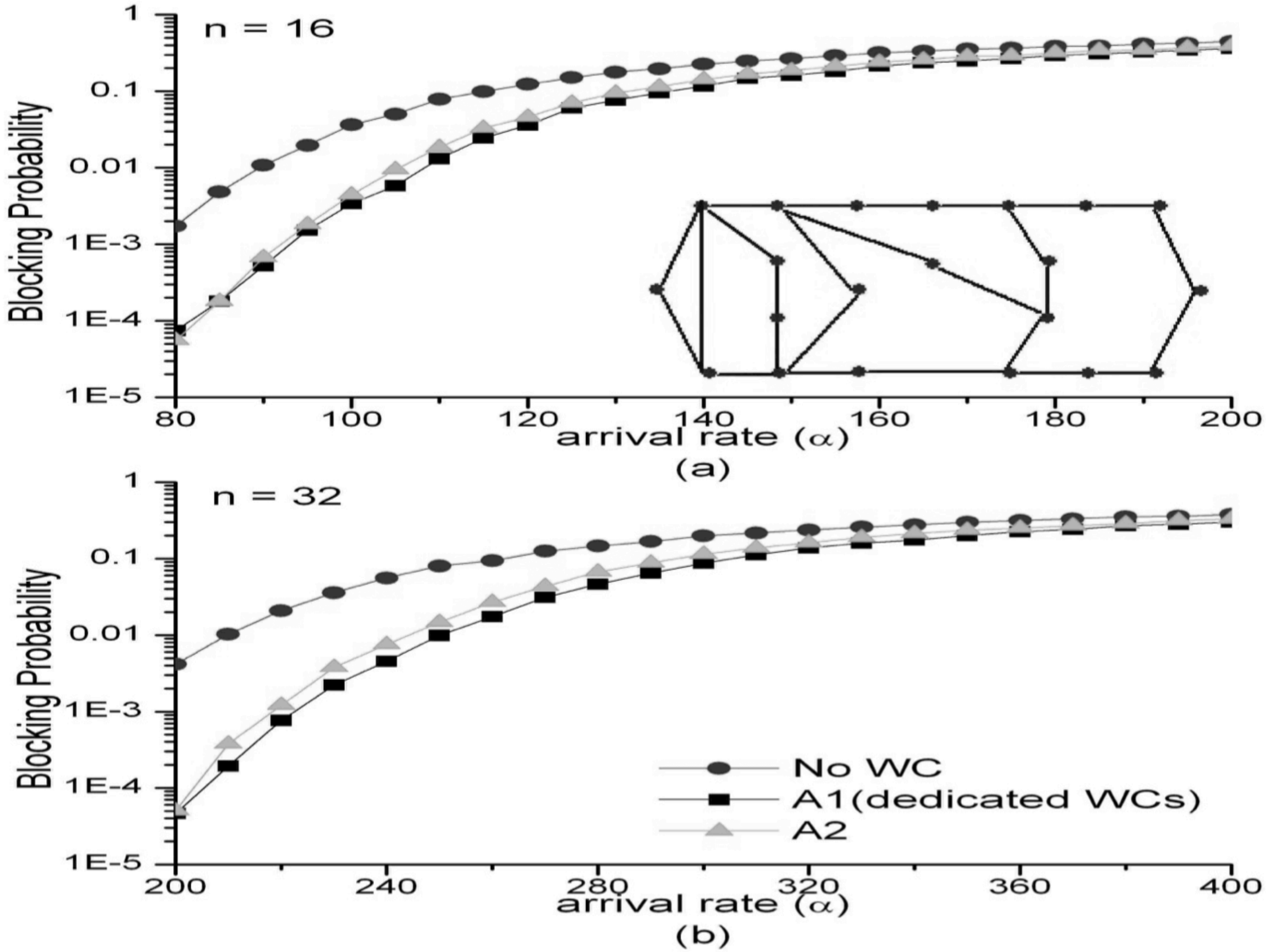
L. Wosinska et al.: "Large Capacity Strictly Non-Blocking OXCs Based on MEOMS Switch Matrices. Reliability Performance analysis," IEEE/OSA JLT, Vol.19, No.8, Aug. 2001

Ex. 3: All-optical OXC with TWC



J. Chen, A. Jirattigalachote, L. Wosinska and L Thylén, "Novel Node Architectures for Wavelength-Routed WDM Networks with Wavelength Conversion Capability", in Proc. of ECOC'08, Brussels, Belgium, September 2008

Performance evaluation



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Shortcomings with OCS

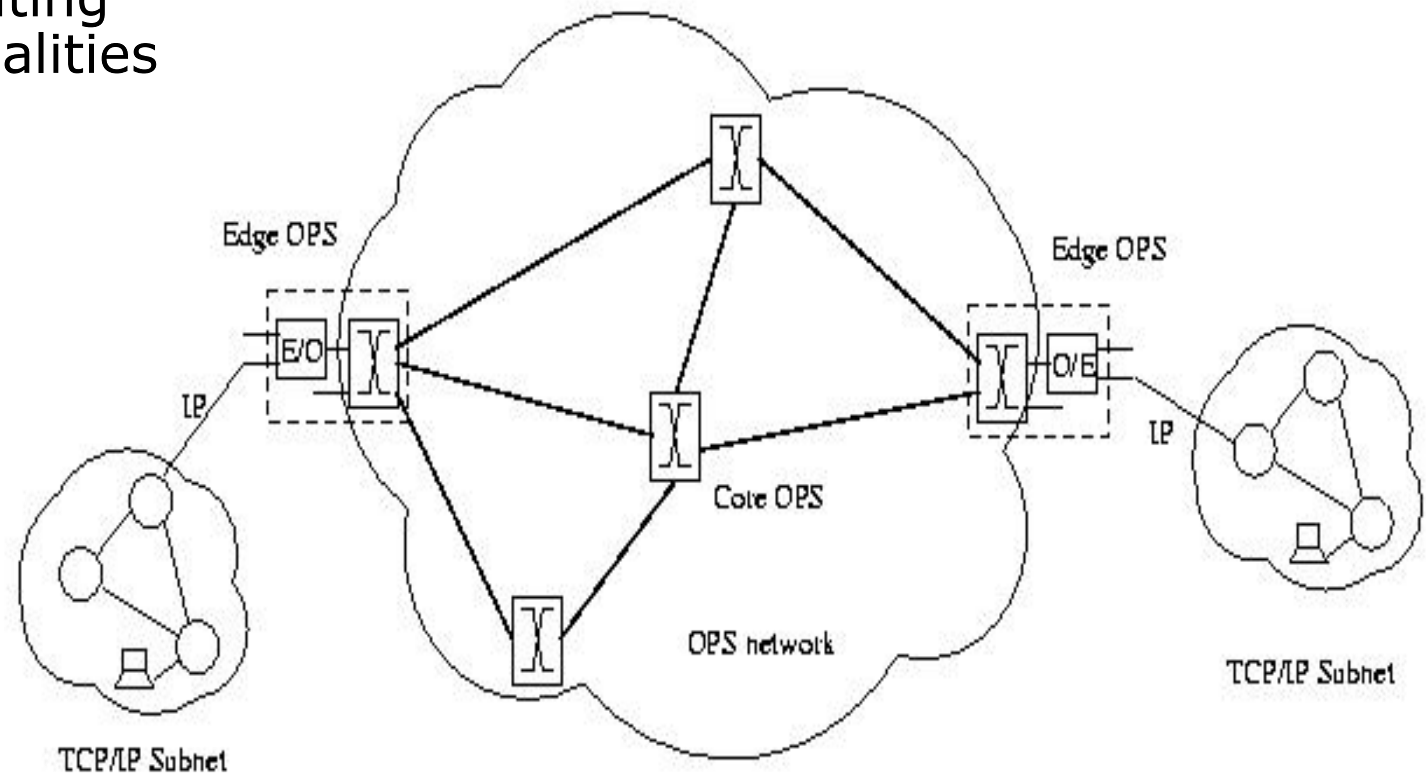
- Low utilisation of resources
- Hard optimization problems need to be solved (LTD and RWA)

Solution: Optical Packet Switching (?)

Optical packet switching

OPS networks

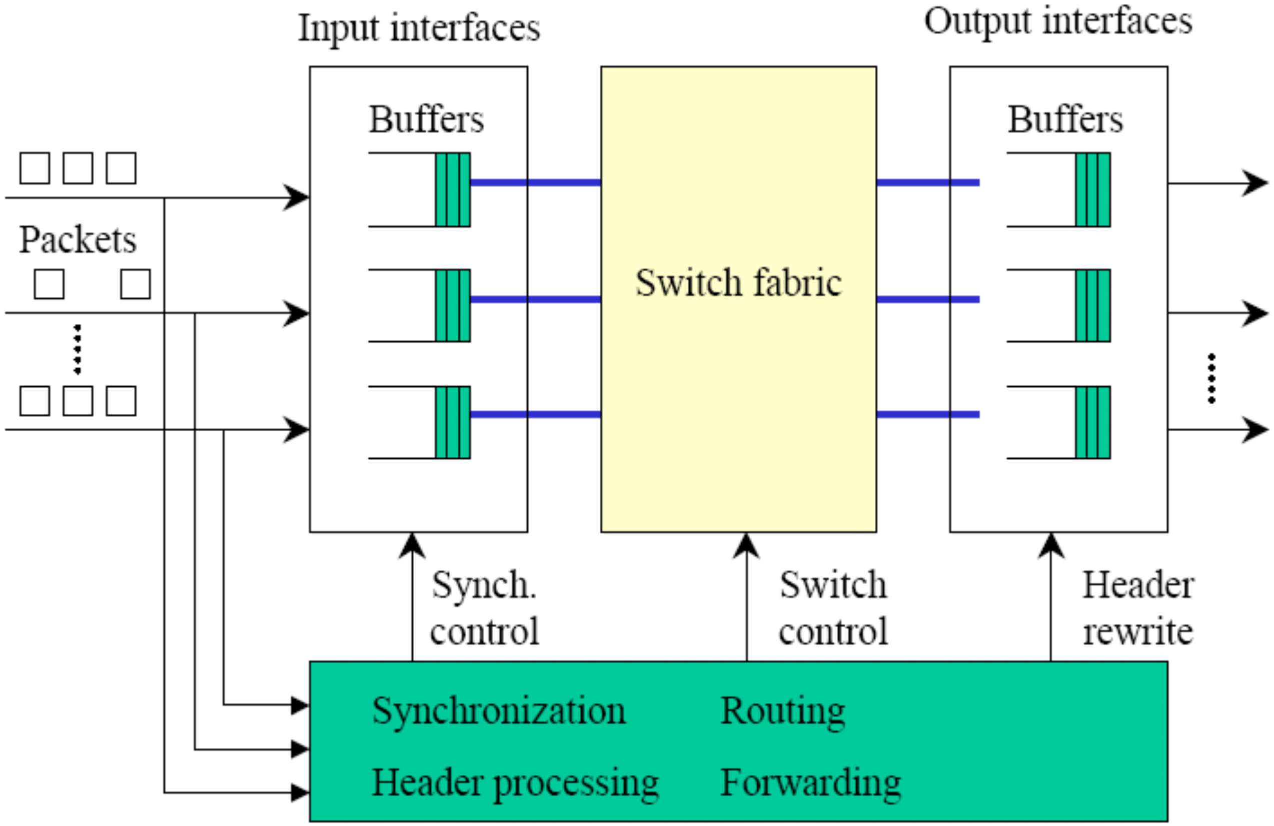
- Large capacity
- High bandwidth efficiency
- Rich routing functionalities



Optical packet switching

- Advantages
  - Complements WDM
    - Allows grooming in optical domain
    - Allows statistical multiplexing
      - Can improve bandwidth utilization within the optical layer
- Problems
  - Technological problems
    - Optical control functions
    - Synchronization
    - Optical buffering
  - High complexity
    - High **cost**
    - Low reliability

A routing node in the network



Optical router (OPS node): Needed functions

- Decoding of packet header
  - Could be electronic: header encoded at lower bit rate
- Setup of switch fabric
  - Packet delayed until setup done (a fixed delay)
  - Setup requires scheduling of packets from all inputs
    - Simplified for fixed packet size and synchronized operation
  - Fast reconfiguration of fabric (200 ns for 250 byte packet at 10 Gb/s)
- Synchronization: Elastic buffering of packets to align packets at all inputs
  - Only needed when switch fabric is synchronous
    - Synchronous fabric has better throughput
- Multiplexing of lower-speed streams (and reverse operation, i.e. demultiplexing)
- Contention resolution (e.g. buffering of packets if output busy)

Contention resolution in OPS networks

- Contention is inherent in packet switching
- Contention may be dealt with in
  - Time
  - Wavelength
  - Space
- Electronic packet switching typically rely on the time domain by means of queuing
  - Queuing in optics is not feasible
  - Queuing may be “emulated” by delaying packet in fiber loops
- What about optical packet switching (OPS) ?
  - Queuing in optical domain is difficult

If output busy: Handling packet contention

- Drop a packet
  - Packet loss probability can be high even at moderate loads
- Deflect the packet
  - Send it on a free output
  - Restrict the deflection
    - Output that leads to destination
    - Output with a route to the destination that is at most *m* hops longer
    - Also called *hot-potato routing*
  - Increases delay and network load
  - Creates variable delays and potentially reordering
- Change the wavelength (TWC)
  - Chose a wavelength available at the output
  - All-optical tunable wavelength converters required
- Buffer the packet
  - Store the packet until the output is available
  - Applying TWC may allow for decrease of the buffer size

Contention resolution techniques

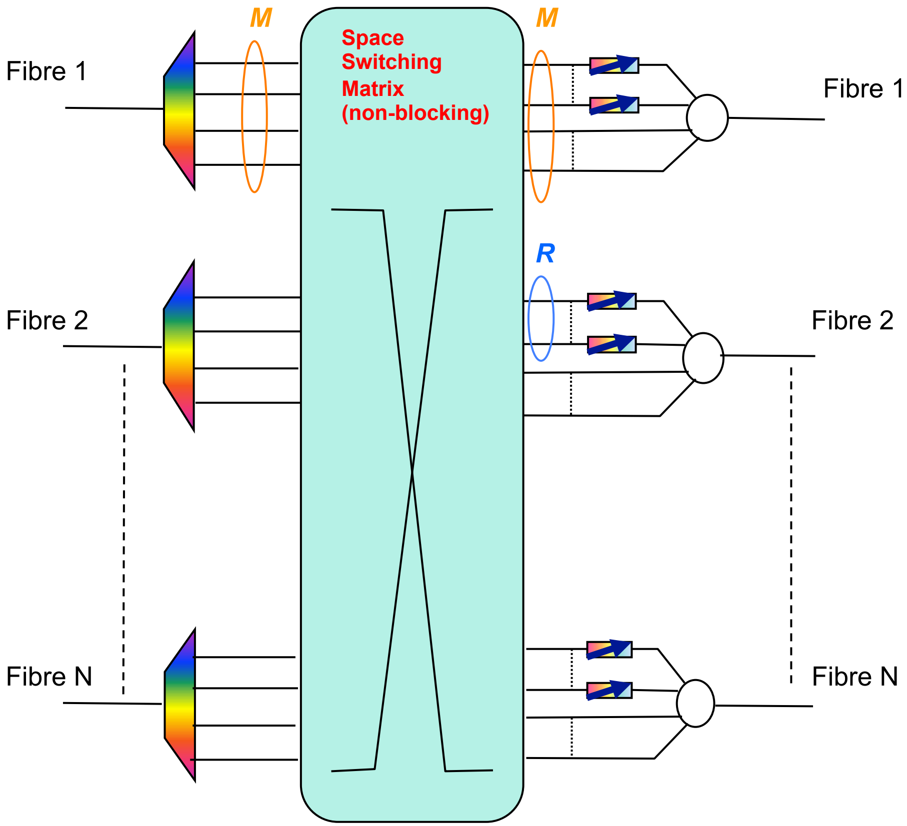
- Bufferless architectures
  - Deflection routing
  - TWC
- Optical buffers
  - Placement at a node
    - Output buffer
    - Input buffer
    - Recirculation buffer
  - Dedicated or shared buffers
  - Technology
    - FDLs
    - Novel optical memories
      - EIT
      - Opt. resonators

Bufferless OPS: sources of packet loss

- Internal blocking
  - It is a consequence of resource limitation (TWCs, links) inside the switch
- Output blocking
  - Overload on output link in a time slot
  - Excess packets require the same output link in a time slot
- Channel blocking
  - Overload on a wavelength channel on output link in a time slot
  - Can be resolved by finding a different channel on the same link to forward the packet → requires wavelength conversion

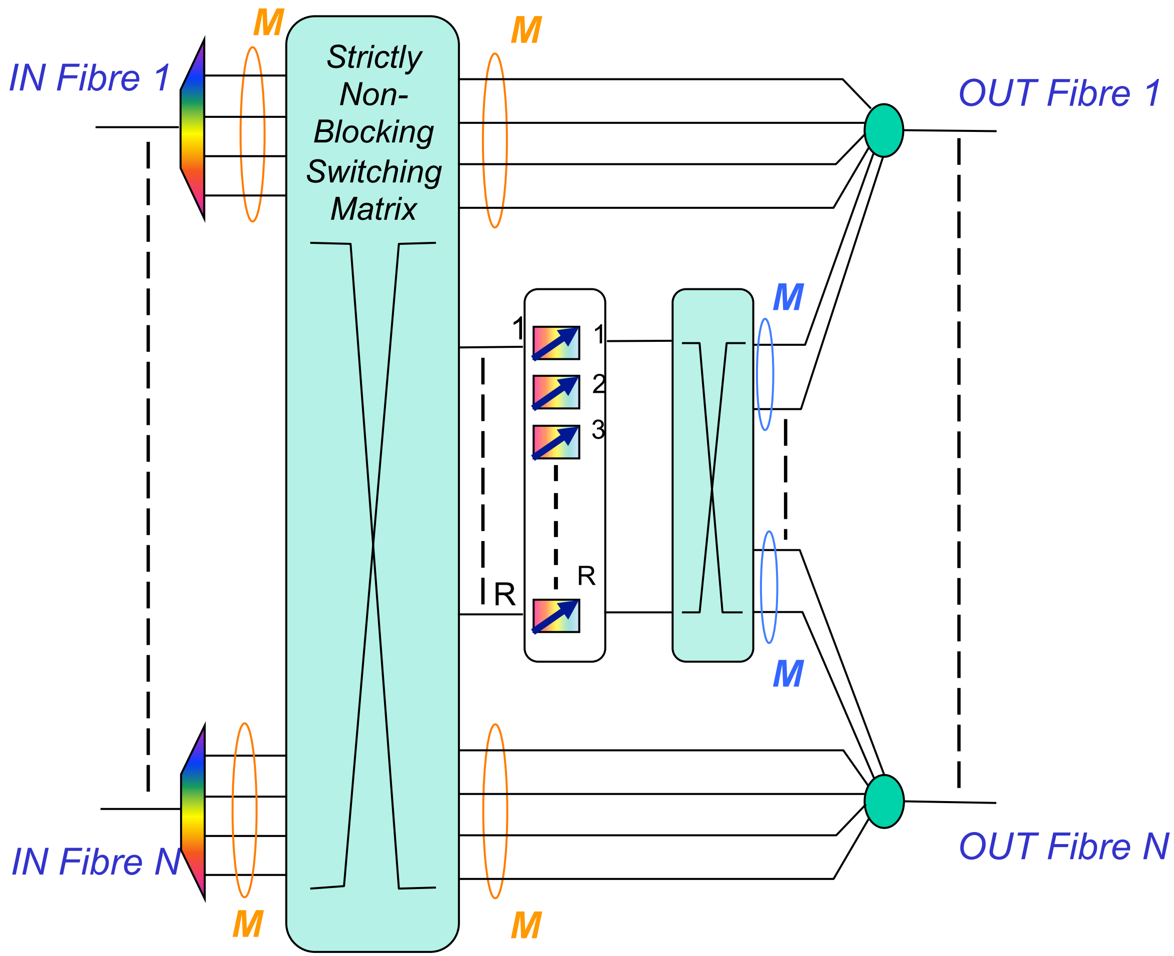
TWC: Shared per output link architecture

- Set of R TWCs at each output link.
- TWCs of the same set can be used only by packets addressed to the related output link.
- Optical switching fabric configured depending on traffic conditions.
- Packet scheduling:
  - Input packets are first considered to be transmitted at the same wavelength.
  - If contention occurs, wavelength conversion is performed.



TWC: Shared per node architecture

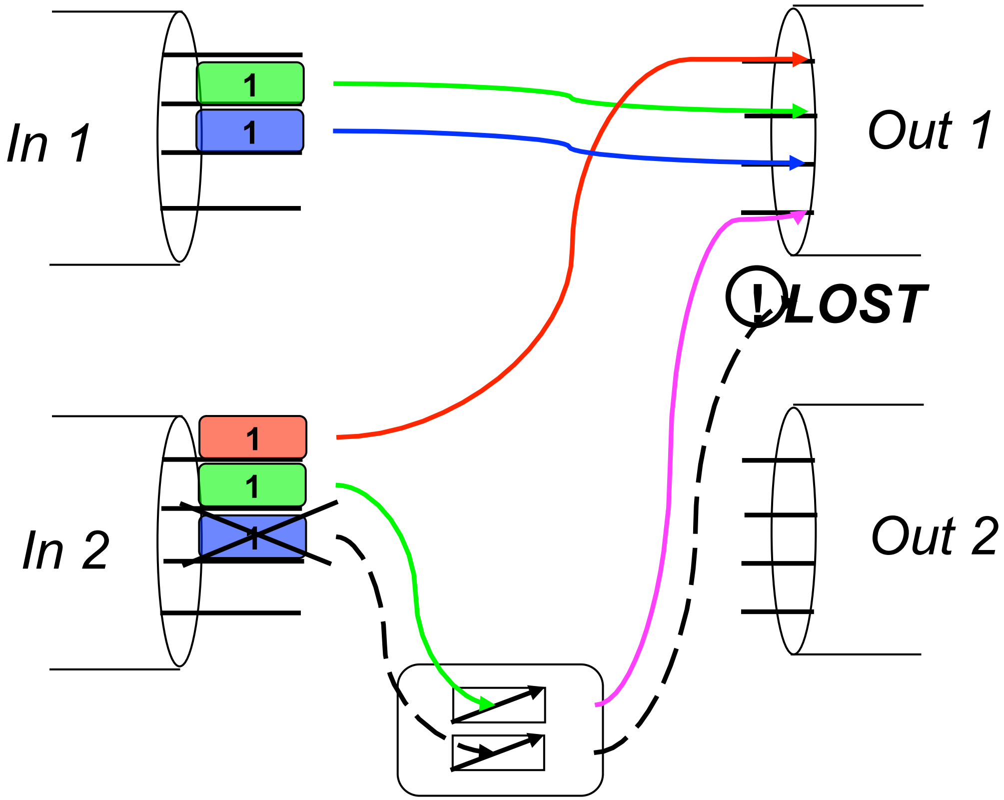
- All TWCs (R) are grouped in the common set
- TWCs can be used by all input channels
- Scheduling
  - Only the packets that require conversion are sent to TWCs
  - The converted packets are sent to the appropriate output link by an optical switching stage



$[N \cdot M] \times [N \cdot M + K]$

Case 1: packet lost due to congested output fibre

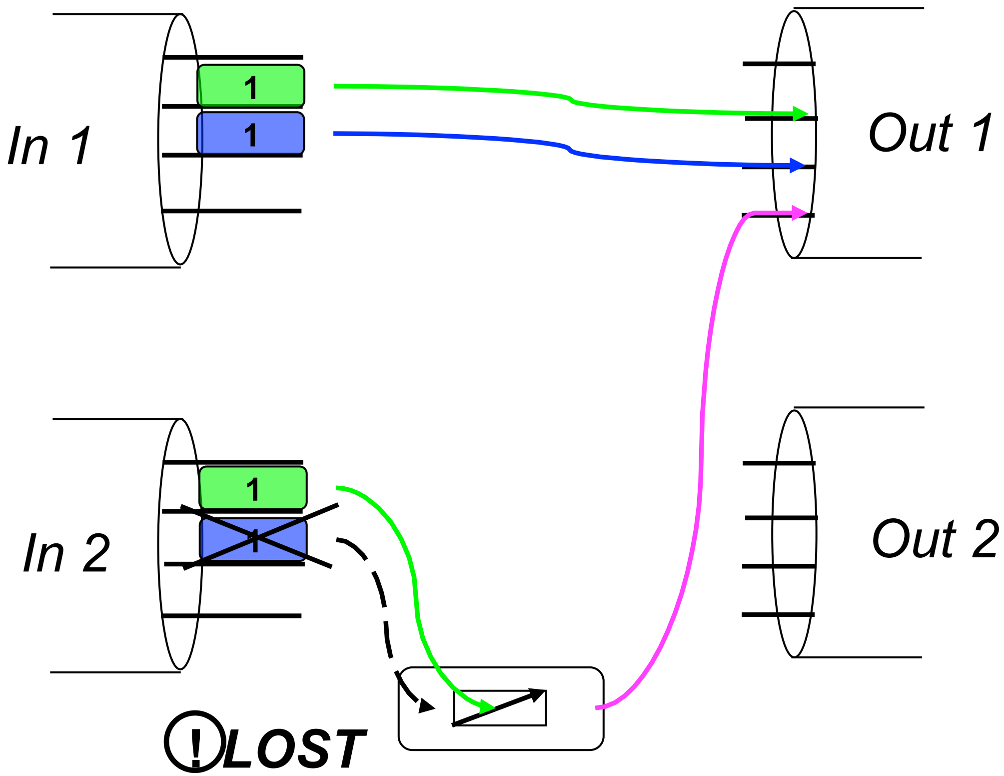
- N=2 input/output fibres;
- M=4 wavelengths per fibre;
- R=2 TWCs;



- 5 packet arrivals directed to output fibre 1 in a time slot;
- First, one packet from each different wavelength is sent without conversion;
- Then, other packets are sent exploiting wavelength conversion;
- If destination output fibre is congested, packet is lost;
- *If destination output fibre is congested, packet is not sent on TWC bank;*
  - *TWC can be exploited from packets that compete for another output fibre;*

Case 2: packet lost due to the lack of TWCs

- N=2 input/output fibres;
- M=4 wavelengths per fibre;
- R=1 TWC;

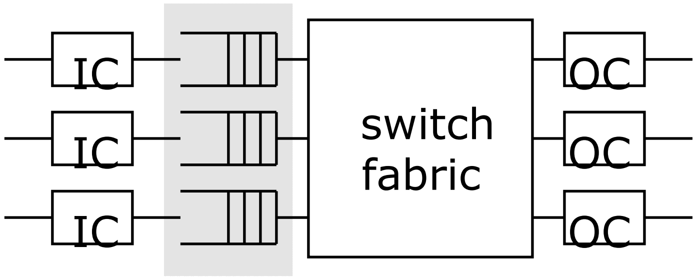


- 4 packet arrivals directed to output fibre 1 in a time slot;
- First, one packet from each different wavelength is sent without conversion;
- Then, other packets are sent exploiting wavelength conversion;
- If no TWC are available, packet is lost even if there are output wavelength on target output fibre available;

Buffer placement at the node

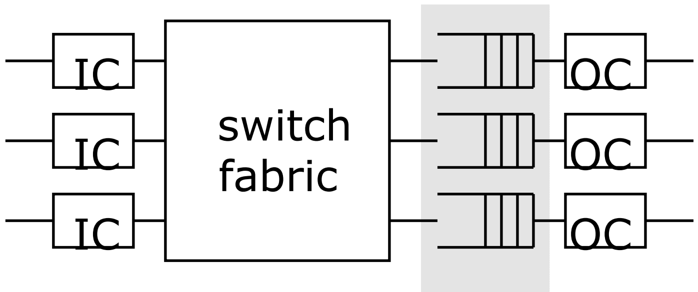
Input buffer

- Simple, FIFO
- Head of the line (HOL) blocking



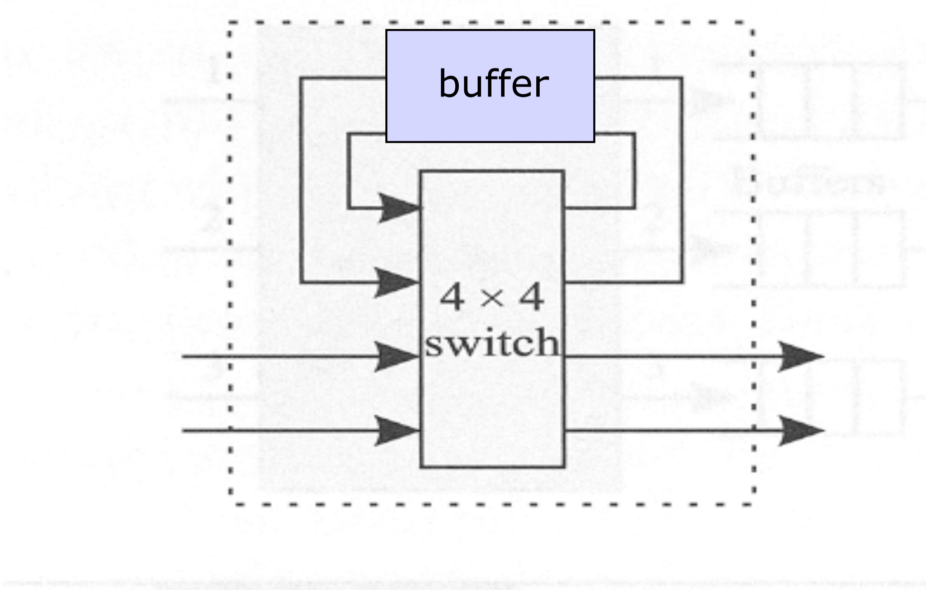
Output buffer

- No HOL blocking
- More difficult to implement



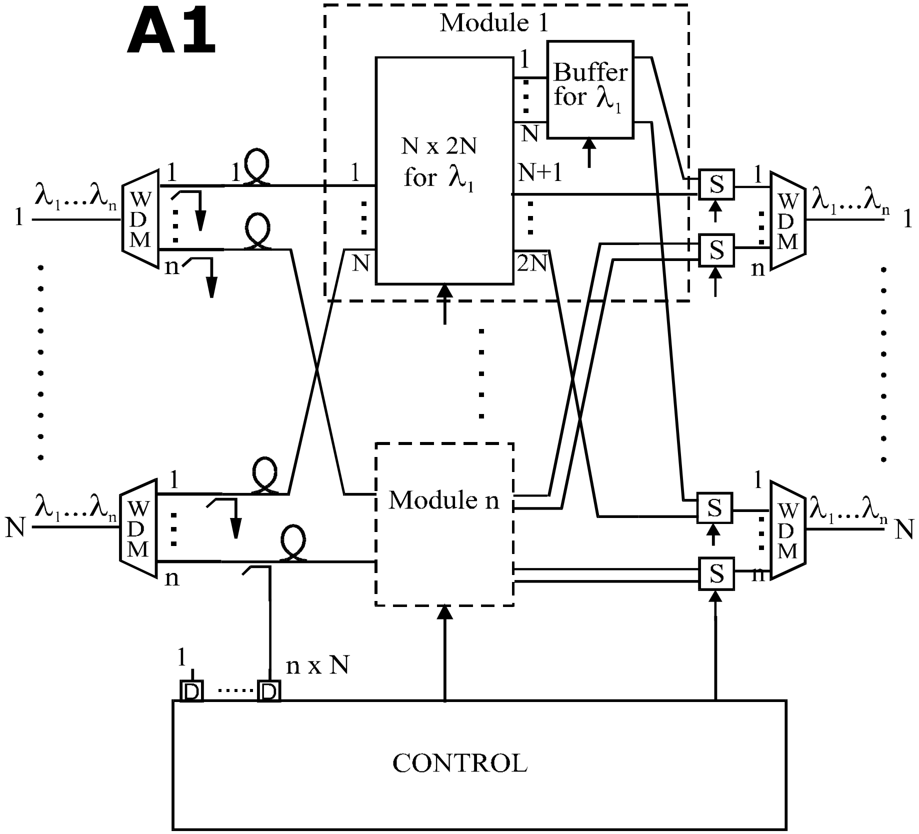
Recirculation buffers

- Shared by all inputs
- Requires larger switch size

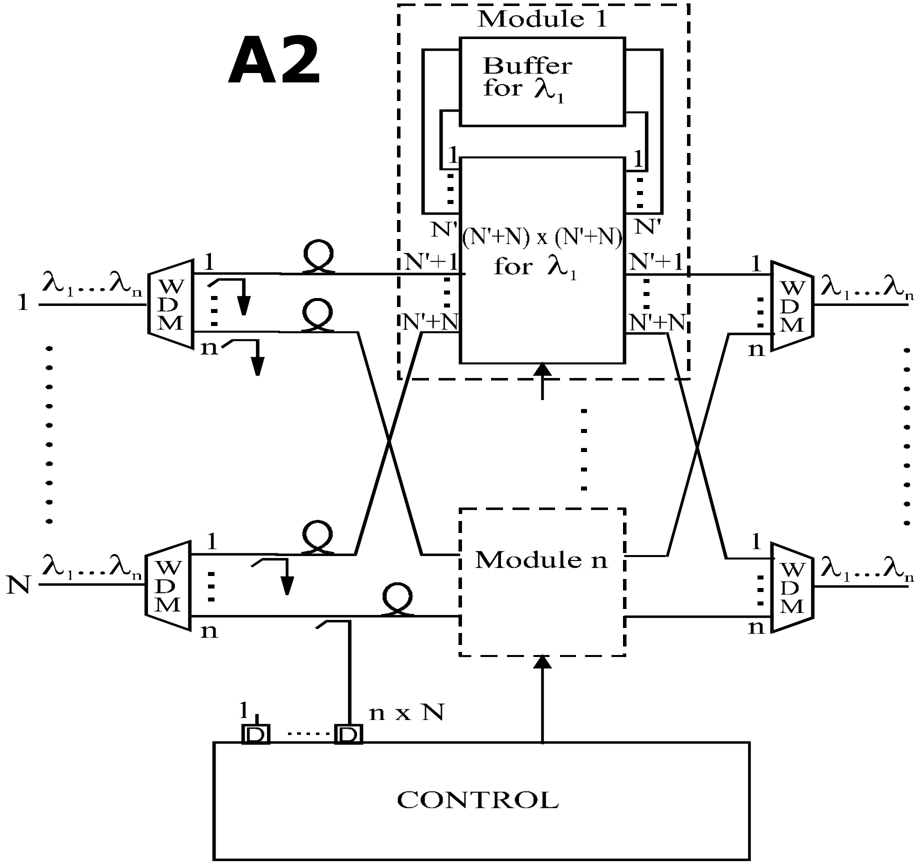


OPS with electrical buffer

A1



A2



L. Wosinska and G. Karlsson, "A photonic packet switch for high capacity optical networks", in Proc. NFOEC ´02, Dallas, Texas, September 2002

COMPARISON

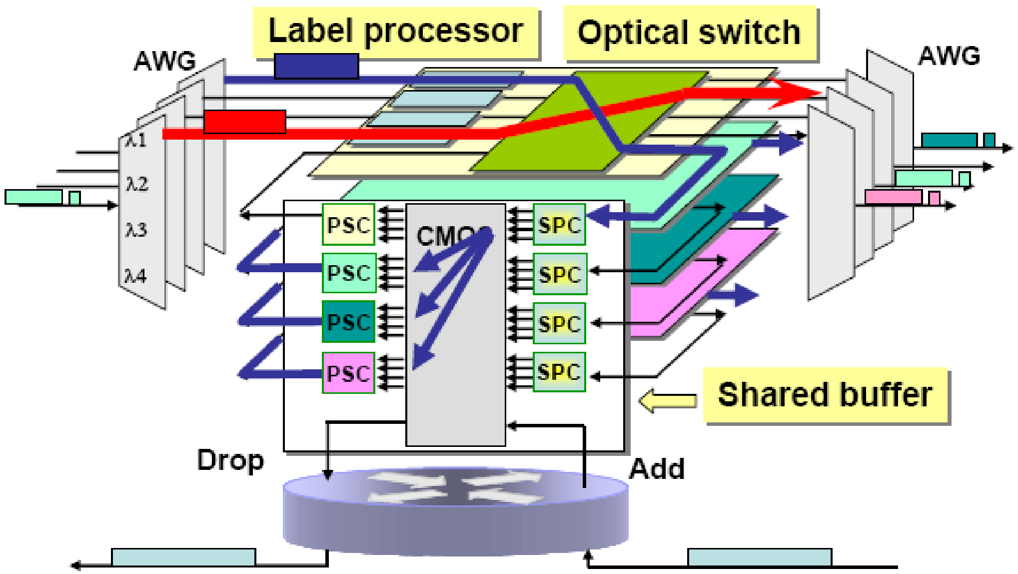
Architecture	I	II
Buffer	Dedicated	Shared
Packet loss probability	High	Low
Flexibility	Low	High
Scheduling	Simple	Complex

- L. Wosinska and G. Karlsson, "A photonic packet switch for high capacity optical networks", in Proc. NFOEC ´02, Dallas, Texas, September 2002

Hybrid optoelectronic router

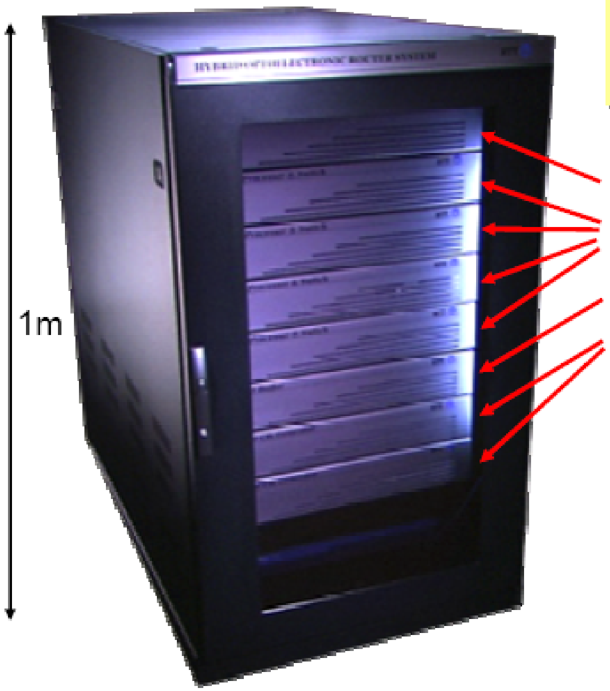
Alcatel Lucent & NTT
demonstrator at ECOC 2009

Node Architecture



Buffering in CMOS RAM
Traffic engineering between wavelength layers
3R regeneration based on TTL
Services (QoS, Multicast)

Exhibition of Prototype Router (Booth #604)

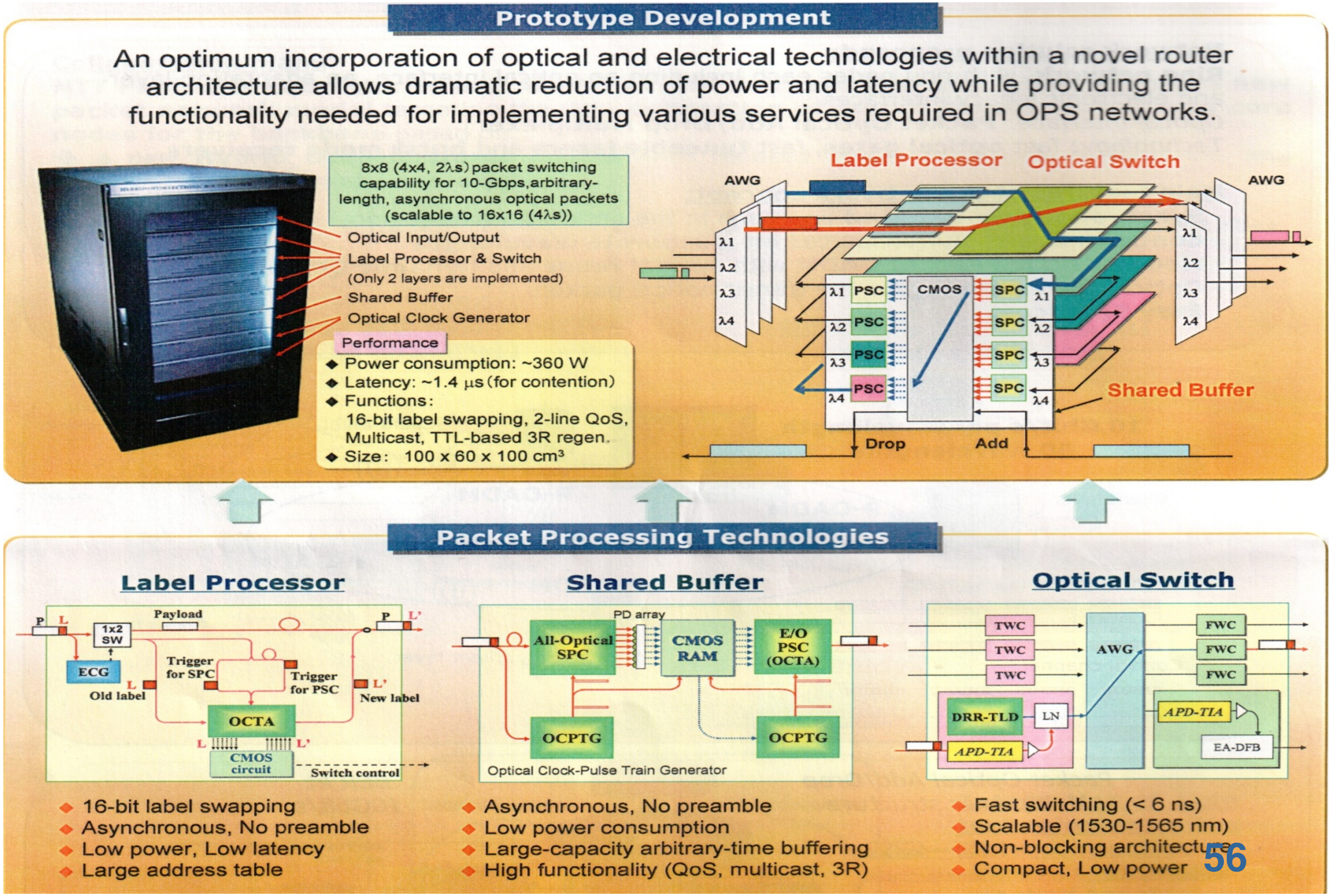


8x8 Router System for 10-Gb/s, Asynchronous Optical Packets
(Scales to 16x16 System)

Performance

- Throughput: 160 Gb/s
- Functions:
  - 16-bit Label Swapping
  - 2-line QoS
  - Multicast Routing
  - 3R Regeneration
- Size: 100 x 60 x 100 cm^3

Hybrid optoelectronic router

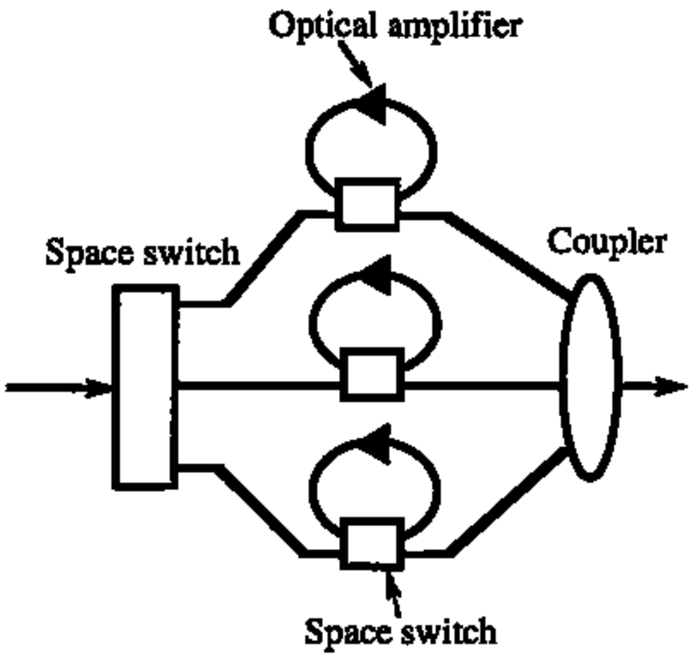


Optical buffering

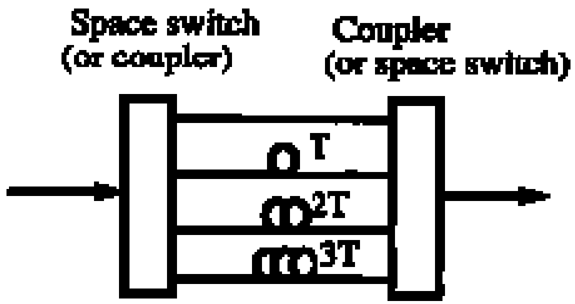
- Fiber delay lines (FDLs)
  - Not random access
  - Require synchronization
  - Supported packet format
    - Constant packet size
    - Some configurations support variable packet size
      - A certain granularity
    - Not compatible with packet formats of different packet size
  - Long fiber delay lines
    - Not very practical solution
    - Ex.: For packets containing 53 bytes (ATM cell) at 2.5 Gb/s the length of fiber in the FDLs needs to be the multiples of 640 m
  - Feed-forward or feed-back configurations
- Novel solutions for optical memory
  - Material subjected to EIT (Electromagnetically induced transparency)
  - Optical Cavities

Examples of buffers based on FDL

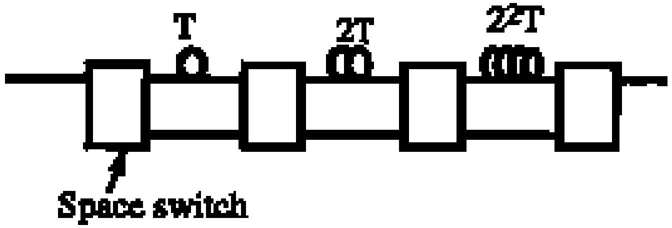
Feed-back



Feed-forward

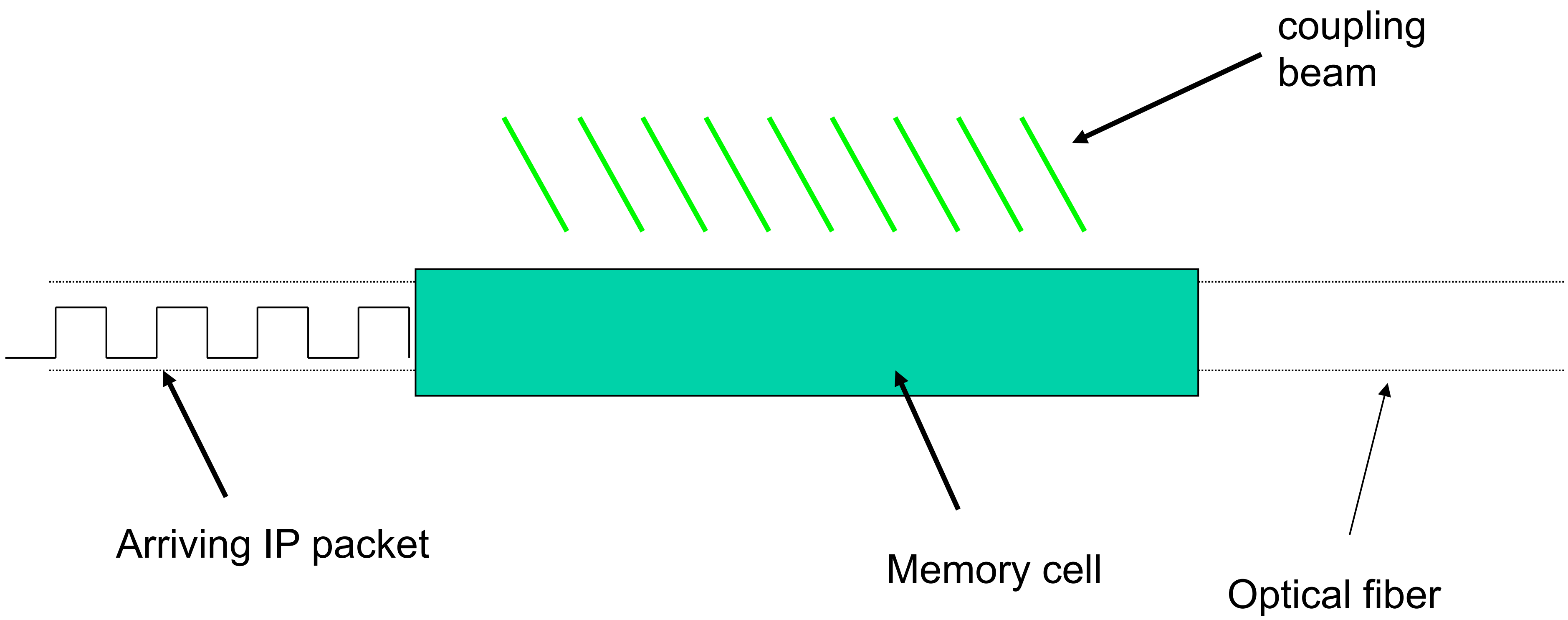


(a) Parallel structure



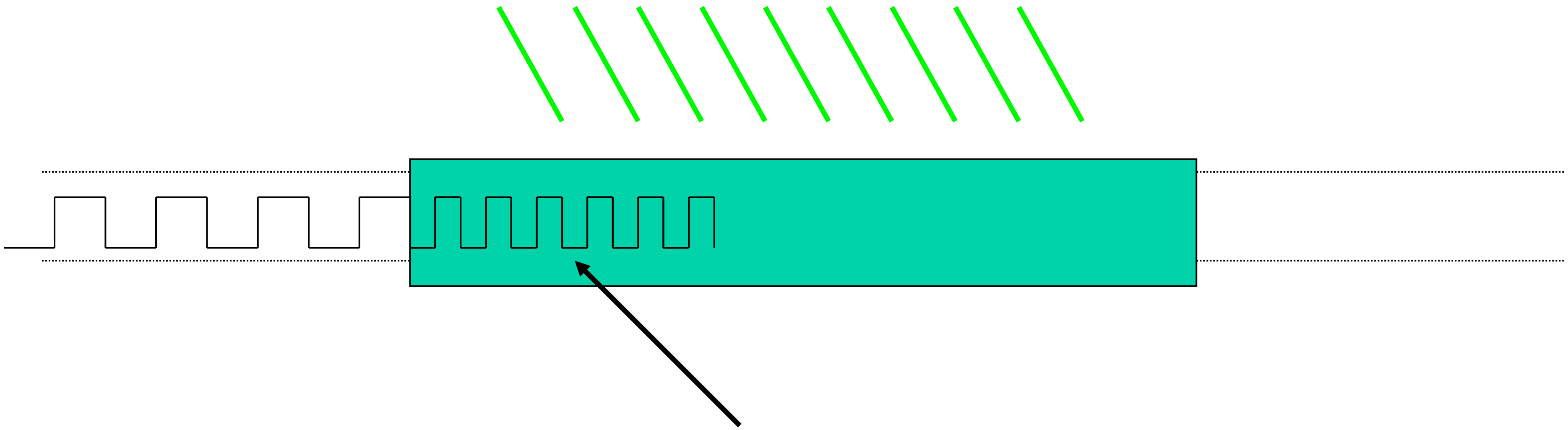
(b) Serial binary structure

EIT (Electromagnetically Induced Transparency)



EIT (Electromagnetically Induced Transparency)

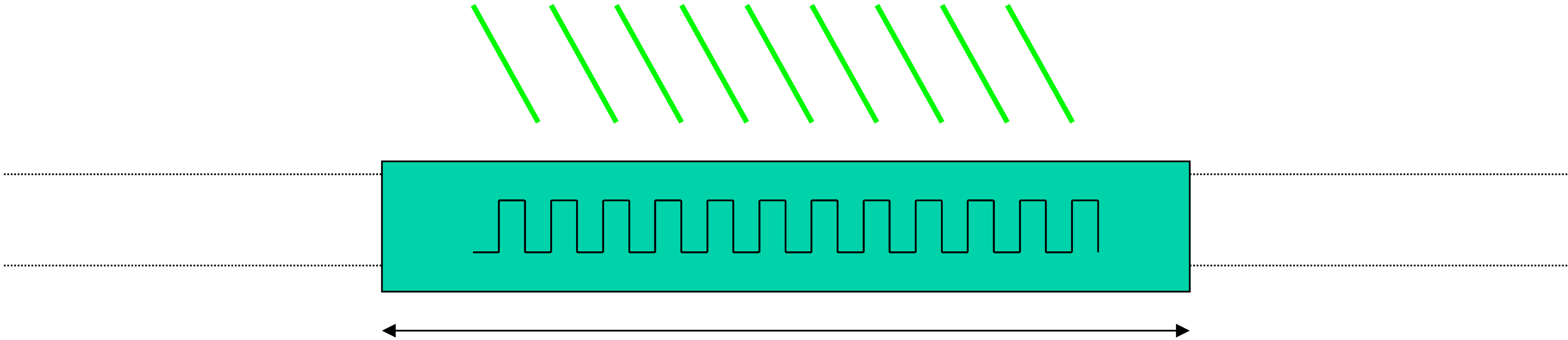
Phase 1 : writing



Light slows down inside the cell and is spatially compressed

EIT (Electromagnetically Induced Transparency)

Phase 1 : writing



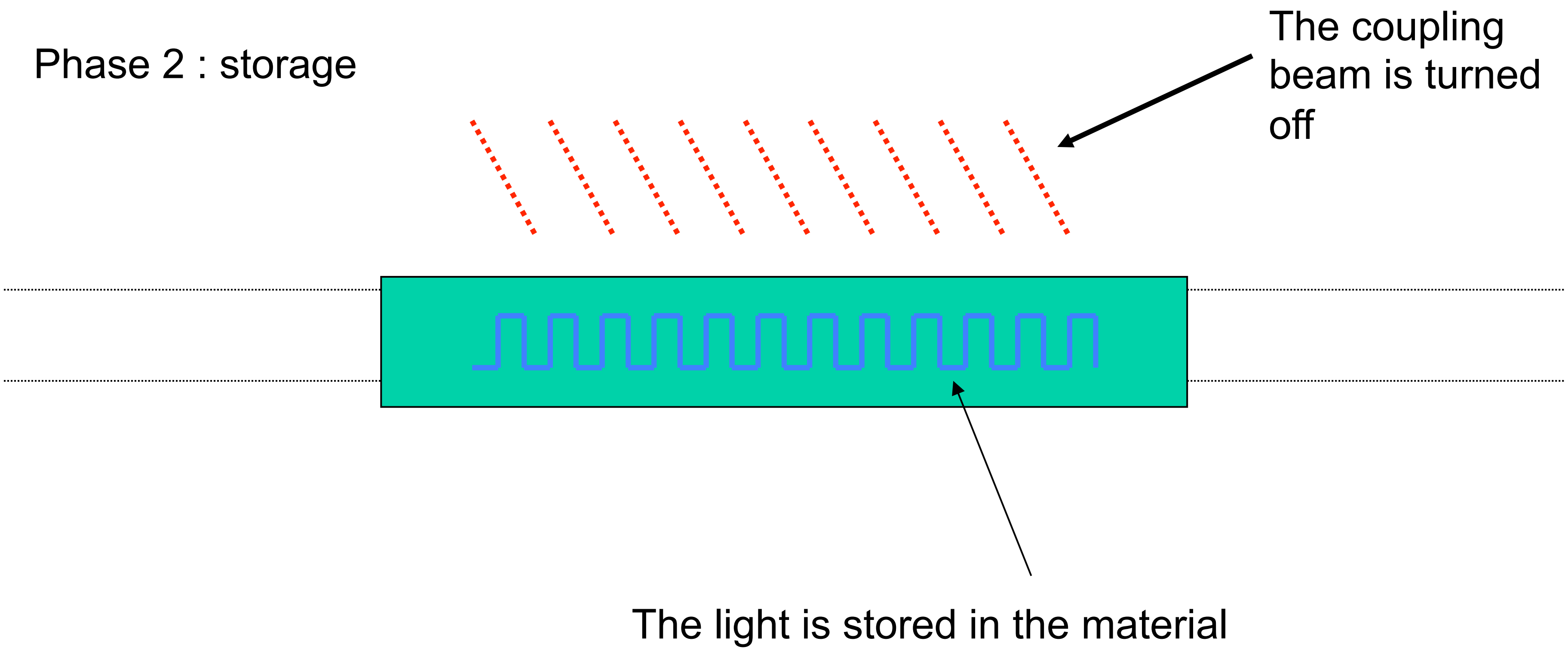
Cell length

The memory cell needs to be long enough to fit the entire packet

IP packet of 1500bytes at 2,5Gb/s is 1,4 km long in free space and about 1km long in an optical fiber

EIT (Electromagnetically Induced Transparency)

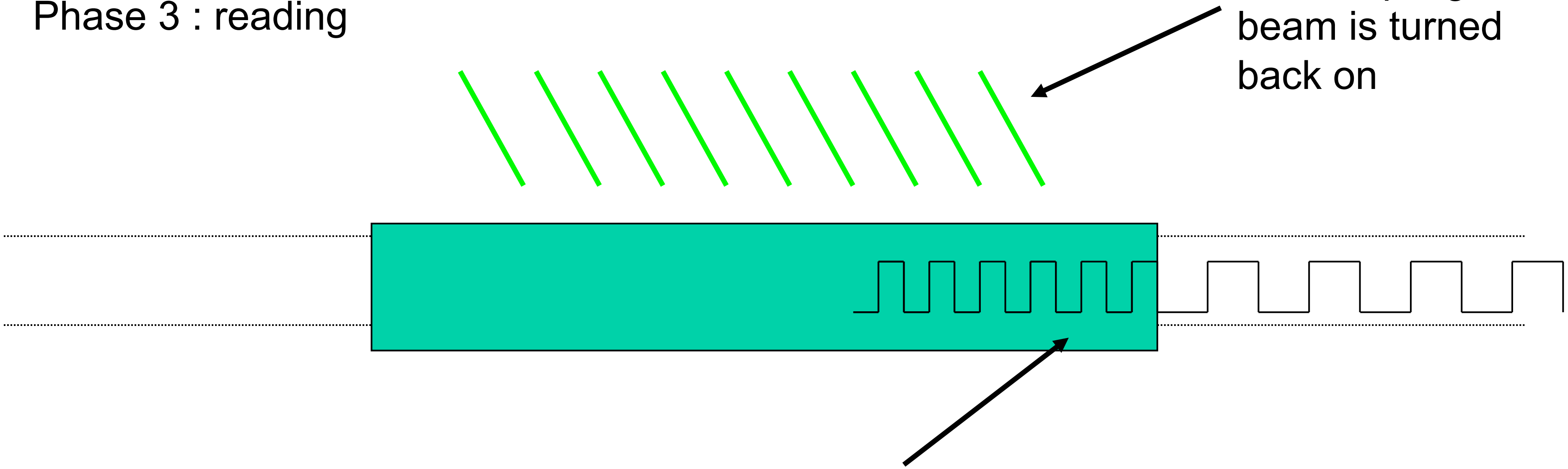
Phase 2 : storage



EIT (Electromagnetically Induced Transparency)

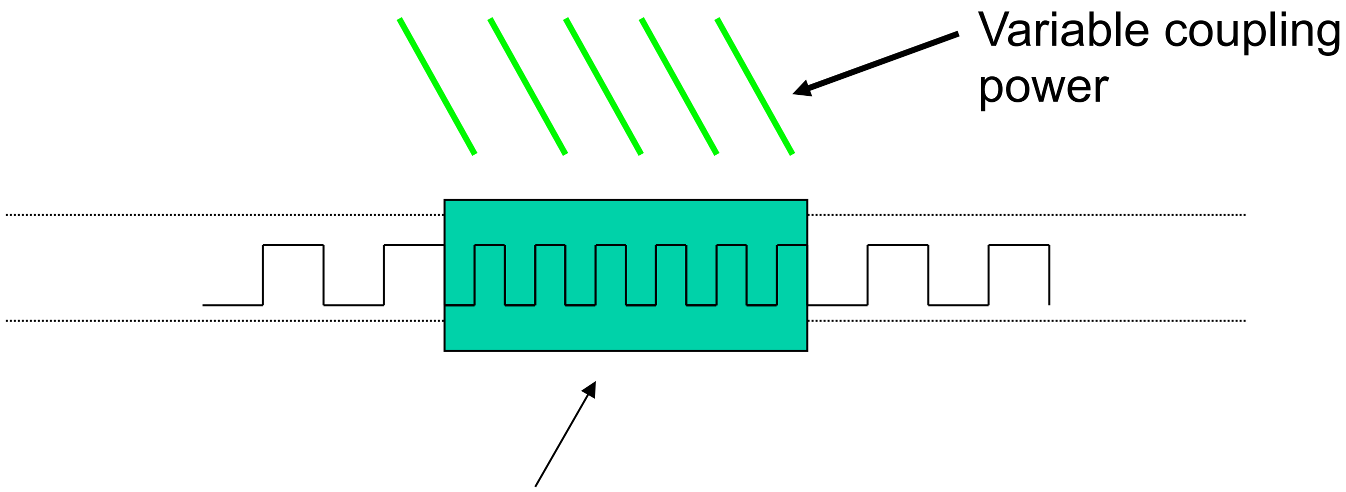
Phase 3 : reading

The coupling beam is turned back on



The light is recovered and leaves the cell

EIT (Electromagnetically Induced Transparency)



The packet is slowed down in the cell

No storage of light

We regulate the slowdown factor by varying the coupling power

EIT (Electromagnetically Induced Transparency)

material	slow down factor	storage time
Quantum dots	40 in room temperature 10^7 in very low temperature	8.7ns
Atomic vapor	10^5	up to 0.5 ms depends on the gas

Slow down factor and storage time depend on the material, temperature, coupling power, bandwidth and wavelength

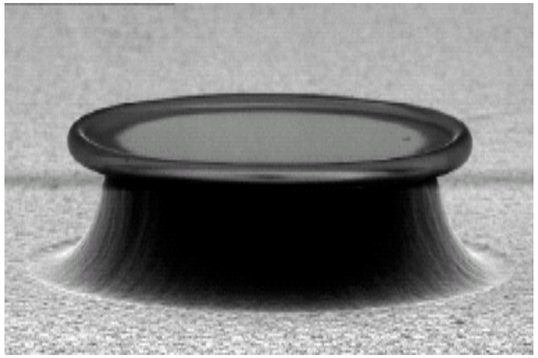
Novel types for opt. memory - Optical cavities

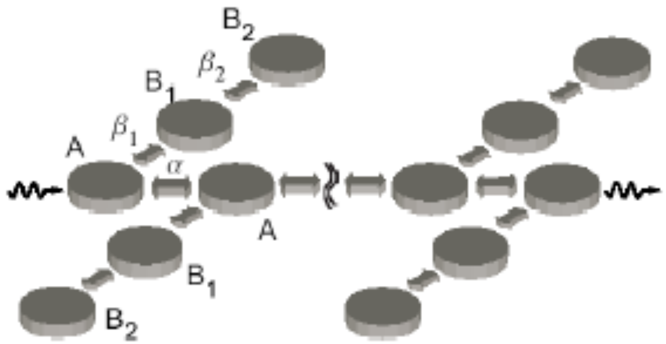
Optical cavities use optical resonance in photonic structures

Slow down factor of 10^4 (depending on the number of side cavities)

Storage time: 50 ns

Chip scale implementation of the system foreseeable





Requirement for optical memory

Telecommunications

- Wavelength
- Attenuation and distortion
- Bandwidth
- Packet length
- Control memory cells separately

Technology

- Compression rate (cell size)
- Tuning of the intensity of the control field
- Temperature and mechanical stress
- Cost

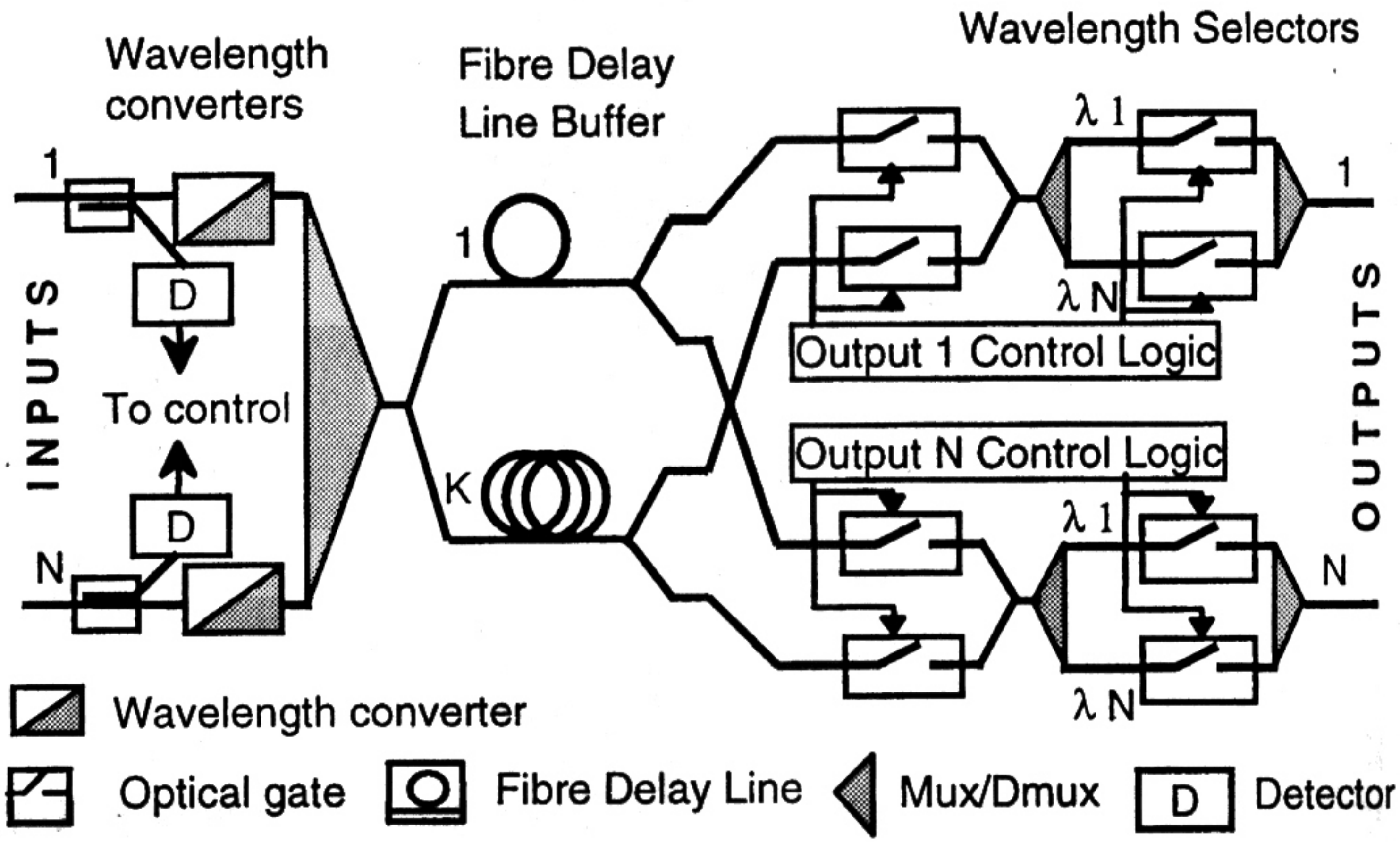
QoS

- The storage time
- Pulse distortion
- Priority classes

Comparison

	storage time	cell size	temperature	bandwidth-wavelength
EIT	✓ Up to 0.5 ms	✗ Order of cm	✗ Close to 0K or 80C	✗ Depends on the material
Optical cavities	✗ Order of ns	✓ Size of a chip	✓ Room temp.	✓ No limitations

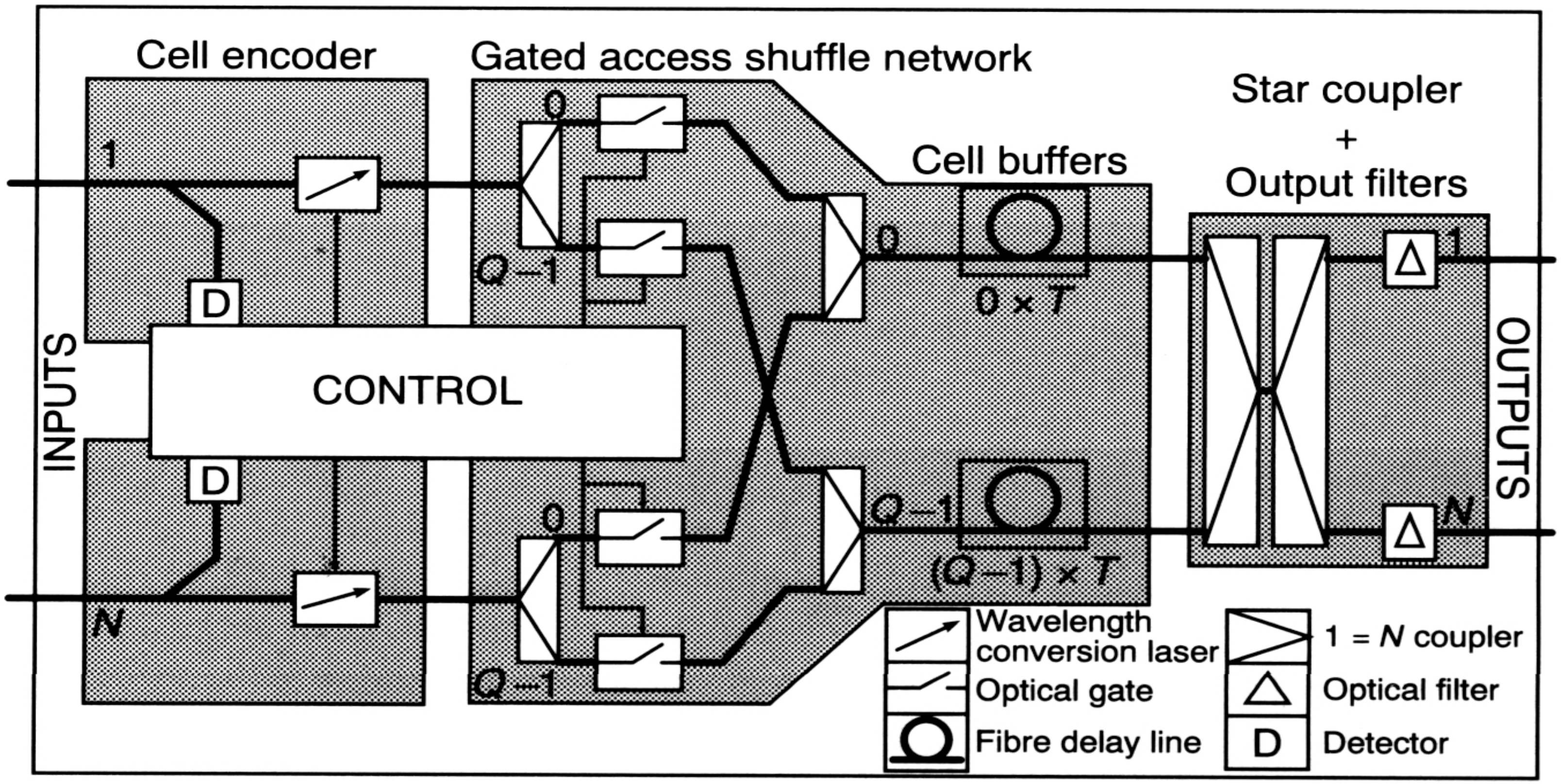
Ex. 1: Broadcast-and-select OPS



P. Gambini, et al: "Transparent Optical Packet Switching: Network Architecture and Demonstrators in the KEOPS Project," *IEEE JSAC*, vol. 16, no. 7, pp. 1245-1257, Sept. 1998.

Ex. 2: Broadcast-and-select optical ATM switch

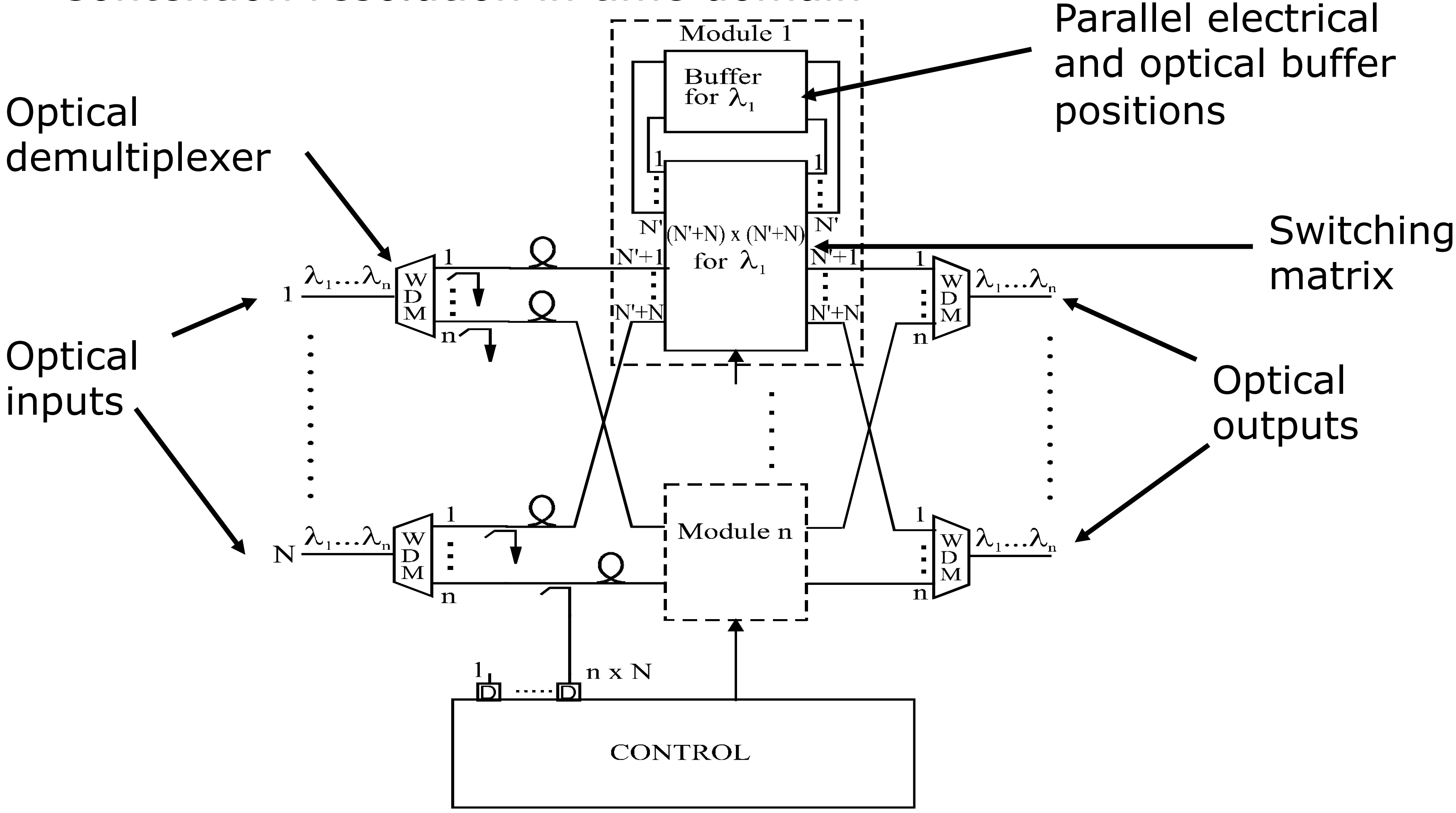
Contention resolution in time domain



J.M. Gabriagues, et al.: "Design, modeling and implementation of the ATMOS project fiber delay line photonic switching matrix" Optical and Quantum Electronics, vol. 26, no.5, pp. 497-516, May 1994.

Ex.3: OPS with recirculation buffer.

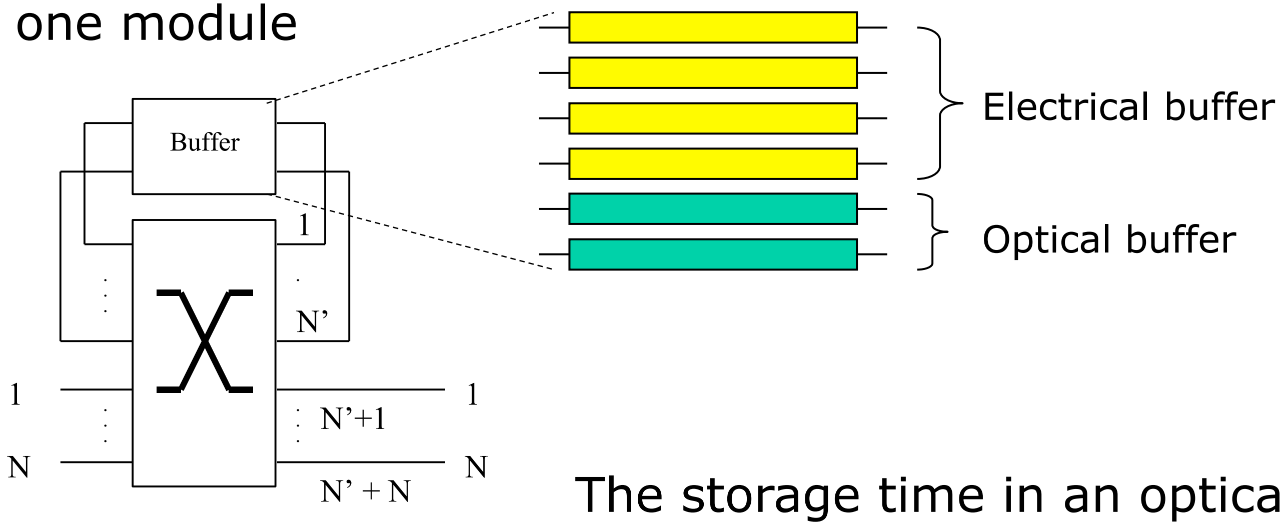
Contention resolution in time domain



L. Wosinska, " Buffering and control in all-optical packet switching nodes", (Invited paper), in Proc. of ICTON'05, Barcelona, Spain, July 2005

Optical packet switch. Example, cont.

one module



The storage time in an optical buffer:

- is limited
- can be composed of fix write and read
  time and variable storage time
  or variable write and read time
- can only take pre-defined values

Optical packet switch - simulation

Simulation assumptions:

ATM traffic: storage time **0.256µs**, granularity: 2ns*

IP traffic: **0.6144µs** for IP granularity 4,8ns

Priority classes:

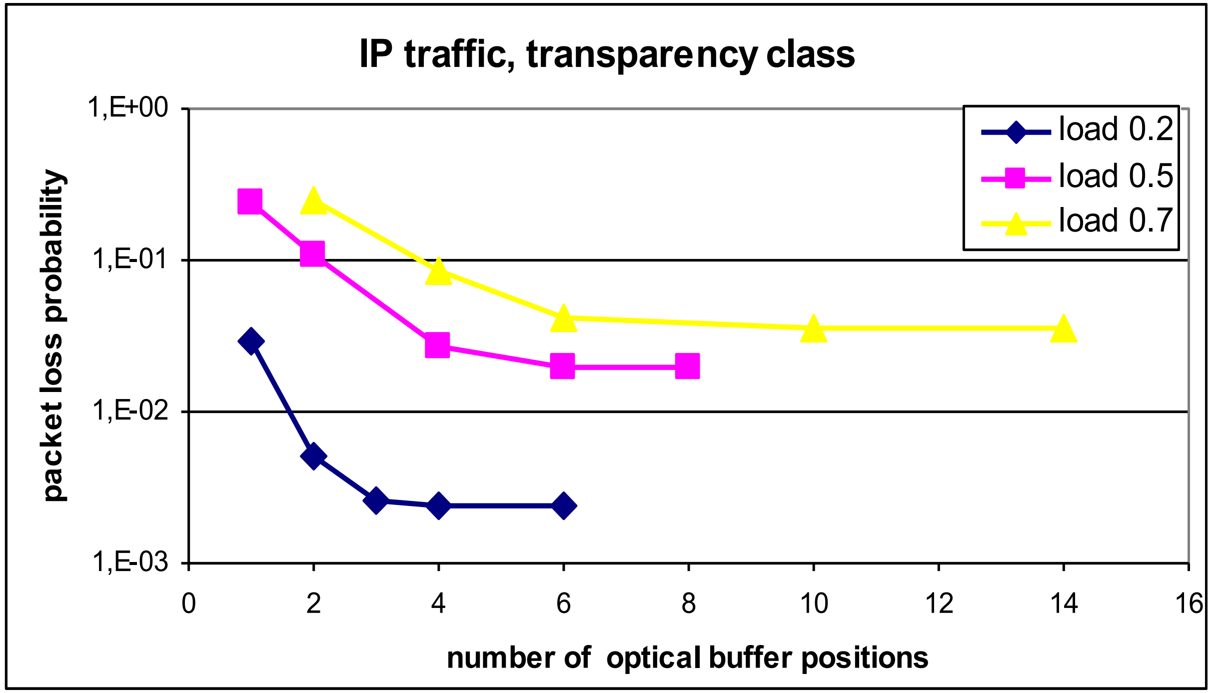
- Transparency Class 20%
- Low Loss Class 20%
- Normal 60%

Equal load at each input and output

Exponentially distributed inter-arrival time

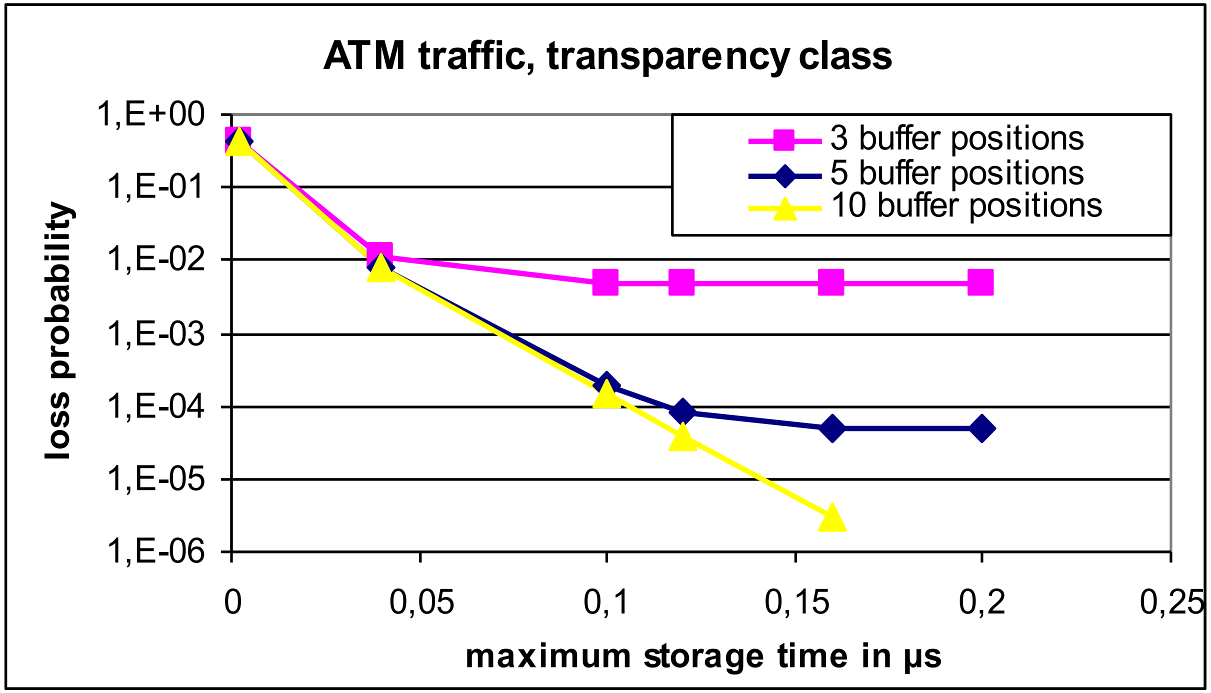
*The granularity has been chosen for the simplicity of the control unit to obtain 128 (2^7=1 byte) values of possible delay.

Optical packet switch - simulation results



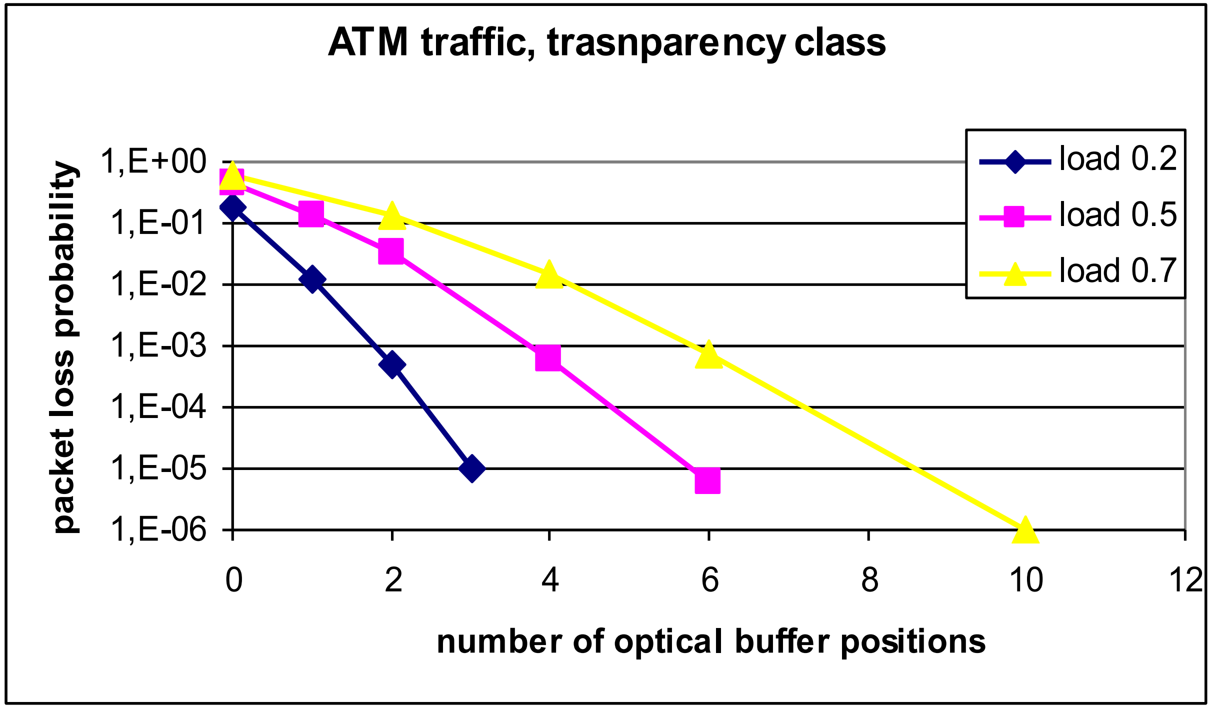
The loss probability goes down to a certain point and than stays constant as the buffer increases.

Optical packet switch - simulation results



The lowest achievable packet loss probability for a given number of buffer positions reaches a limit that cannot be overcome by increasing the maximum storage time.

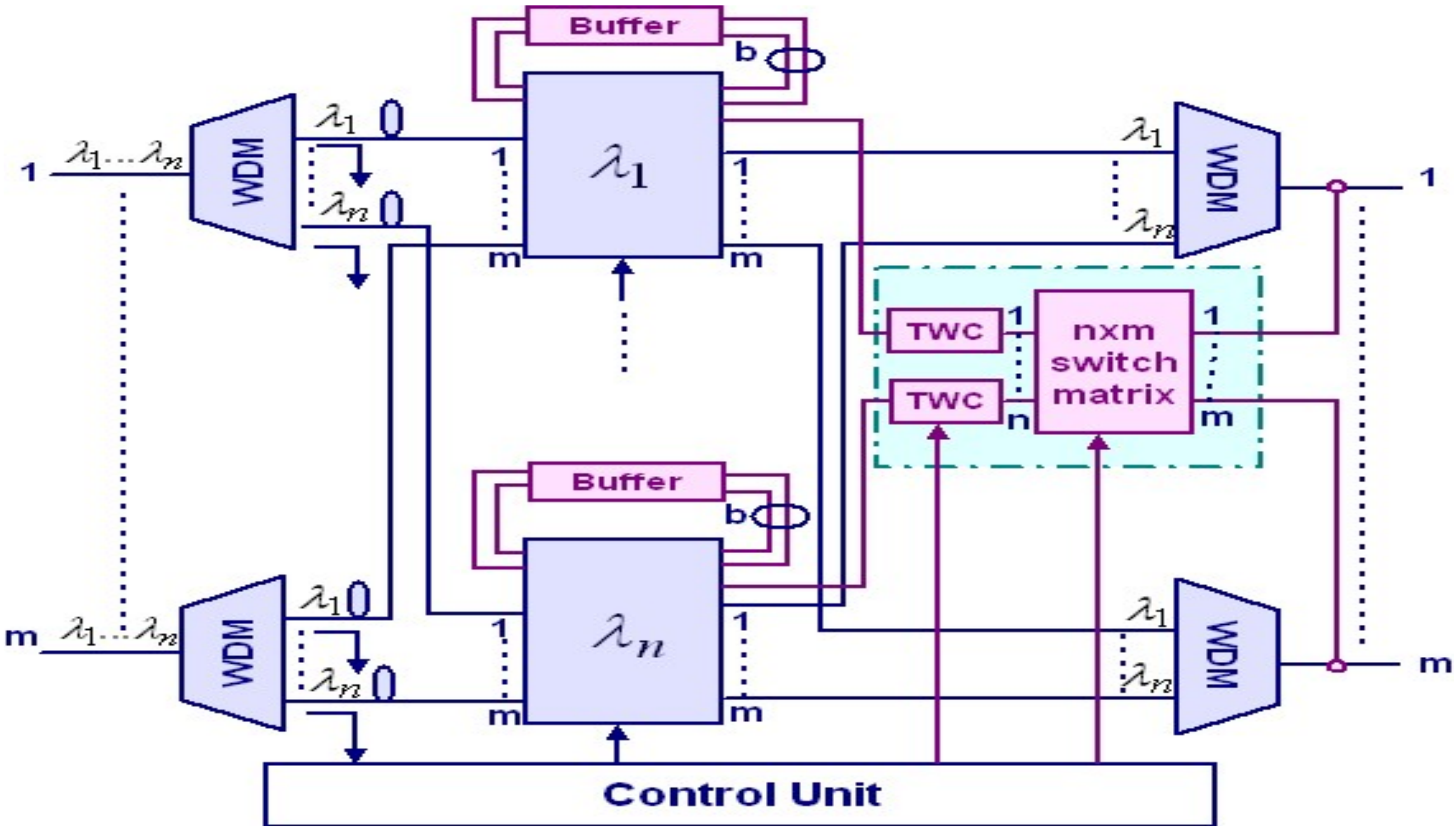
Optical packet switch - simulation results



Storage time of 0.5ms is enough to obtain any value of loss probability for any traffic load.

Ex. 4: Optical packet switch

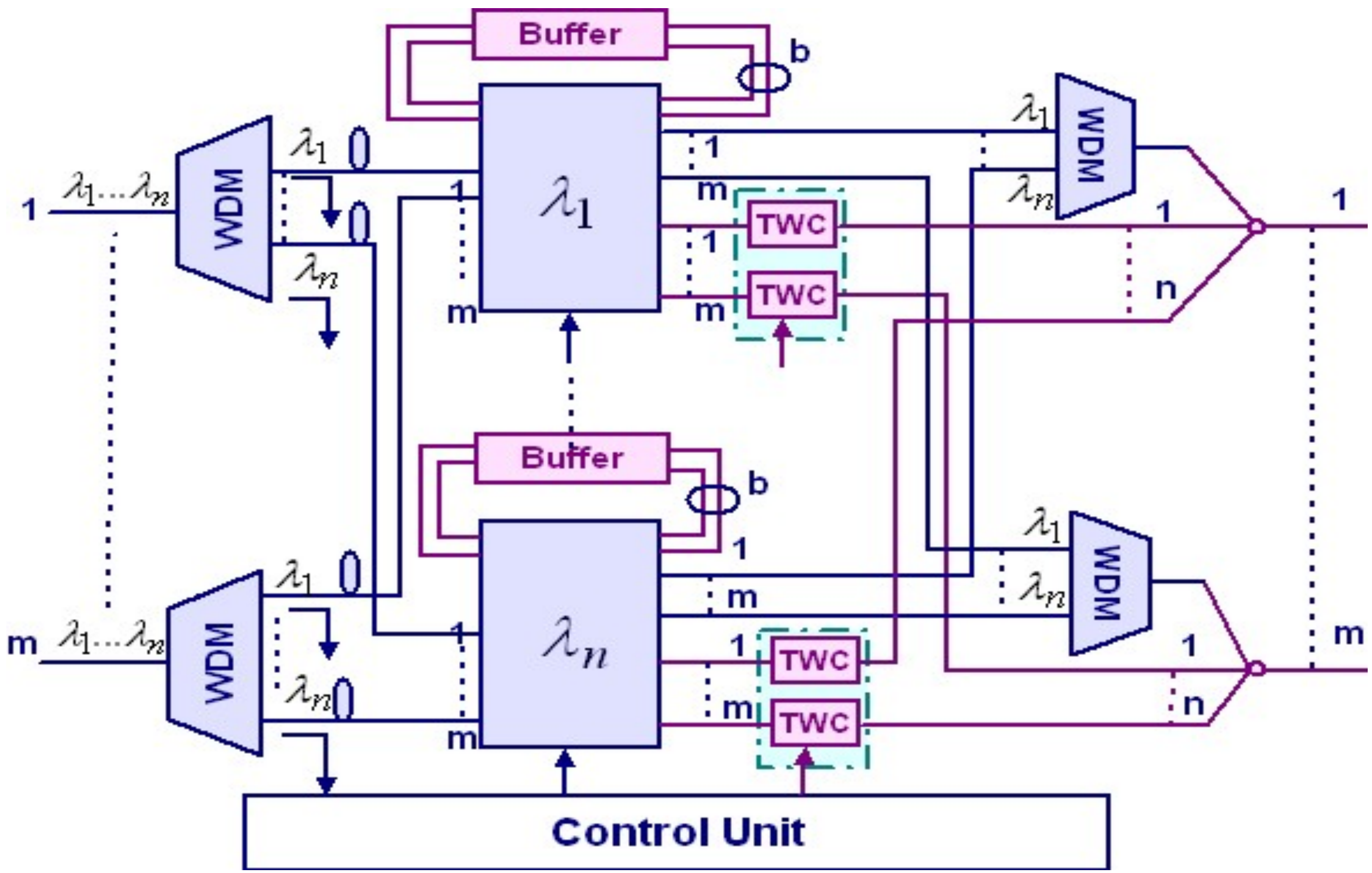
Contention resolution in time and wavelength domain



L. Wosinska and JiaJia Chen, " Contention Resolution in an Asynchronous All-Optical Packet Switch", (Invited paper), in Proc. of PS'06, Crete, Greece, Oct. 2006

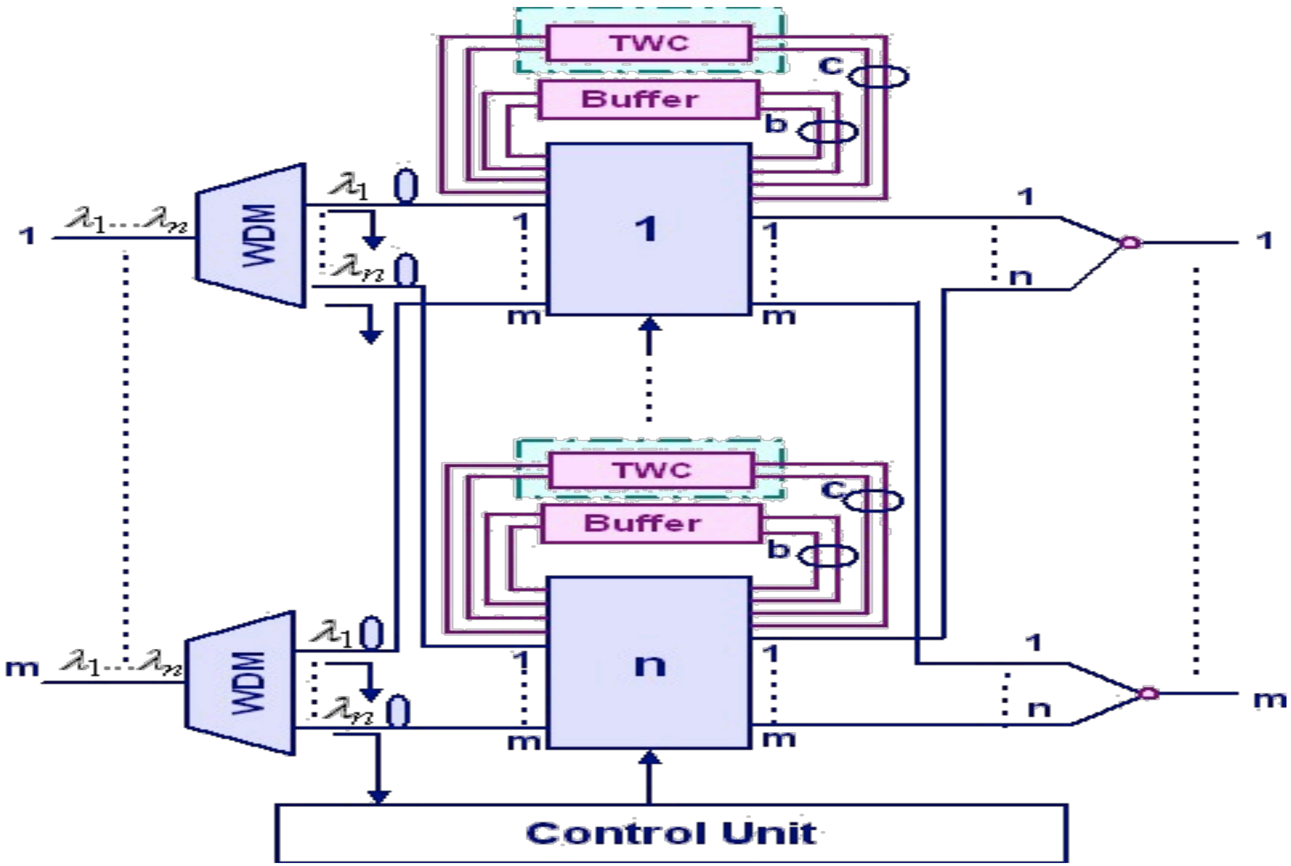
Ex. 5: Optical packet switch

Contention resolution in time and wavelength domain



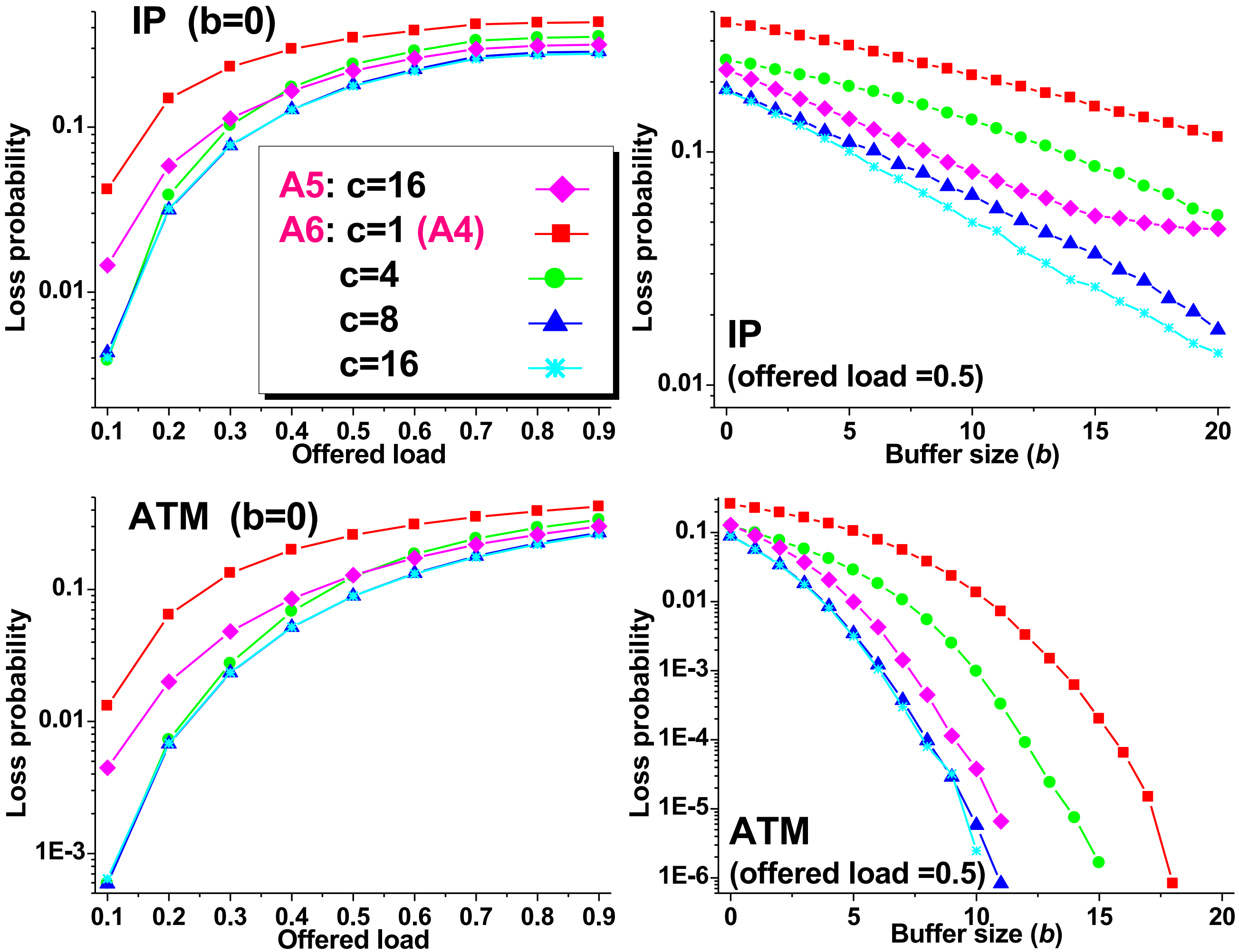
JiaJia Chen and L. Wosinska, " Novel Architectures of Asynchronous Optical Packet Switch", ECOC'07

Ex. 6: Optical packet switch



J. Chen and L. Wosinska, "Novel Architectures of Asynchronous Optical Packet Switch", in Proc. of European Conference on Optical Communication ECOC'07, Berlin, Germany, September 2007

Evaluation



J. Chen and L. Wosinska, "Novel Architectures of Asynchronous Optical Packet Switch", in Proc. of European Conference on Optical Communication ECOC'07, Berlin, Germany, September 2007

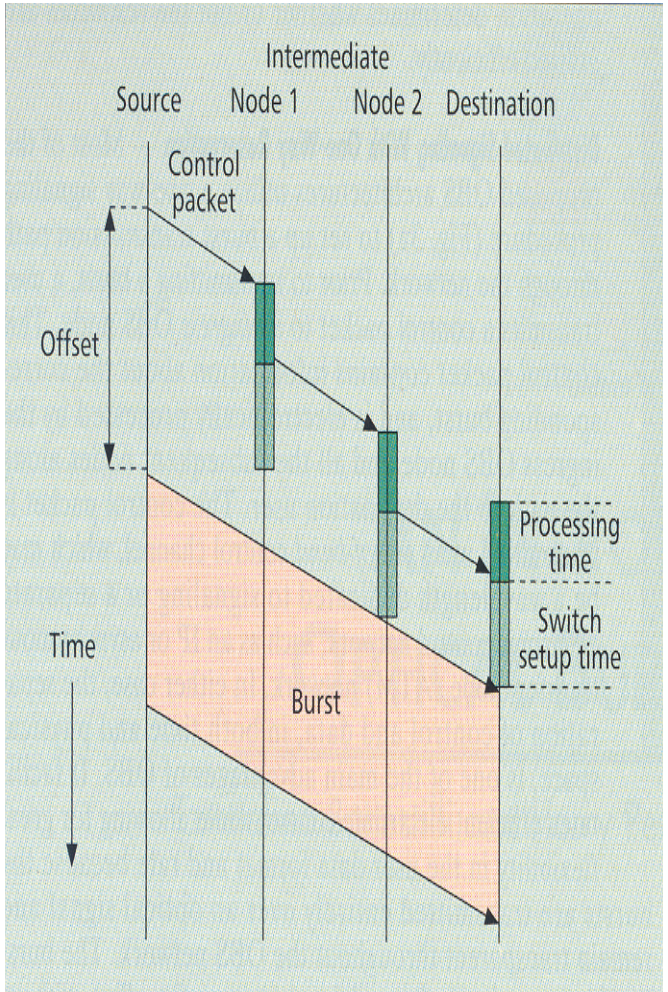
Optical burst switching

Optical Burst-Switched Networks

- A compromise between circuit-switching and packet-switching
- A control packet is first sent to set up the "connection" for a burst, which is released as soon as the burst is sent
- Bandwidth is reserved for a shorter time than circuit-switching ➔ higher bandwidth efficiency

OBS: the main idea

- Sort data at optical network ingress according to destination
  - Collect a burst of data for a destination
  - Send a control packet to set up a path
  - Send burst when path should be established
- OBS is a hybrid of circuit and packet switching
  - Tends towards CS when burst is large
- Main performance parameter: <u>burst loss</u>

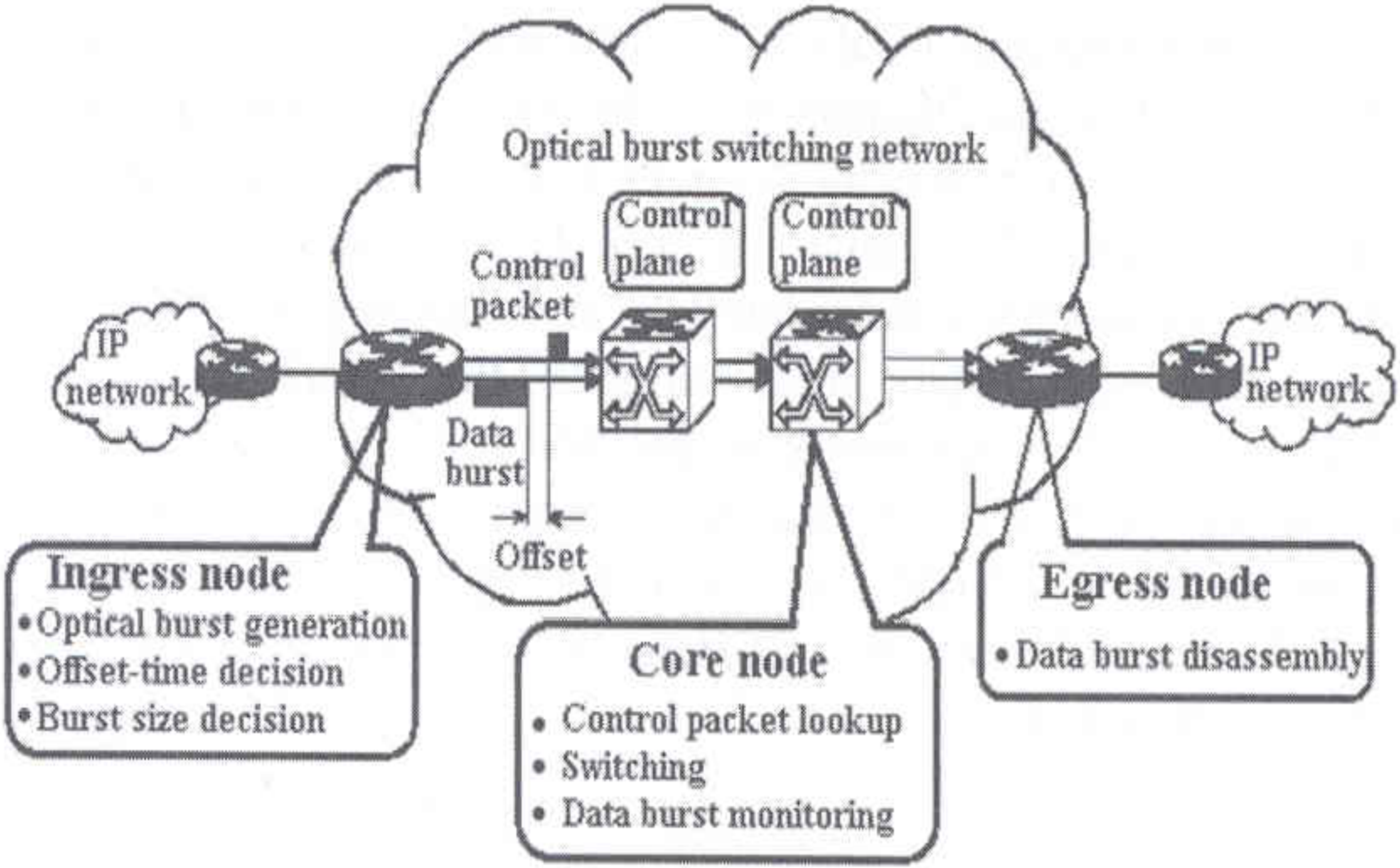


(a) One-way reservation

Design issues

- Burst assembly and scheduling
- When to send control packet
  - When burst is ready (size is known)
  - In anticipation of burst
- Determine the time offset between transmissions of control packet and burst
  - Should account for processing and setup delays
  - Need to consider number of hops
- Resource scheduling for burst switches

OBS network



Optical burst switching network
Control plane
Control plane
Control packet
IP network
IP network
Data burst
Offset
Ingress node
• Optical burst generation
• Offset-time decision
• Burst size decision
Core node
• Control packet lookup
• Switching
• Data burst monitoring
Egress node
• Data burst disassembly

OCS, OBS, OPS: Comparison

Property	Wavelength routing OCS	Optical Burst Switching OBS	Optical Packet Switching OPS
Granularity	Large	Middle	Small
Hardware limitations	Low	Low	High
Optical buffer	No	No	Yes
Wavelength converter	Yes/No	No	Yes
Electronic bottleneck	Yes/No	No	Yes
Control overhead	Low	Low	High
Scalability	Low	High	High
Flexibility	Low	High	High
Cost	Low	Low	High

Summary

- Switched networks
- Photonic circuit switching
- Photonic packet switching
  - Technological and architectural challenges
    - Buffering for contention resolution
    - Scheduling for contention resolution with possible deflection
    - Switching speeds
- Optical burst switching
  - Slower switching speeds than packet switching
  - Allows time division of resources
  - Promising technique with practical feasibility