

## **IO2654 Optical Networking**

# Photonics in switching

*Lena Wosinska*  
KTH/ICT

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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

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## 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

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## Switching

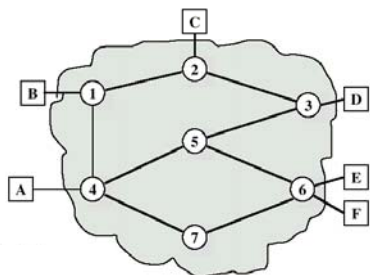
- Needed to efficient utilize the network resources
- Full mesh connectivity vs. switched connectivity
- Resource sharing

### Types

- 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.

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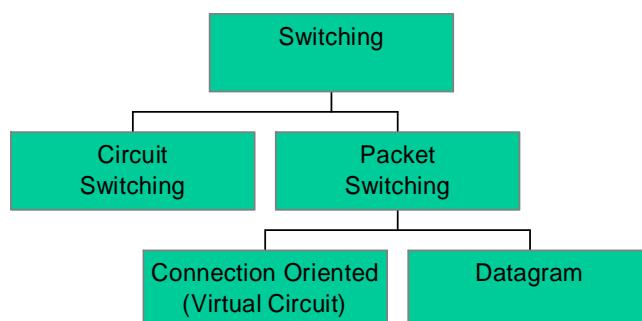
## Switched networks



- ① 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

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## Switching



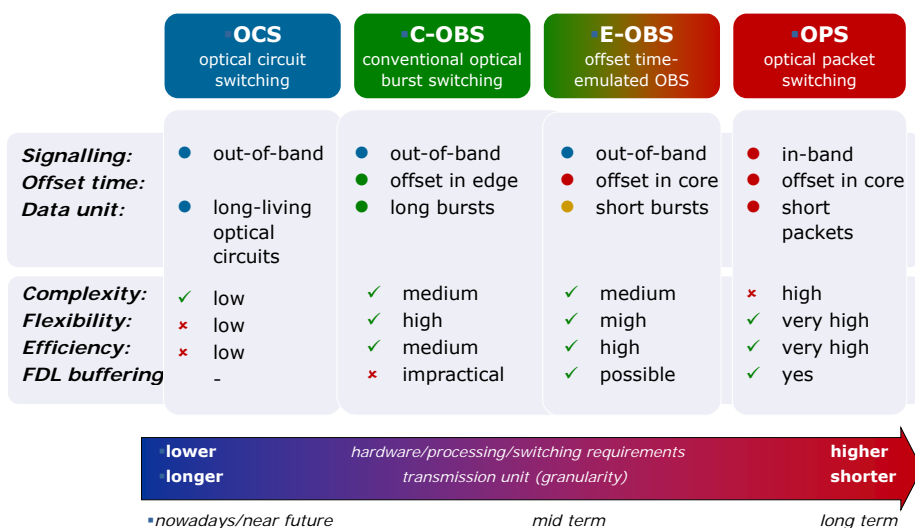
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## Photonics in switching

- 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?

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## Migration towards OPS



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# Optical circuit switching

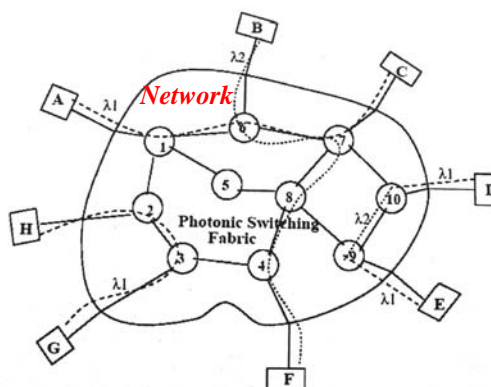
## *Wavelength-Routed Networks*

### Wavelength-Routed Networks

- W-R switches
- Provide lightpaths

**Problems:**

- Low bandwidth efficiency
- Large granularity



- ① Wavelength-routing switch
- Ⓐ Access (client) node (e.g., IP router): contains (tunable) transmitters and receivers

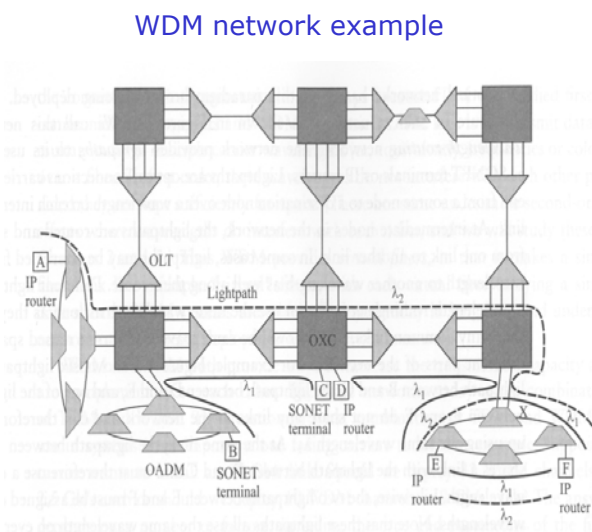
## Optical circuit switching

- 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)

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## WDM network elements

- Optical line terminals (OLTs)
- Optical add-drop multiplexers (OADM)
- Optical cross-connects (OXC)
- Optical line amplifiers



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## Architecture Features

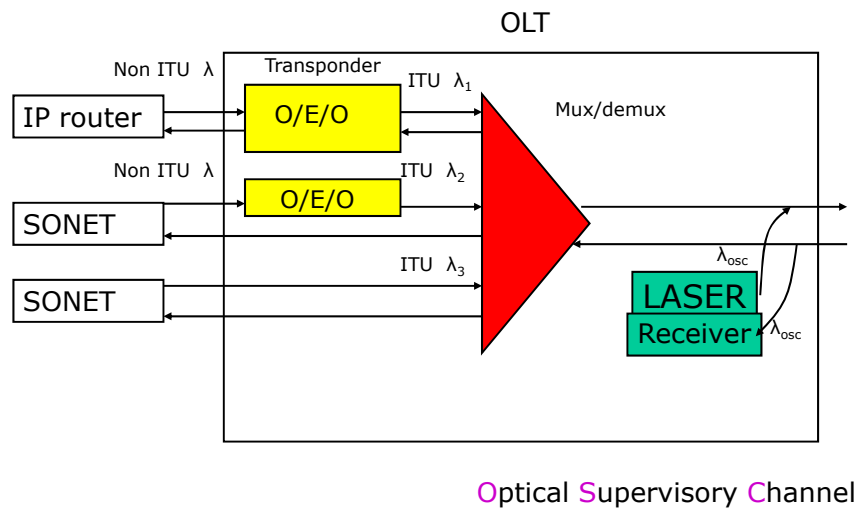
- Wavelength reuse
- Wavelength conversion
- Transparency
- Survivability
- Lightpath topology

## Optical Line Terminal (OLT)

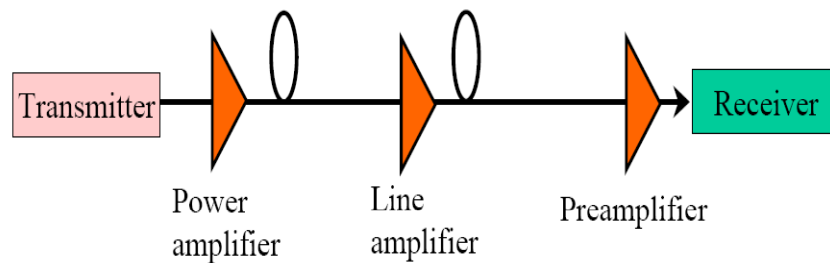
### Three functional elements

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

## Block diagram of an OLT

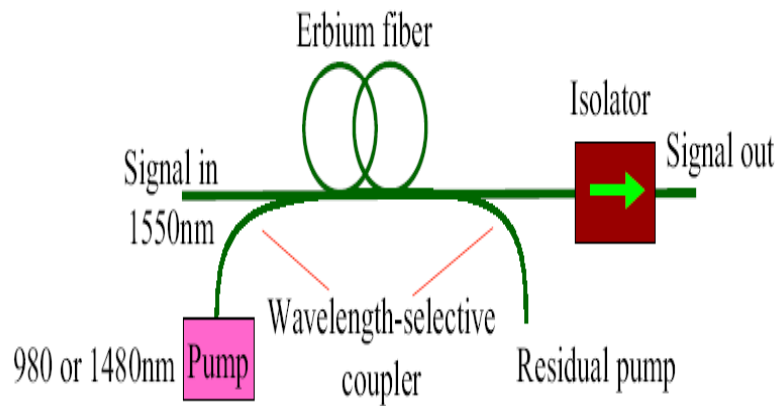


## Optical line amplifier





## Erbium Doped Fiber Amplifier (EDFA)



## Optical add/drop multiplexer (OADM)

- **Drop and add one or more wavelength channels**
  - 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

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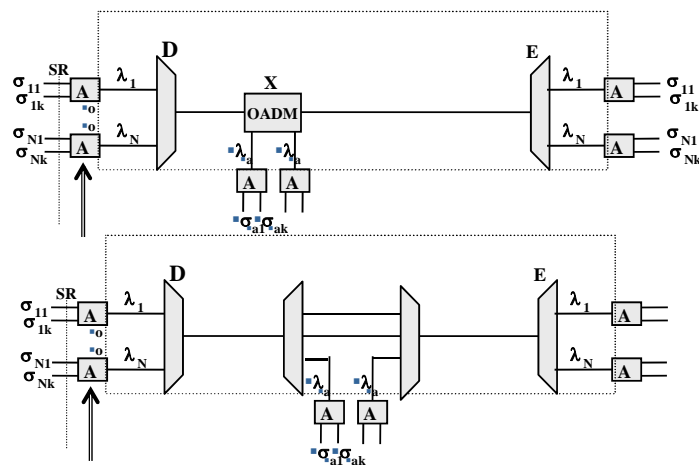
## Ideal OADM

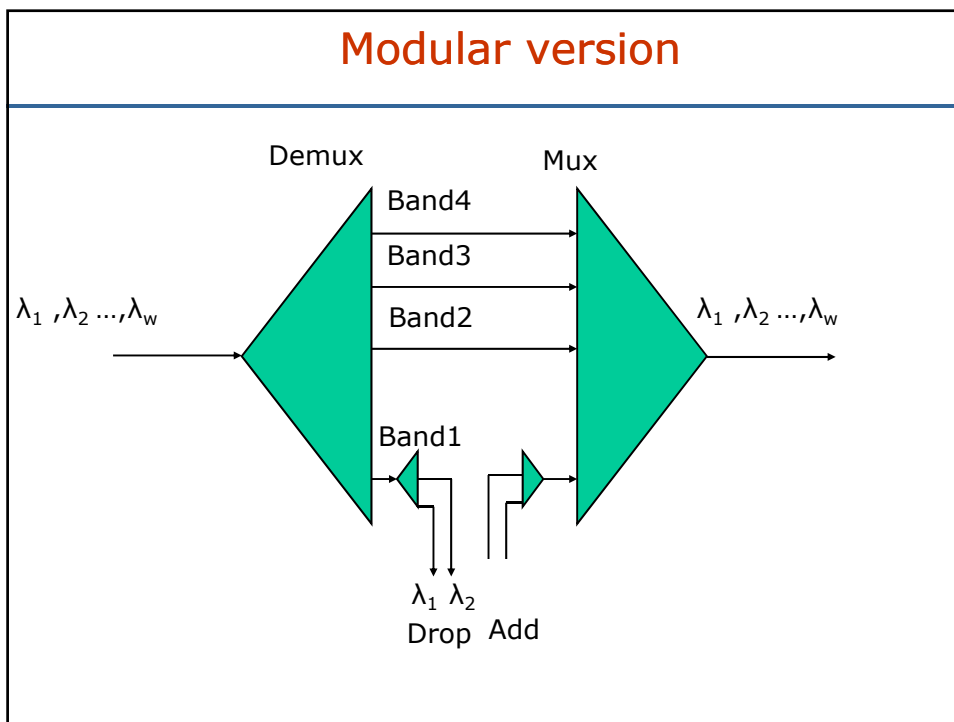
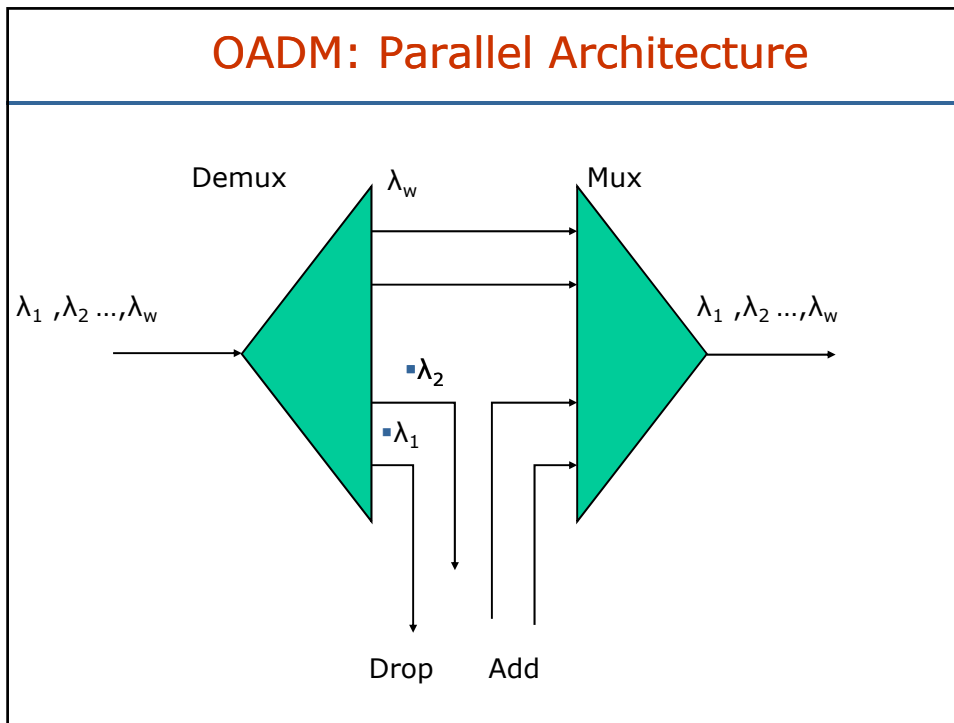
- Would drop and add any channel
  - And any number of channels
- Remotely controlled
  - Reconfiguration without disturbance to unaffected channels
  - No plan-ahead needed
- Low and fixed loss
  - Independent of set of wavelengths dropped

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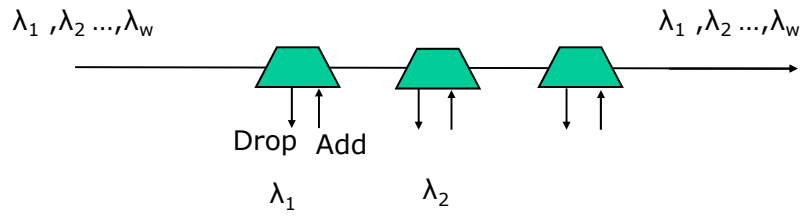
## OADM's benefits

Cost effective OADM

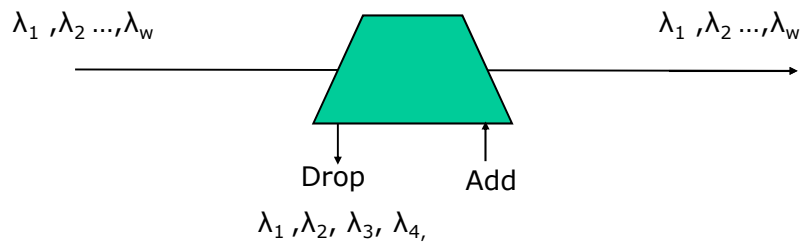




### OADM: Serial architecture



### OADM: Band drop



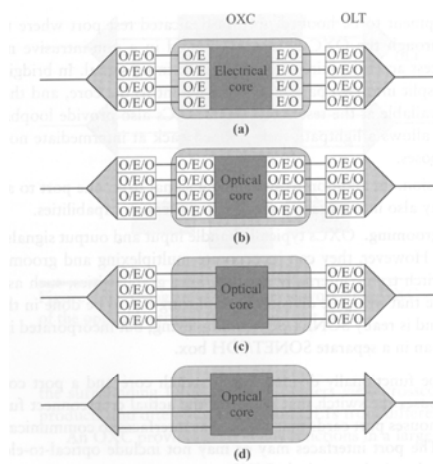
## Optical Cross-connects (OXC)

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

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## Types of OXCs

- Electrical or optical core
  - Transparency
  - Cost
  - Size
- Transparent or opaque core
  - Signal converted
  - Electronic signal
    - Signal monitoring
  - Optical signal
    - Transparency



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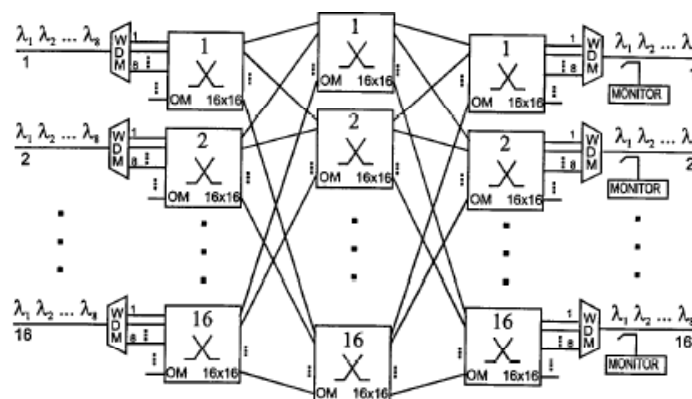
## All-optical OXCs

### 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

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### Ex. 1: All-optical OXC. Clos architecture

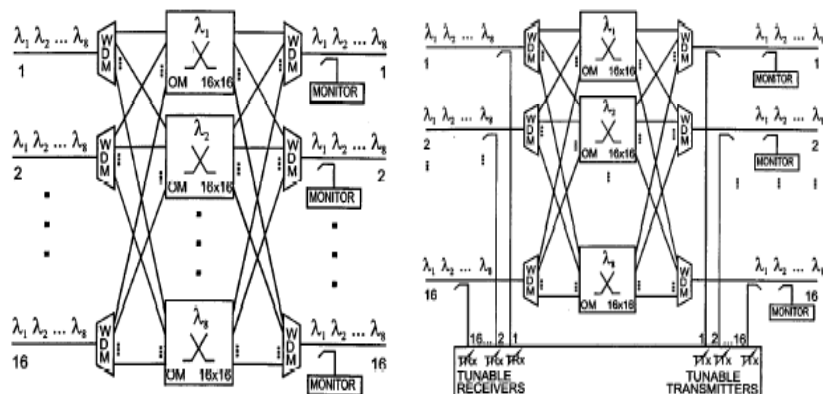


Three stage strict internal non-blocking Clos architecture.

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.

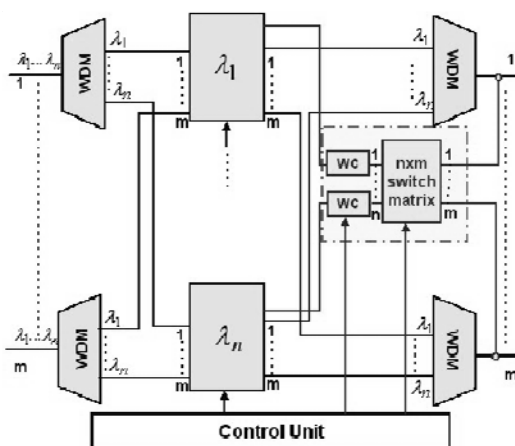


Strict internal non-blocking wavelength routing architecture.

Size 128x128

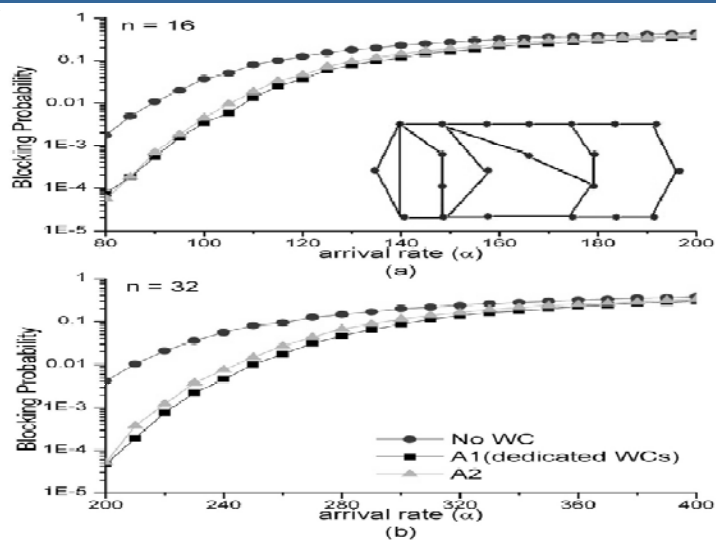
L. Wosinska et al.: "Large Capacity Strictly Non-Blocking OXCs Based on MEOMS Switch Matrices. Reliability Performance analysis," IEEE/OSA JLT, Vol.19, No.8, Aug. 2001

### 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



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

## Shortcomings with OCS

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

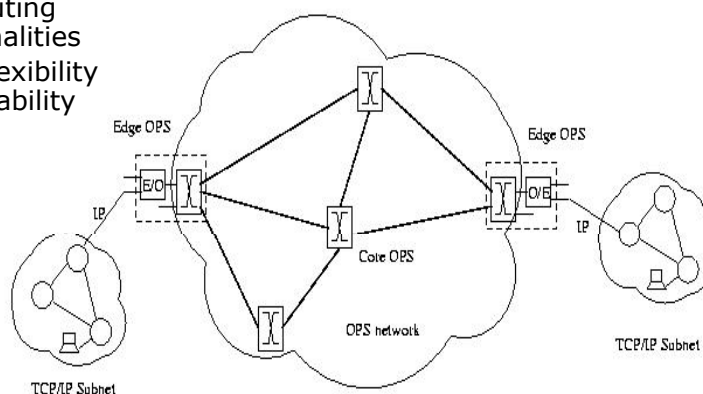
**Solution:** Optical Packet Switching (?)



# Optical packet switching

## OPS networks

- Large capacity
- High bandwidth efficiency
- Rich routing functionalities
- Great flexibility and reliability



## Optical packet switching

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

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## 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)

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## Contention resolution in OPS networks

- Congestion 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

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## 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 not available yet
- Buffer the packet
  - Store the packet until the output is available
  - Applying TWC may allow for decrease of the buffer size

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## 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

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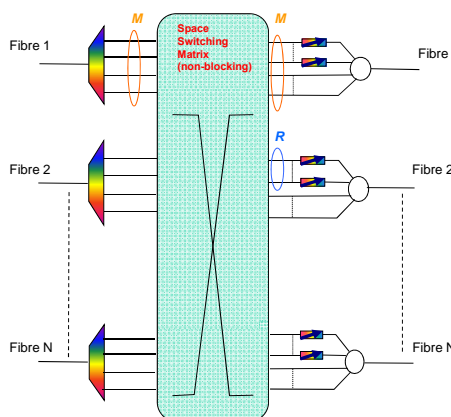
## Bufferless OPS: sources of packet loss

- 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

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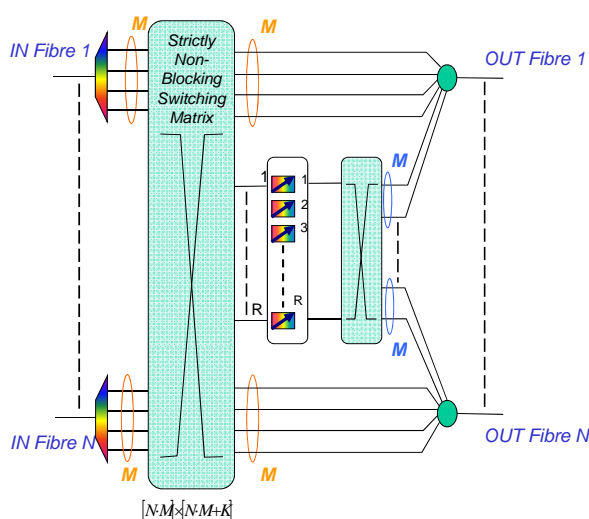
## TWC: Shared per output link architecture

- 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.



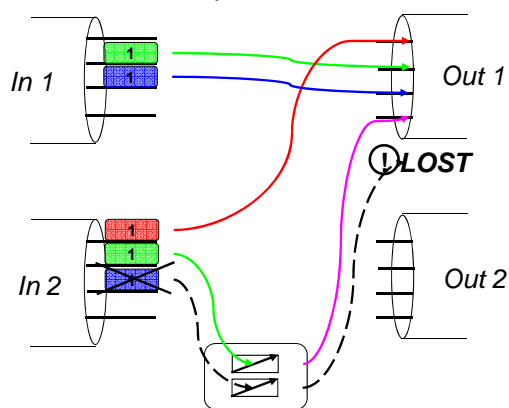
## TWC: Shared per node architecture

- 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



### Case 1: packet lost due to congested output fibre

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



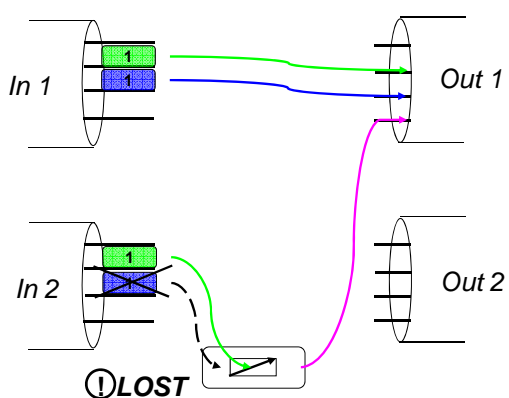
- 5 packet arrivals directed to output fibre 1 in a time slot;
- First, one packet from each different wavelength is sent without conversion;
- Then, other packets are sent exploiting wavelength conversion;
- If destination output fibre is congested, packet is lost;
- *If destination output fibre is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

Carla Raffaelli, University of Bologna

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### 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;

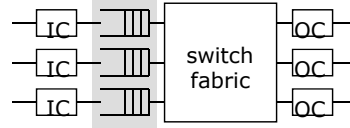
Carla Raffaelli, University of Bologna

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## Buffer placement at the node

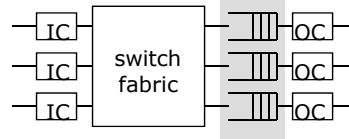
### Input buffer

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



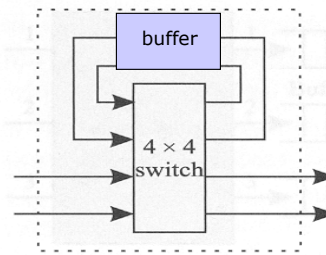
### Output buffer

- No HOL blocking
- More difficult to implement

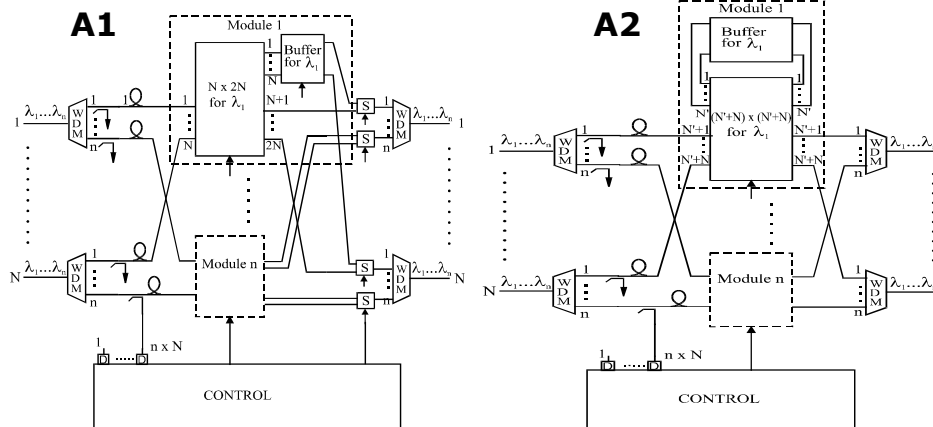


### Recirculation buffers

- Shared by all inputs
- Requires larger switch size



## OPS with electrical buffer



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

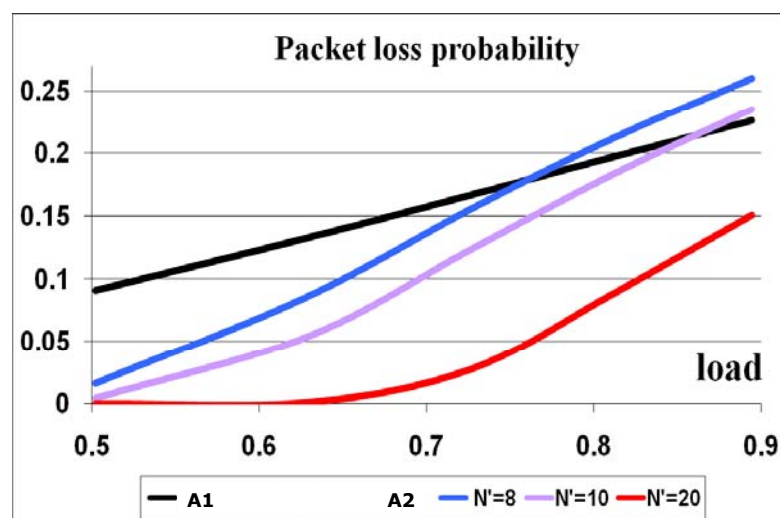
## COMPARISON

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

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## Comparison. N=20



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

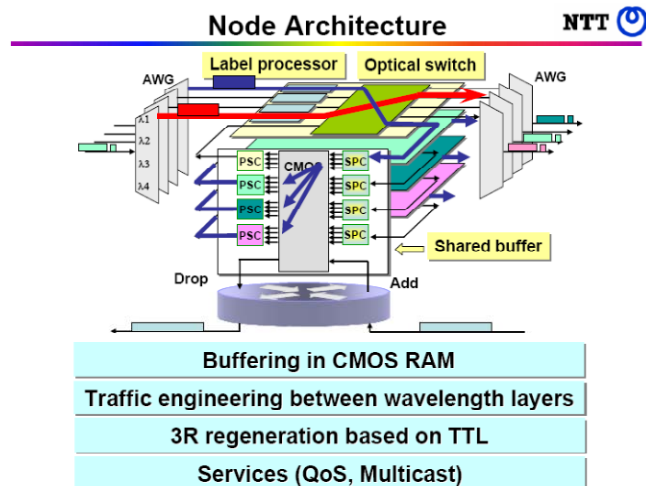


## Hybrid optoelectronic router

Alcatel Lucent & NTT  
demonstrator at ECOC 2009

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### Exhibition of Prototype Router (Booth #604)

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

- Optical Input/Output
- Label Processor & Switch (2λ)
- Shared Buffer
- Optical Clock Generator

**Performance**

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

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## Hybrid optoelectronic router

Prototype Development

An optimum incorporation of optical and electrical technologies within a novel router architecture allows dramatic reduction of power and latency while providing the functionality needed for implementing various services required in OPS networks.

- 8x8 (4x4, 2λ) packet switching capability for 10-Gbps arbitrary-length, asynchronous optical packets (scalable to 16x16 (4λ))
- Optical Input/Output
- Label Processor & Switch (Only 2 layers are implemented)
- Shared Buffer
- Optical Clock Generator

**Performance**

- ◆ Power consumption: ~360 W
- ◆ Latency: ~1.4 μs (for contention)
- ◆ Functions: 16-bit label swapping, 2-line QoS, Multicast, TTL-based 3R regen.
- ◆ Size: 100 x 60 x 100 cm<sup>3</sup>

Packet Processing Technologies

**Label Processor**

- ◆ 16-bit label swapping
- ◆ Asynchronous, No preamble
- ◆ Low power, Low latency
- ◆ Large address table

**Shared Buffer**

- ◆ Asynchronous, No preamble
- ◆ Low power consumption
- ◆ Large-capacity arbitrary-time buffering
- ◆ High functionality (QoS, multicast, 3R)

**Optical Switch**

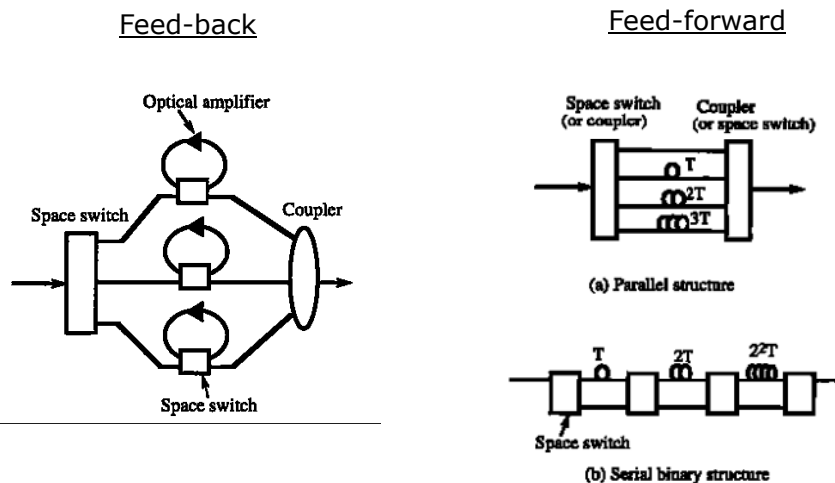
- ◆ Fast switching (< 6 ns)
- ◆ Scalable (1530-1565 nm)
- ◆ Non-blocking architecture
- ◆ Compact, Low power

## Optical buffering

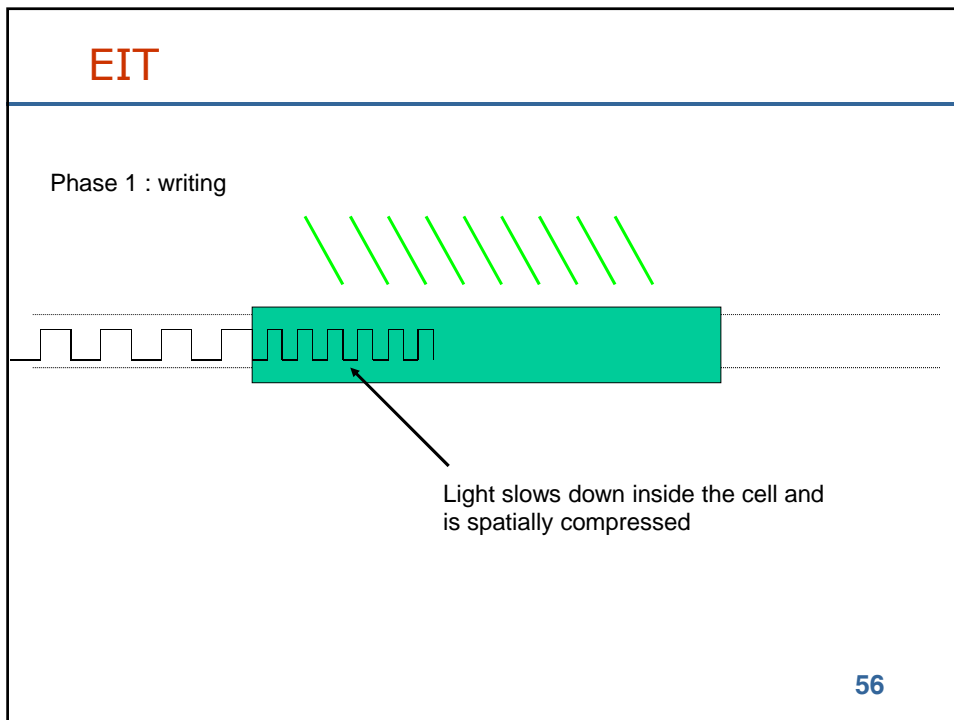
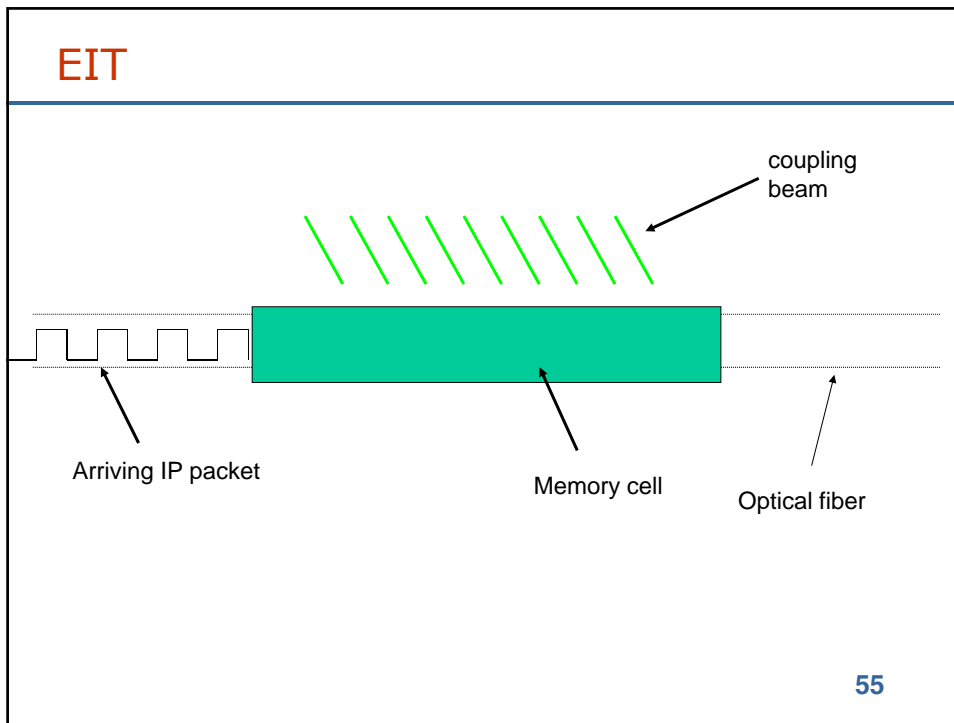
- Fiber delay lines (FDLs)
  - Not random access
  - Require synchronization
  - Supported packet format
    - Constant packet size
    - Some configurations support variable packet size
      - A certain granularity
    - Not compatible with packet formats of different packet size
  - Long fiber delay 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

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## Examples of buffers based on FDL



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## EIT

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

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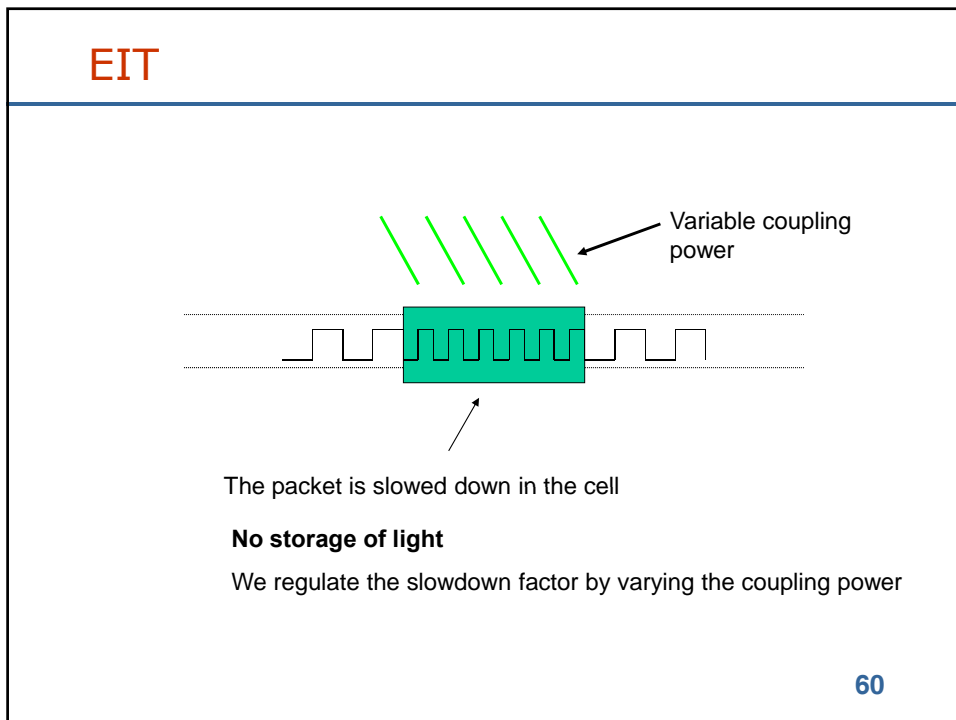
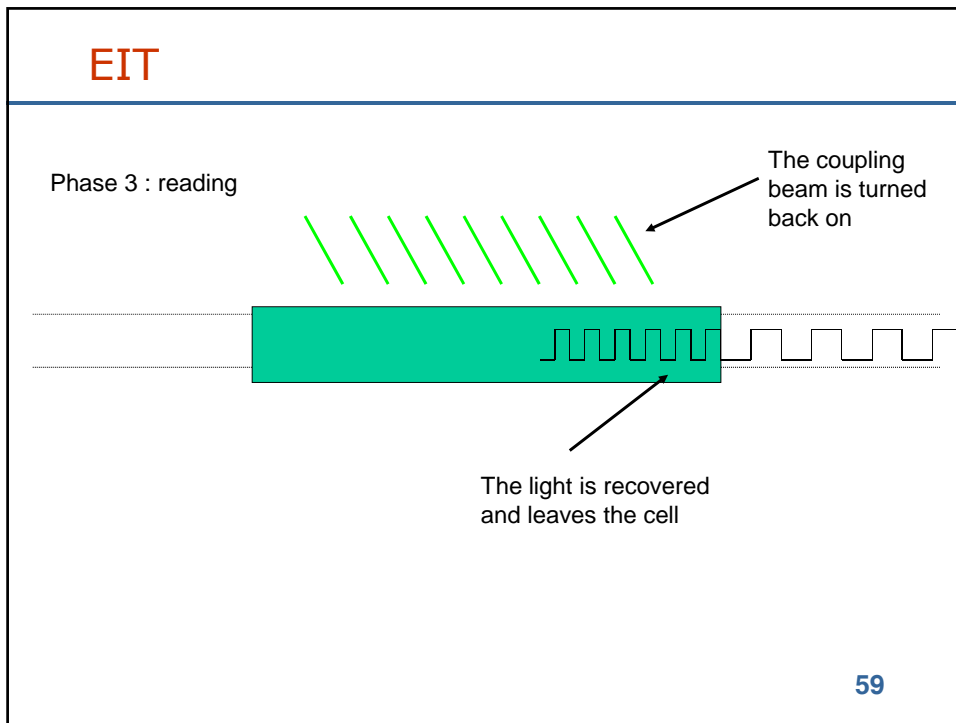
## EIT

Phase 2 : storage

The coupling beam is turned off

The light is stored in the material

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## EIT

material	slow down factor	storage time
Quantum dots	40 in room temperature 10 <sup>7</sup> in very low temperature	8.7ns
Atomic vapor	10 <sup>5</sup>	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

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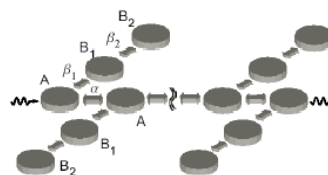
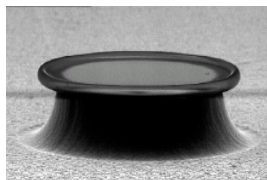
## Novel types for opt. memory - Optical cavities

Optical cavities use optical resonance in photonic structures

Slow down factor of 10<sup>4</sup> (depending on the number of side cavities)

Storage time: 50 ns

Chip scale implementation of the system foreseeable



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## 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

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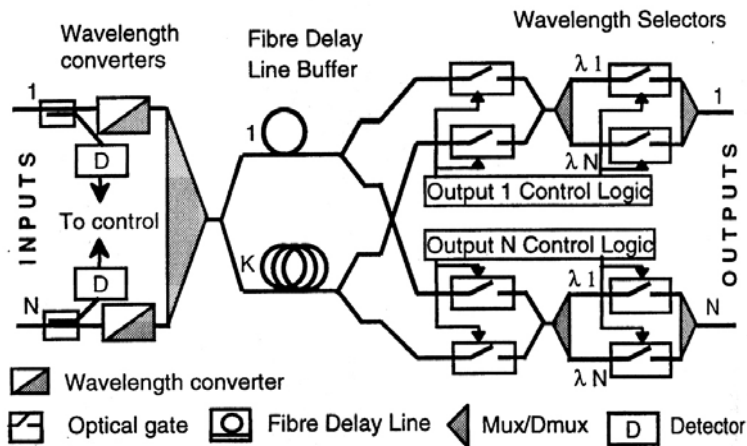
## Comparison

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

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### Ex. 1: Broadcast-and-select OPS

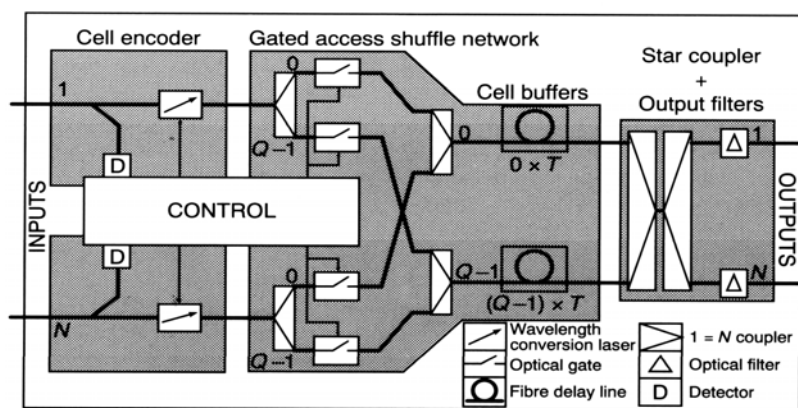


P. Gambini, et al: "Transparent Optical Packet Switching: Network Architecture and Demonstrators in the KEOPS Project," *IEEE JSAC*, vol. 16, no. 7, pp. 1245-1257, Sept. 1998.

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

Contention resolution in time domain

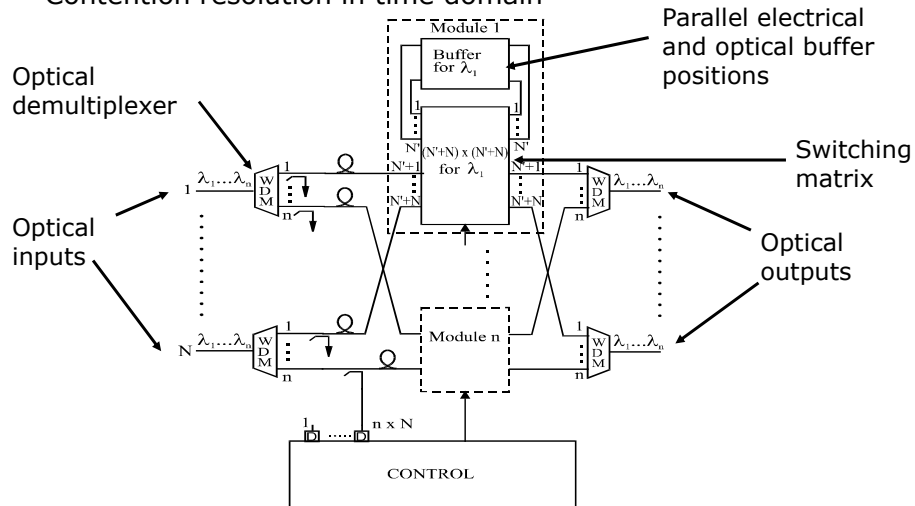


J.M. Gabriagues, et al.: "Design, modeling and implementation of the ATMOS project fiber delay line photonic switching matrix" *Optical and Quantum Electronics*, vol. 26, no.5, pp. 497-516, May 1994.

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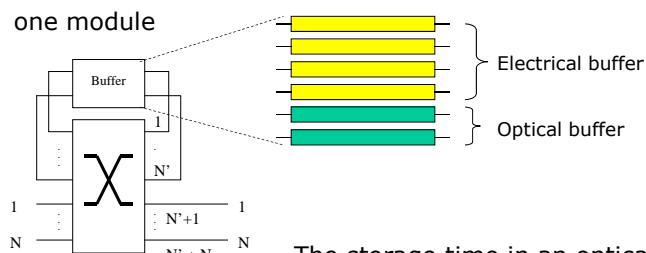
### Ex.3: OPS with recirculation buffer.

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.



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%

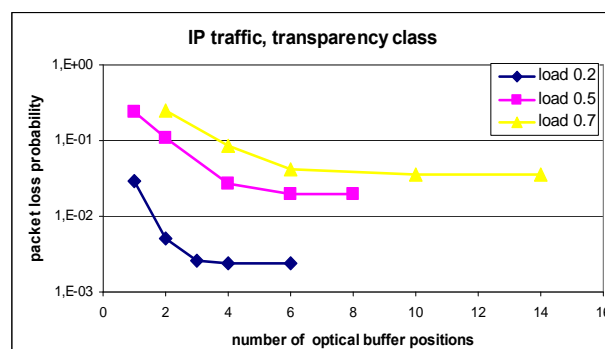
Equal load at each input and output

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.

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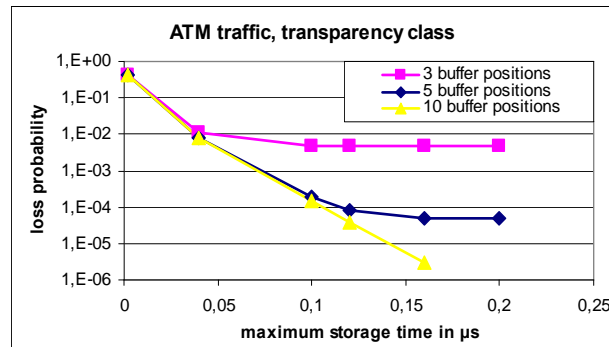
## Optical packet switch - simulation results



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

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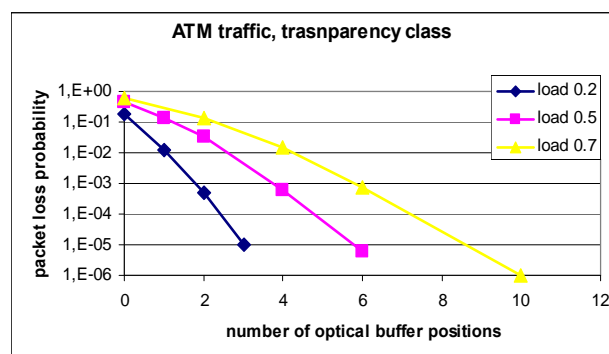
## Optical packet switch - simulation results



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.

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## Optical packet switch - simulation results

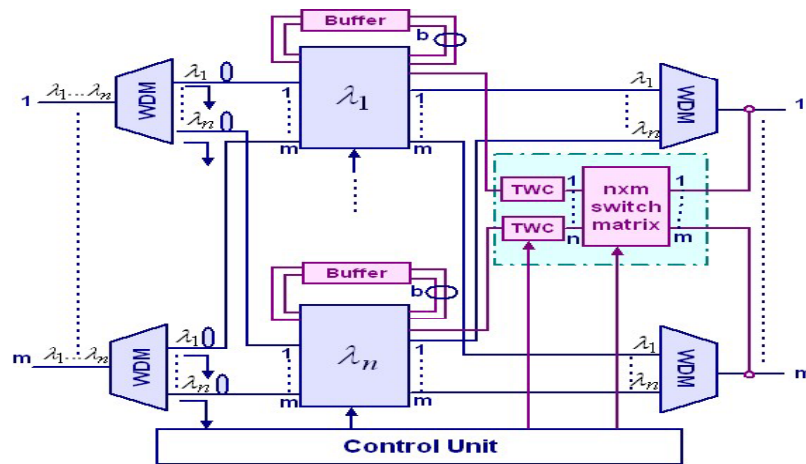


Storage time of 0.5ms is enough to obtain any value of loss probability for any traffic load.

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### Ex. 4: Optical packet switch

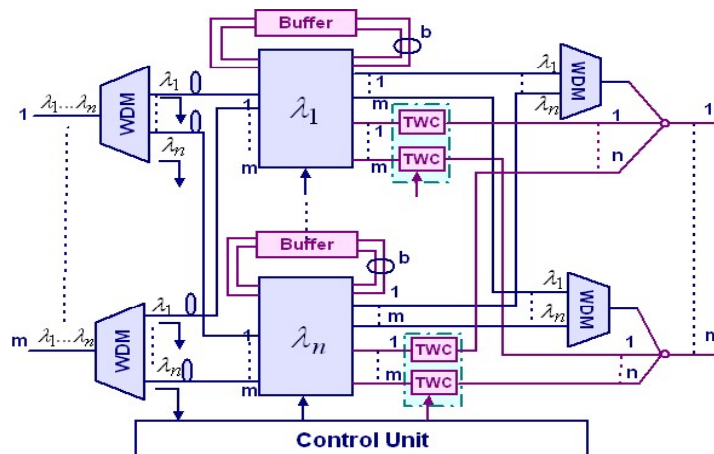
Contention resolution in time and wavelength domain



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

## Optical burst switching

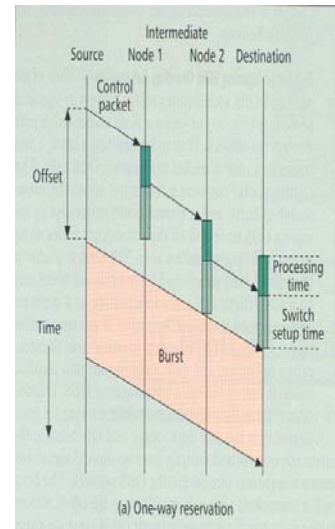
### Optical Burst-Switched Networks

- 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

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## 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: burst loss



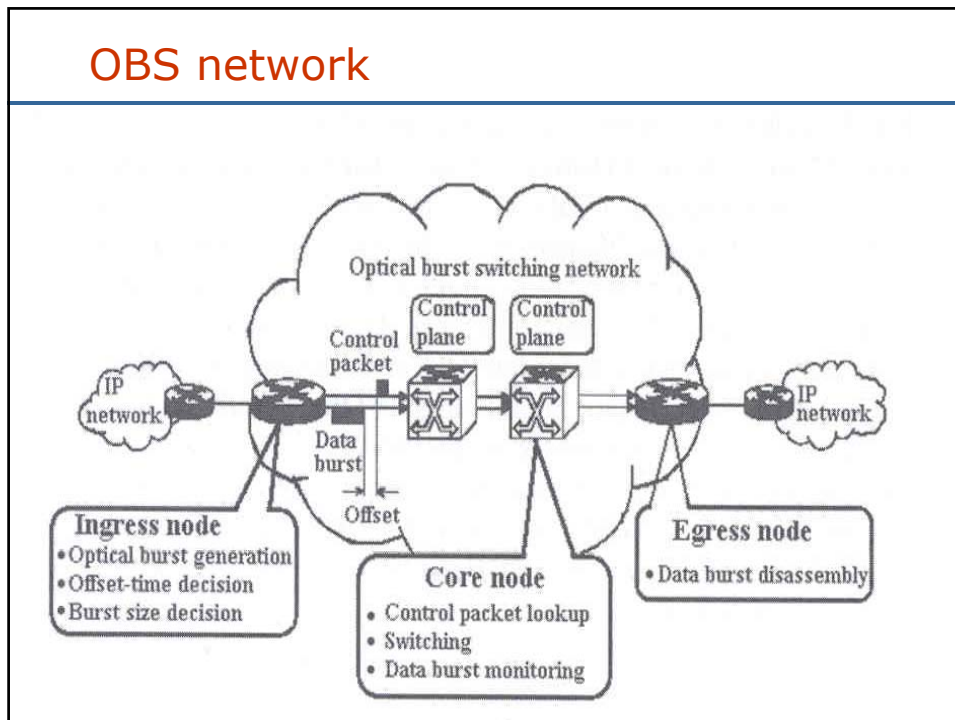
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## Design issues

- 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

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## OBS network



## 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
  - Makes networks more efficient
  - Many technical challenges for switch design
    - 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 possibility of realization

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