Energy Consumption and Switching Schemes in Optical Networks

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Outline

1) Energy consumption (ICT carbon footprint)
2) Telecom networks
3) IP over WDM
4) Optical Circuit Switching (OCS)
5) Optical Burst Switching (OBS)
6) Optical Packet Switching (OPS)
7) Hybrid Optical Switching (HOS)
8) All-opitcal HOS architecture
9) Optical/electronic HOS architecture
10) Control plane HOS (GMPLS and HOS control)
11) Energy consumption (P_cl, P_sf, P_oac, P_ampli)
12) Results (pwc + perf)

ICT Carbo

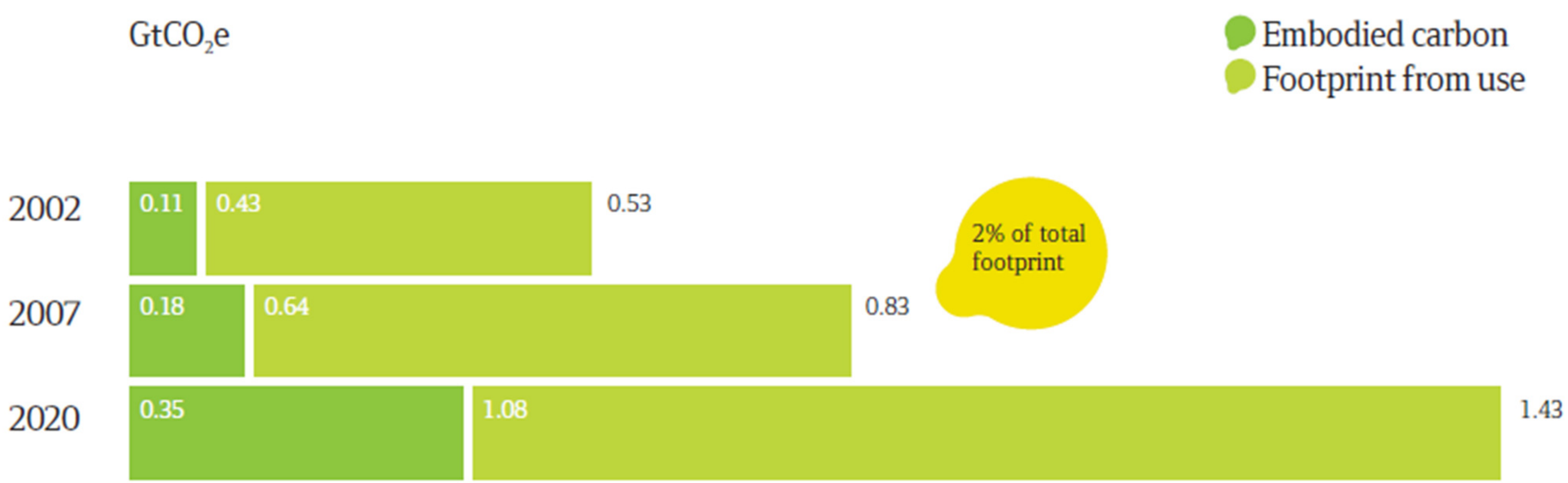
- Climate change is gaining increasing interest in our society in recent years.
- Today, nonrenewable energy resources, such as hydrocarbon energy, provide most of the energy demand (about 85% of primary energy electricity).
- The combustion of hydrocarbon materials releases large amounts of Green House Gases (GHG), a major cause of Global Warming.
- GHG emissions include: Carbon Dioxide (CO2), Methane (CH4), Nitrous Oxide (N2O), Fluorinated Gases -> measured in CO_2e.

- Global consultant "Gartner" estimated that in 2007 the total footprint of the ICT was *830* $MtCO_2e$, about 2% of the estimated total emissions from human activity released that year.

ICT Carb

- The ICT GHG emissions are expected to grow 6% each year until 2020.
- By 2020 ICT is predicted to emit 1430 $MtCO_2e$.

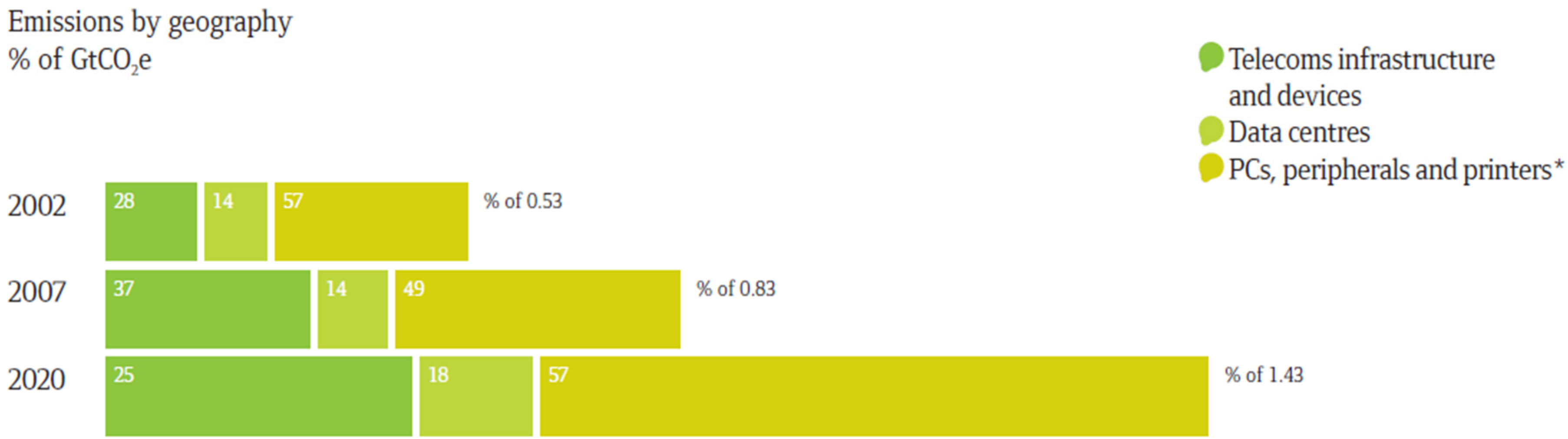
Fig. 2.1 The global ICT footprint*



ICT Carb

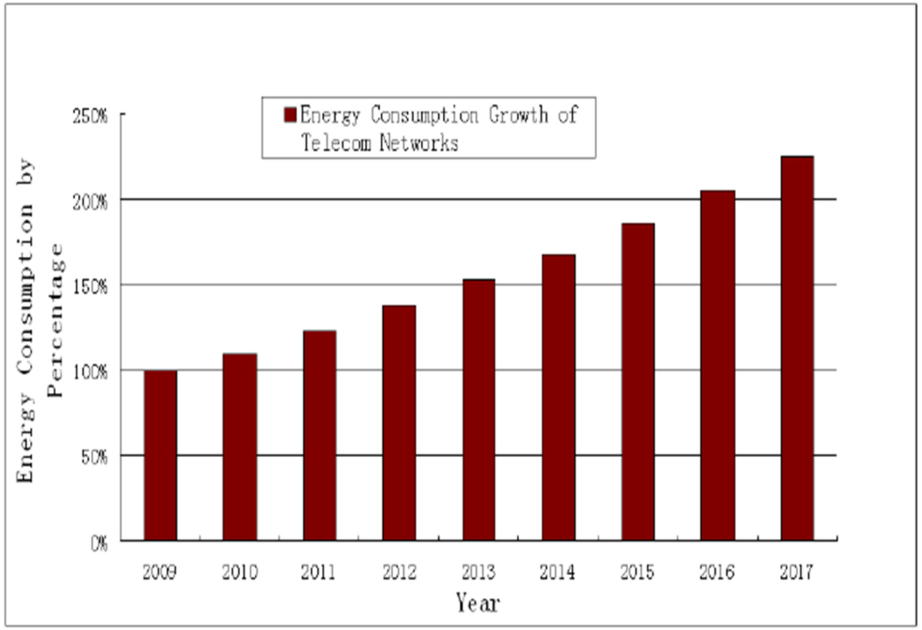
- ICT carbon footprint is given by: Telecom network Infrastructure + Data centers + PCs and peripherals.

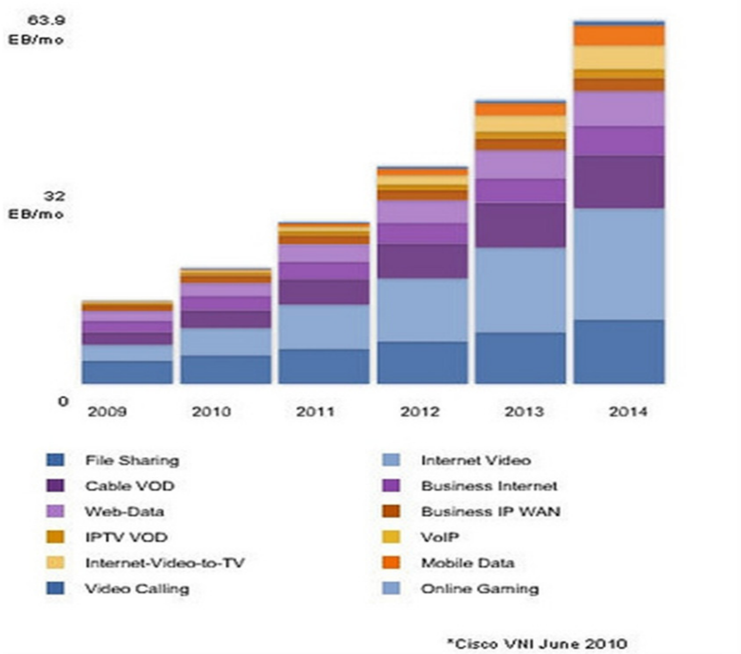
Fig. 2.3 The global footprint by subsector



Telecom Ne tprint

- The traffic volume of broadband telecom networks is expected to grow rapidly in the next years.
- As a consequence, increases the energy consumed by the telecom infrastructure.





- Energy efficiency becomes a main issue when designing new network solutions.

Telecom N

- Access networks:

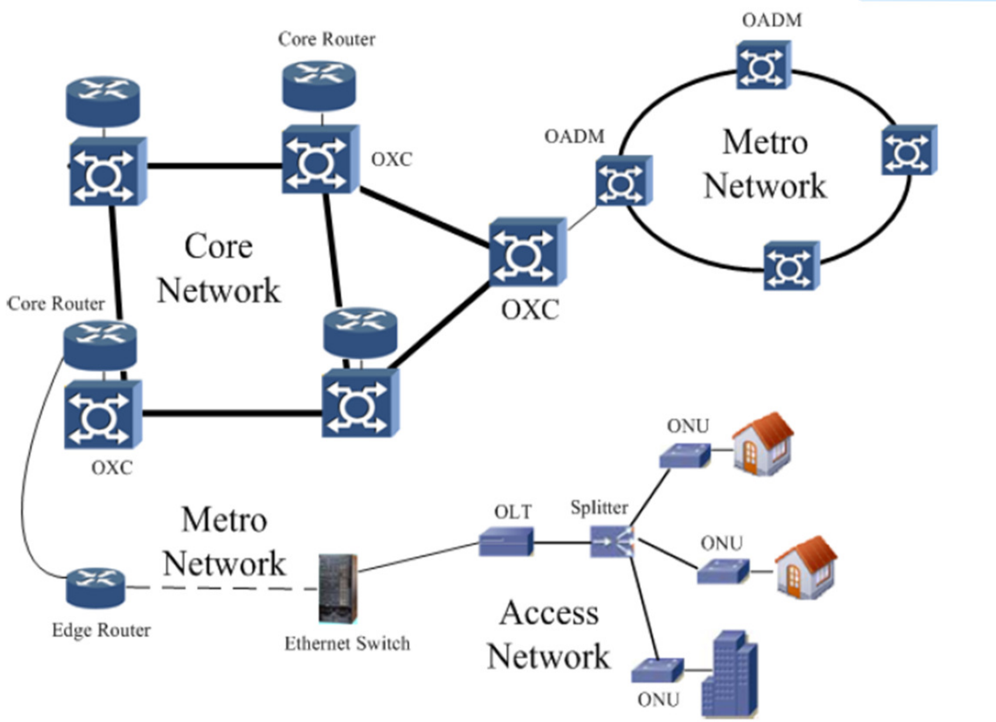
1) connect end-users to the Central Office (CO) of service provider (few kilometers)
2) Usually tree topology

- Metro networks:

1) Metropolitan region (tens or hundreds of kilometers)
2) Usually ring topology

- Core networks:

1) Nationwide or global coverage (thousands of kilometers)
2) Usually mesh topology



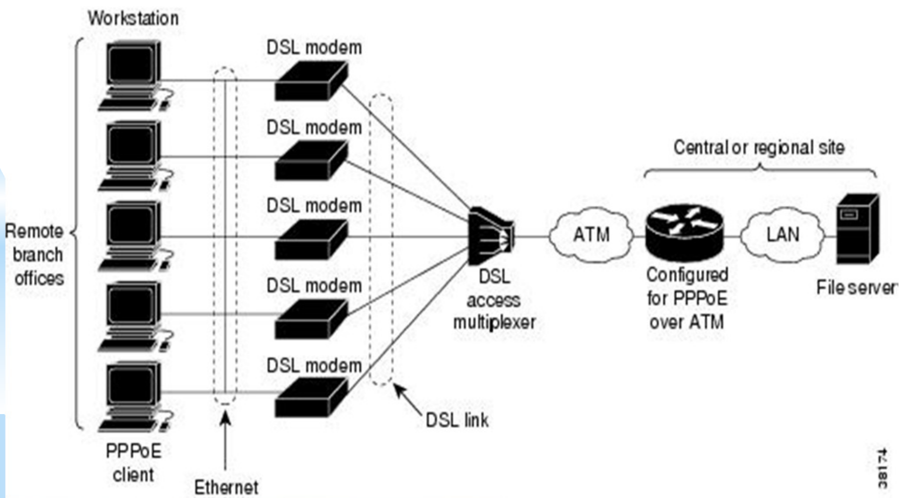
Access Ne

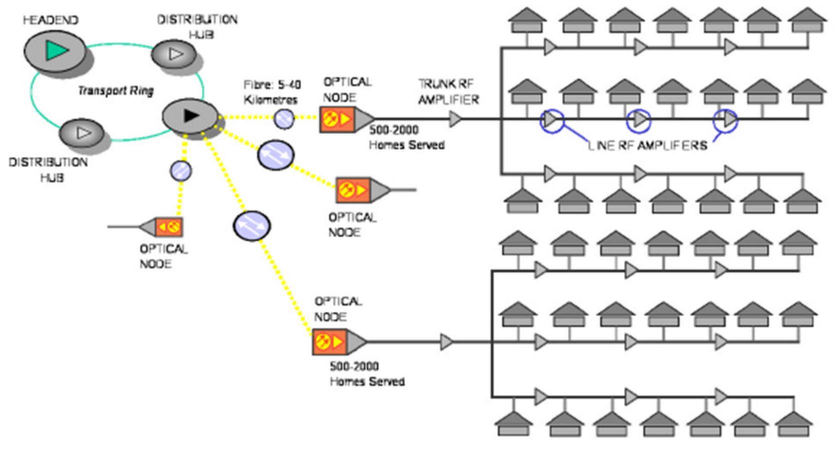
- "Last mile" of the telecom network → high impact on power consumption because of its ubiquity.

1) Wireless solutions: Wi-Fi, Wi-Max, LTE ...

2) Fiber To The Node (FTTN):

- xDSL (Digital Subscriber Line) use existing copper cable and include ADSL, ADSL2, ADSL2+, VDSL (26 Mbps), VDSL2 (250 Mbps), HDSL.
- HFC (Hybrid Fiber Coaxial) use fiber from CO to a Remote Node (RN) and coaxial fiber from node to end-user.





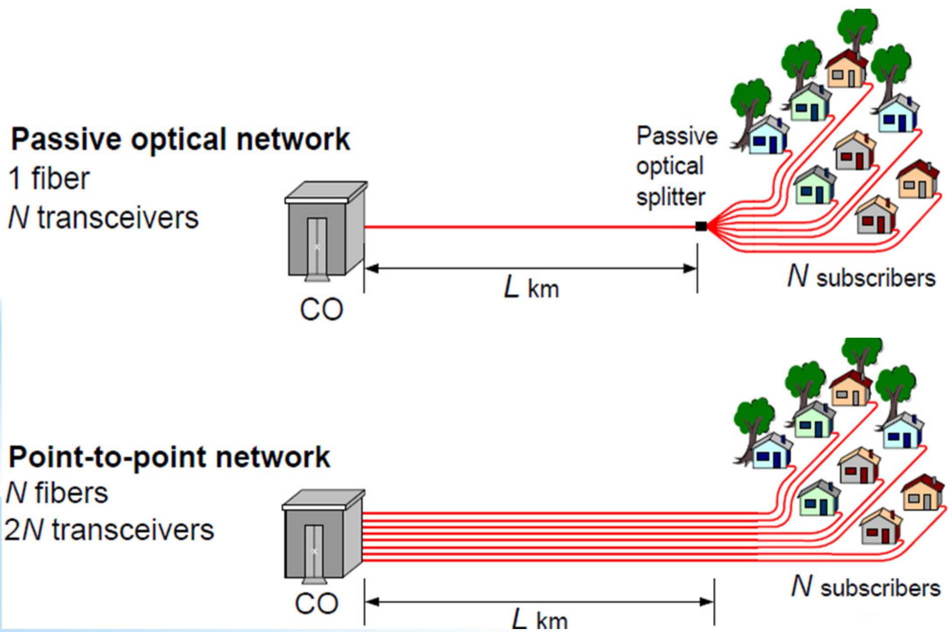
HFC network diagram

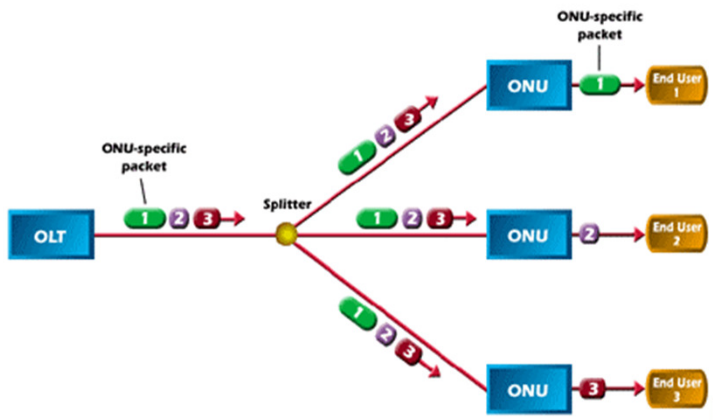
Access Ne

3) Fiber To The Home (FTTH):

- Passive Optical Networks (PON)
  - EPON (IEEE 802.3ah) and GPON (ITU-T G.984)
  - 10G-EPON (IEEE 802.3av) and XGPON (ITU-T G.987)
  - LR-PON (up to *100km*)

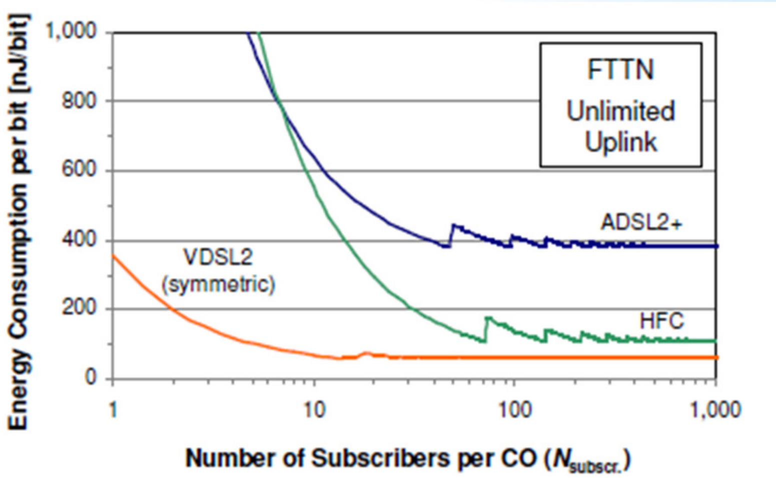
- Point-to-Point optical connection (1G, 10G).

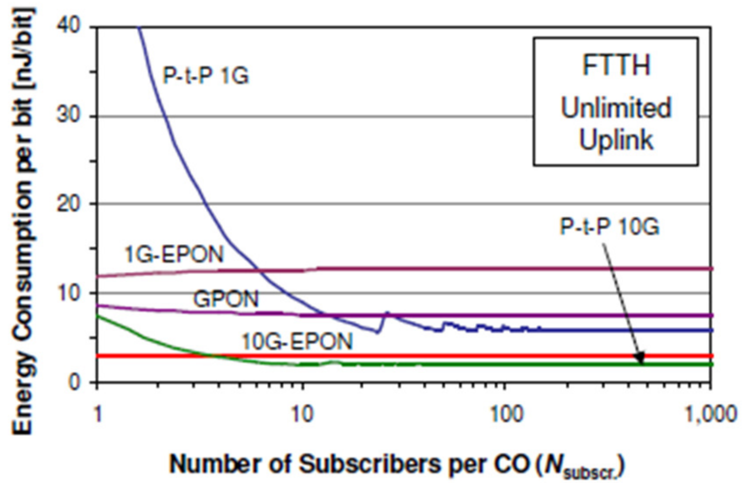




Access Ne

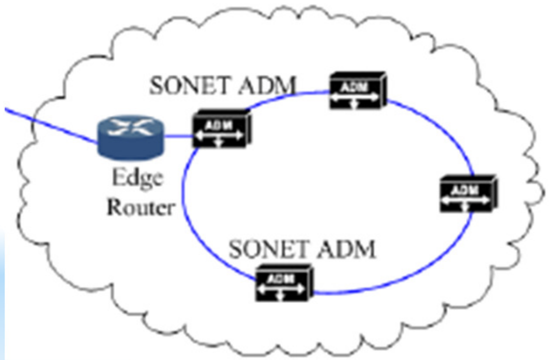
- VDSL2 is the most efficient FTTN solution
- FTTH solutions consume much less power than FTTN solutions
- PONs are the most efficient solution when the number of subscribers is low
- When the number of subscribers is high the point-to-point solutions are more efficient than PONs



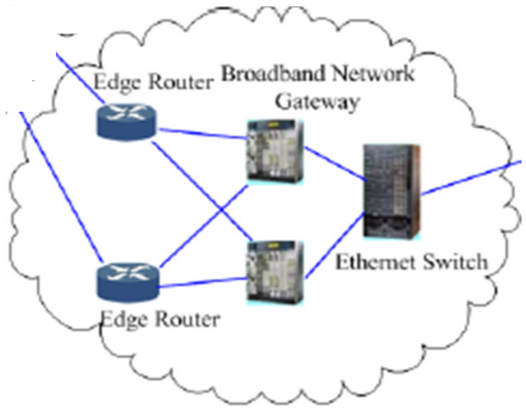


Metro Ne

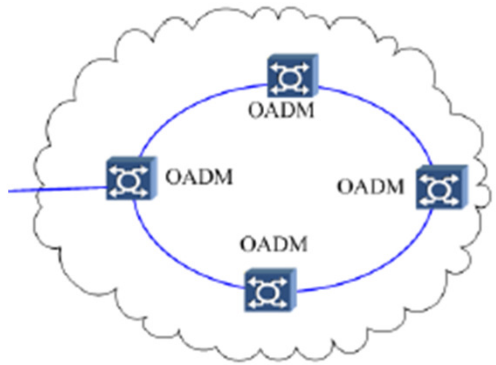
- SONET/SDH aggregate low-bit-rate traffic flows into high-bandwidth optical pipes using SONET/SDH ADMs (Add and Drop Mux).
- Metro Ethernet Layer 2 or/and Layer 3 Ethernet switches or/and routers connected through optical fiber
- Optical WDM Ring employs OADMs (Optical Add and Drop Mux) to add and drop optical signals directly in the optical domain.



SONET/SDH



Metro Ehternet



Optical WDM Ring

Metro Ne

- Power consumption:
  - SONET ADM (Ciena CN 3600 Intelligent Multiservice switch 2100 W
  - Ethernet switch (Cisco Catalyst 6513 switch) 3210 W
  - OADM (Ciena Select OADM) 450 W

Ciena CN 3600

Cisco Catalyst 6513

Ciena Select OADM

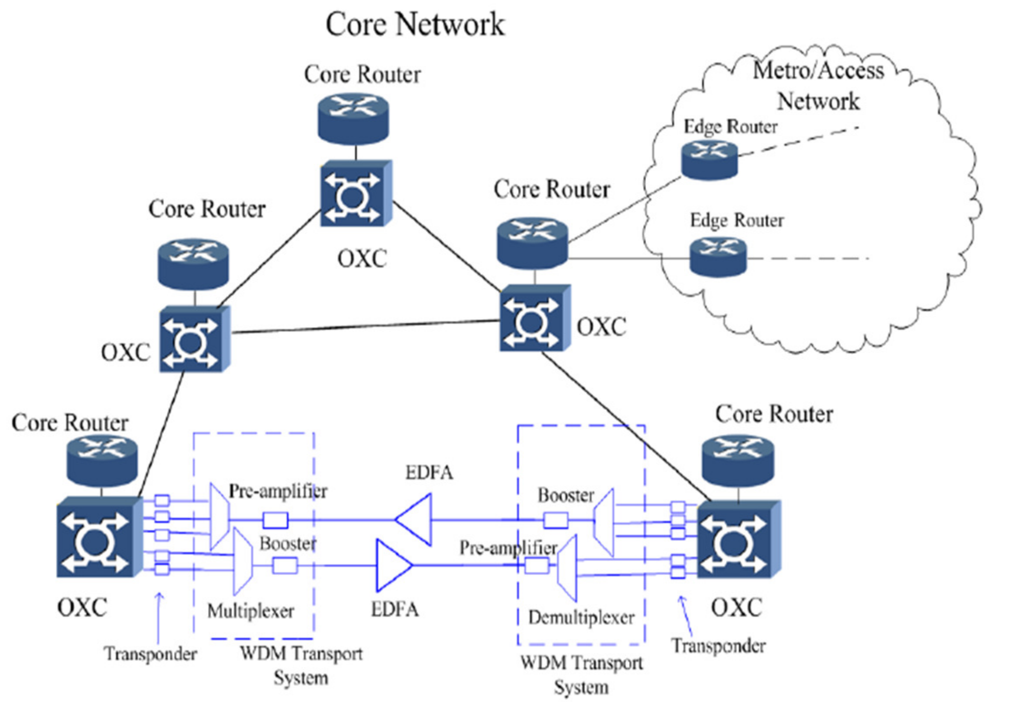
Optical WDM Ring: is expected to have the highest power efficiency

Core Netw

- High impact on power consumption because it carries capacity of several tens or hundred of Tbps.

- IP over DWDM (Dense Wavelength Division Multiplexing):

➔ DWDM: the optical fiber is divided into multiple independent wavelength channels.
➔ Today up to 96 wavelength channels per fiber. Each channel run at 40 Gbps (soon 100 Gbps).
➔ Overlay model: IP layer and optical layer.
➔ Control plane (e.g. MPLS) to integrate IP and optical layers.

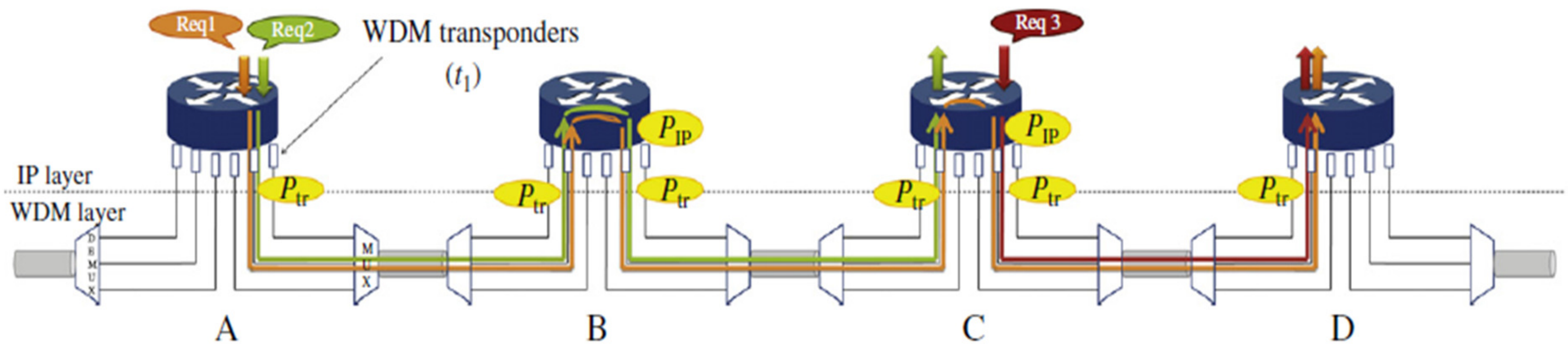


IP over D

Traditional IP over WDM implementations rely on electronic nodes.

- Transmission in the optical domain
- Switching and control information processing in the electronic domain
- Data are O/E/O converted at each node along the path

➔ The optical layer provides lightpath (high capacity optical pipes)
➔ The IP layer performs routing and forwarding decisions
➔ Traffic grooming: many low bit-rate flows are multiplexed on the same lightpath



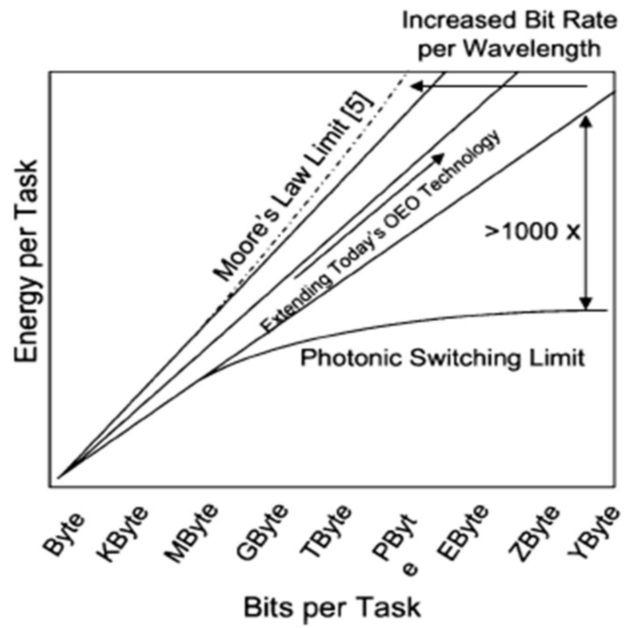
Electronic

Advantages:

- High performance (negligible data losses using efficient scheduling algorithms)
- High bandwidth utilization (statistical mux)
- QoS and traffic engineering policies

Drawback:

- Power consumption (up to 1 MW per node)
- Low scalability (power consumption increases linearly with the bit-rate)



To decrease power consumption → Optical switching solutions

Optical switching:

- Transmission and switching in the optical domain
- Control information processing in the electronic domain

Optical S

Advantages:

- Low power consumption
- High scalability
- No need for O/E/O conversion in the core network

Drawbacks:

- Lack of optical buffering solutions (No optical RAMs)

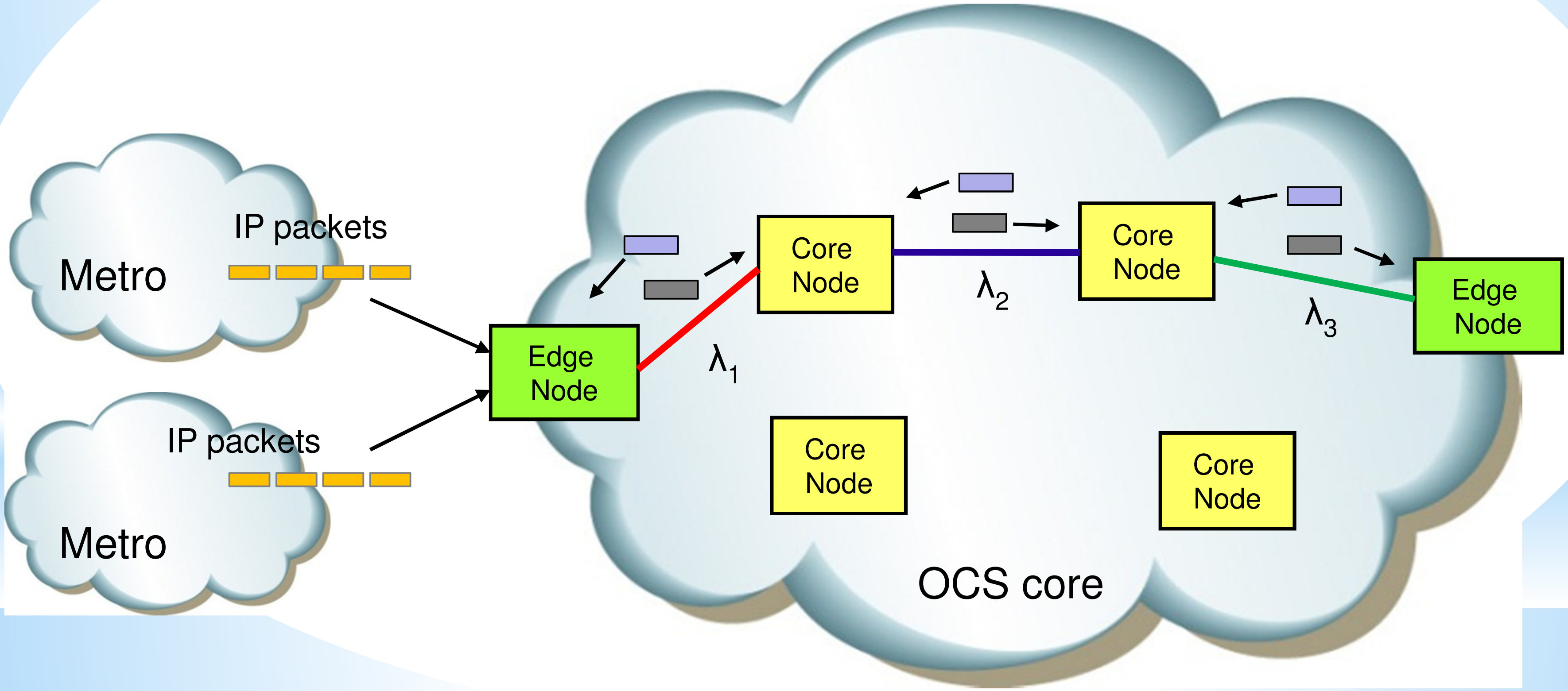
Fiber Delay Lines (FDLs):

➔ Data cannot be accessed at any time but only after fixed intervals
➔ Large physical size that limits the storage capacity (for 10 Gb → 50000 km)

- Lower performance (non negligible data losses)
- Difficult to implement QoS and traffic engineering policies

Optical Ci

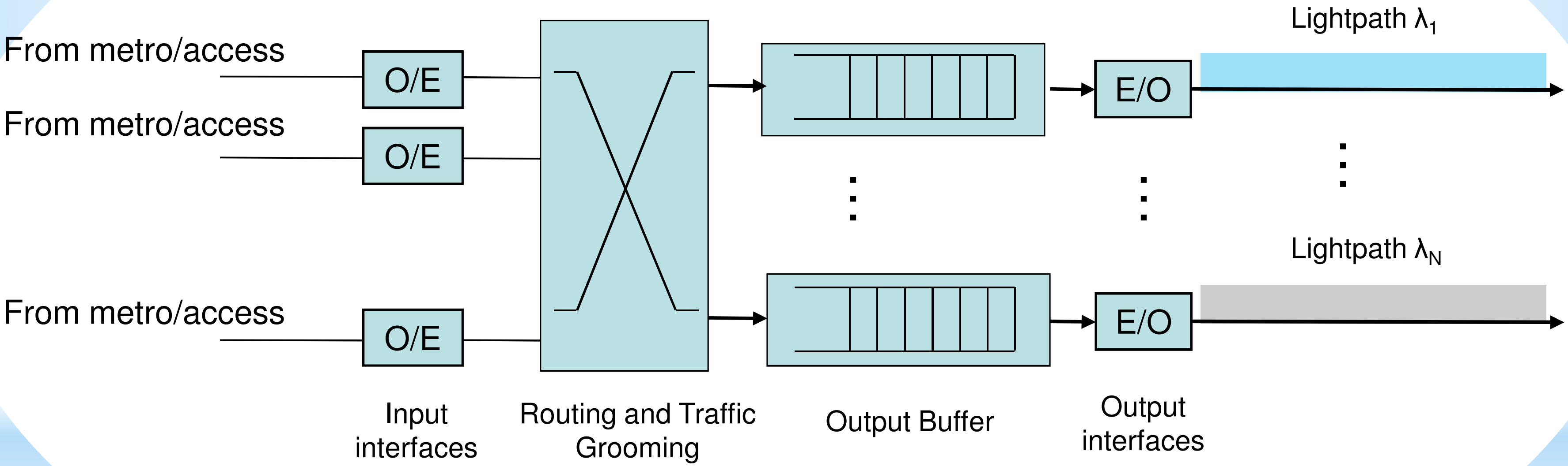
- Edge node: located at the periphery of the network are used to connect to metro/access networks
- Core node: route data from ingress to egress edge nodes
- Two-way reservation mechanism: control packet sent on dedicated control channels



Optical Ci

Edge node architecture:

- Data are buffered until the lightpath has been established
- If the lightpath establishment fails no data is lost



Optical Ci

Advantages:

- ✓ High reliability: based on mature optical technology
- ✓ Low power consumption: using slow optical switches (MEMS)
- ✓ Fits large and stable traffic flows: suitable for multimedia applications

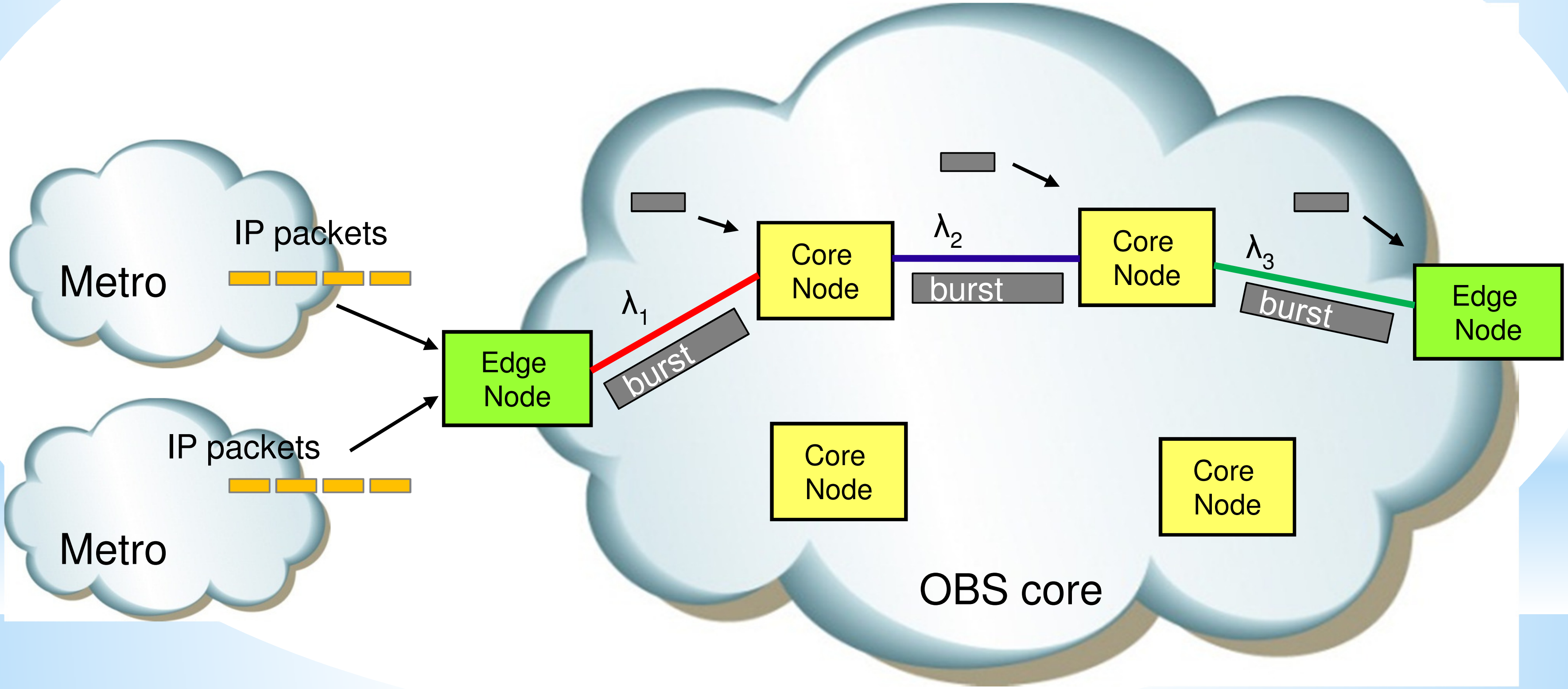
Drawbacks:

- ✗ Low bandwidth utilization with bursty source: not suitable for short and high variable traffic
- ✗ Low network flexibility: not easily adaptable to new applications services

- Today:
  Optical Bypass ⇨ integrates electronic switching and OCS

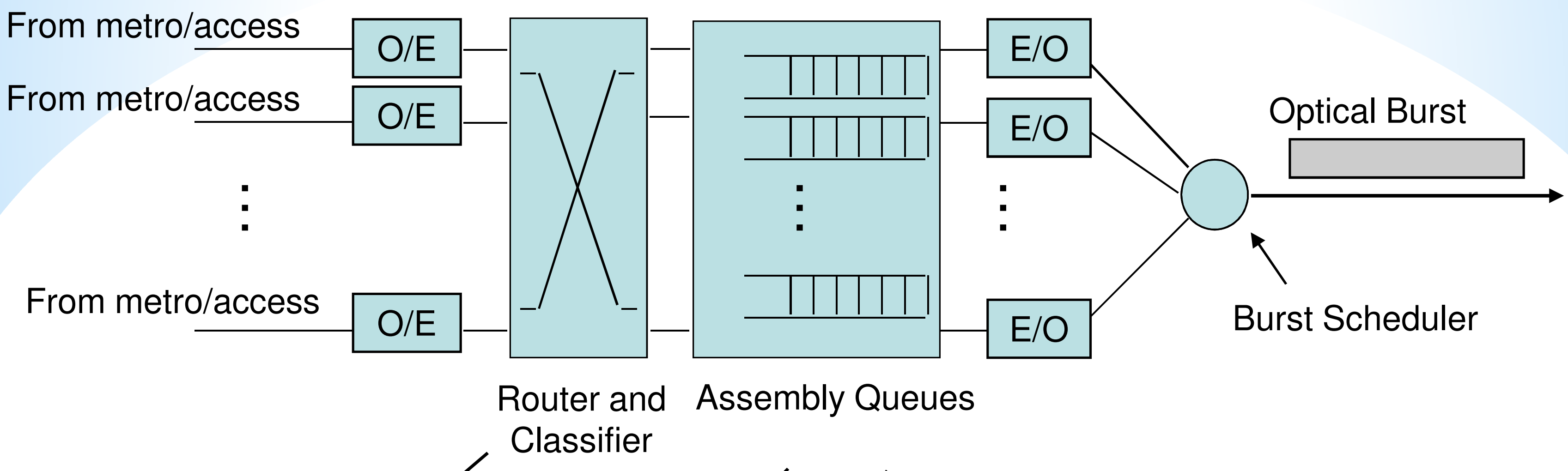
Optical B

- Data are gathered at the edge node and assembled into bursts
- One-way reservation mechanism:
  - control packet sent on dedicated control channels
  - burst sent after a fixed delay (offset-time)



Optical B

Edge node architecture:



Select the assembly queue:

1) Destination node
2) Class of service

Queue discipline:

1) Per flow
2) Mixed flow

Assembly algorithms:

1) Timer based
2) Length based
3) Mixed timer/length

Optical B

- Reservation mechanisms:
  1) **Just-In-Time (JIT)** immediate setup and explicit release
  2) **Just-Enough-Time (JET)** delayed setup and implicit release

- Contention resolution techniques:
  1) Time domain -> use optical buffers (FDLs)
  2) Wavelength domain -> use all-optical wavelength converters
  3) Space domain -> data is transmitted over an alternative route (deflection routing)
  4) Segmentation -> only the conflicting part of the burst is dropped

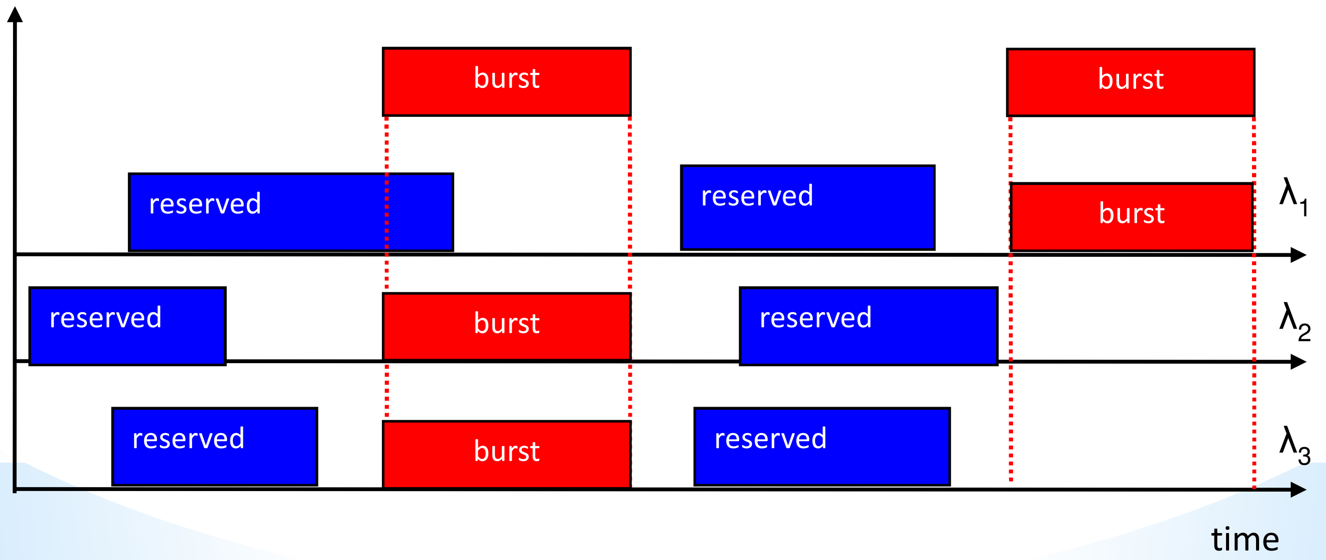
Optical B

- Using JET the core nodes must implement burst scheduling
- Trade-off: efficiency VS processing time
- Scheduling algorithms:

1) Horizon

2) First-Fit Unscheduled Channel with Void Filling (FFUC-VF)

3) Best-Fit with void filling (BF-VF)



Optical B

Advantages:

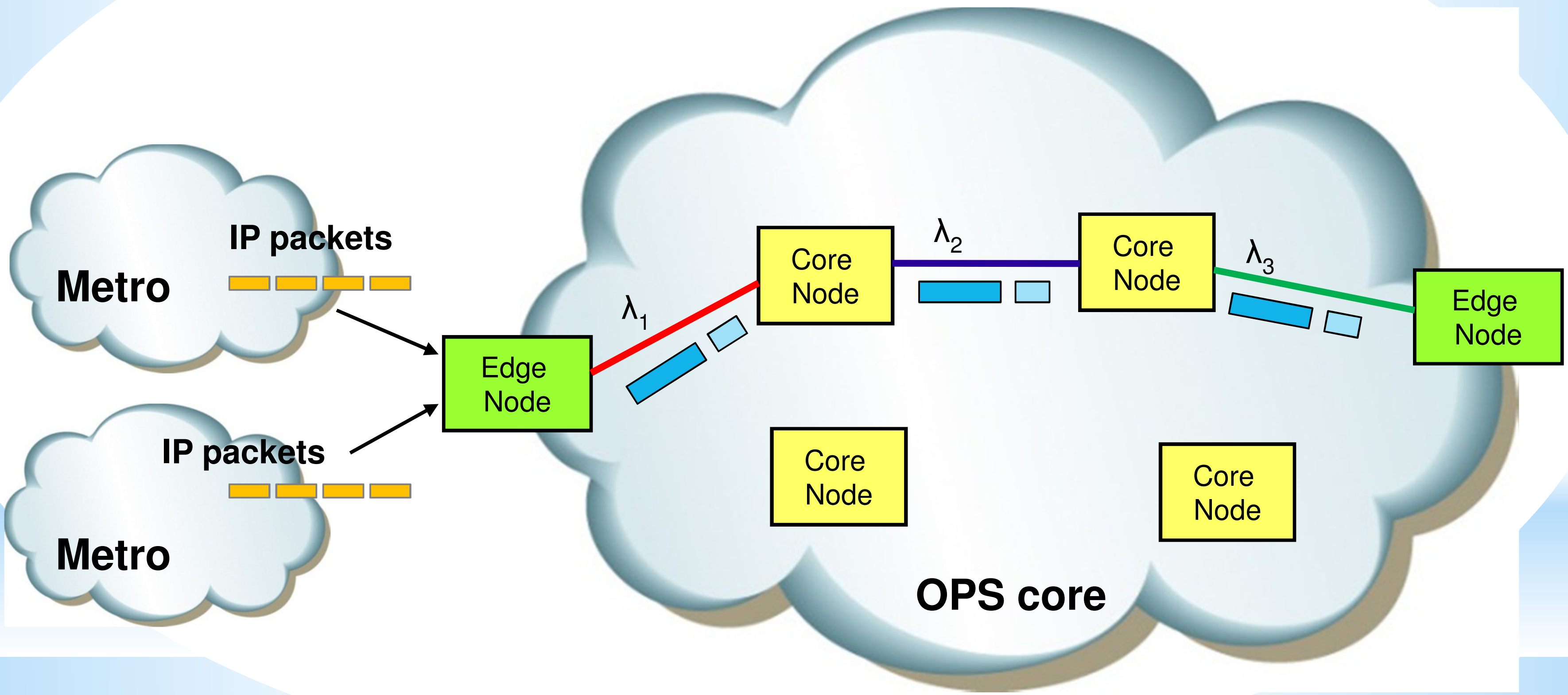
- ✓ High bandwidth utilization (statistical multiplexing)
- ✓ No need for optical buffers (FDLs)
- ✓ Low power consumption

Drawbacks:

- ✗ High burst blocking probability, that can be solved only with expensive and power consuming techniques
- ✗ High complexity of the control logic

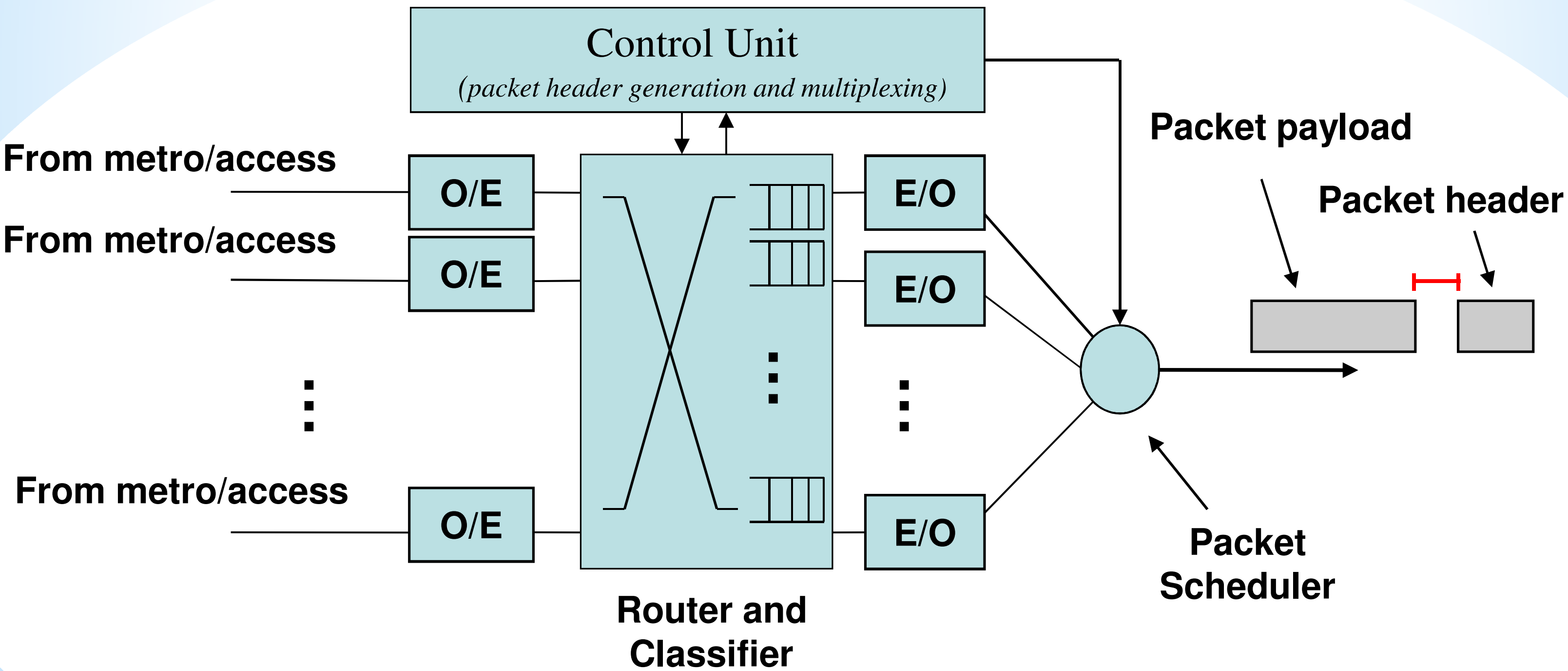
Optical Pa

- The resources are reserved on-the-fly using the optical packet header
- Packet header and payload are separated by a time guard



Optical Pa

Edge node architecture:



Optical Pa

d

Advantages:

- ✓ Very high bandwidth utilization (statistical multiplexing)
- ✓ High network flexibility (suites perfectly IP data traffic)

Drawbacks:

- ✗ Need for optical buffers (FDLs)
- ✗ Based on immature and expensive optical components

Hybrid Op

- Integrates on the same network: ***OCS*** + ***OBS and/or OPS***
- Large and stable traffic flows (e.g. multimedia traffic) are carried over circuits or long bursts
- Short and dynamic traffic flows (e.g. IP data traffic) are carried over packets or short bursts

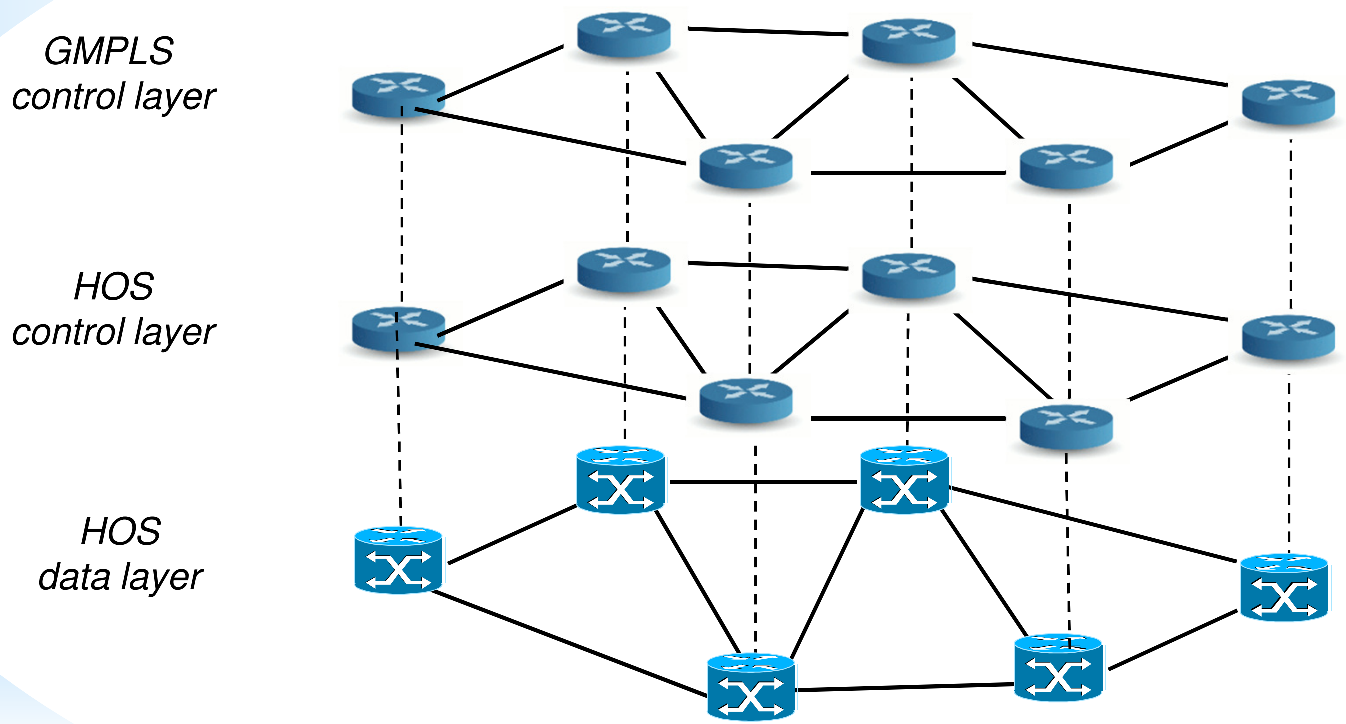
✓ High bandwidth utilization -> packets/bursts can fill unused slots of circuits with the same destination

✓ Low power consumption -> using hybrid switches that combine slow switching elements for circuits/long bursts and fast switching elements for packets/short bursts

✓ High network flexibility -> each new application or service can be served using the more suitable switching scheme for it

Hybrid O

- Network overlay model:



GMPLS

- Generalized Multiprotocol Label Switching (GMPLS): set of protocol for routing, signaling and link management
- Routing:

➔ Exchange routing informations among the nodes
➔ Protocols: OSPF or IS-IS with Traffic Engineering (TE) extension
➔ OSPF-TE: collect info about the links state and usage (in terms of bit/s), and flood the info using the Link State Advertisements (LSA)

- Signaling:

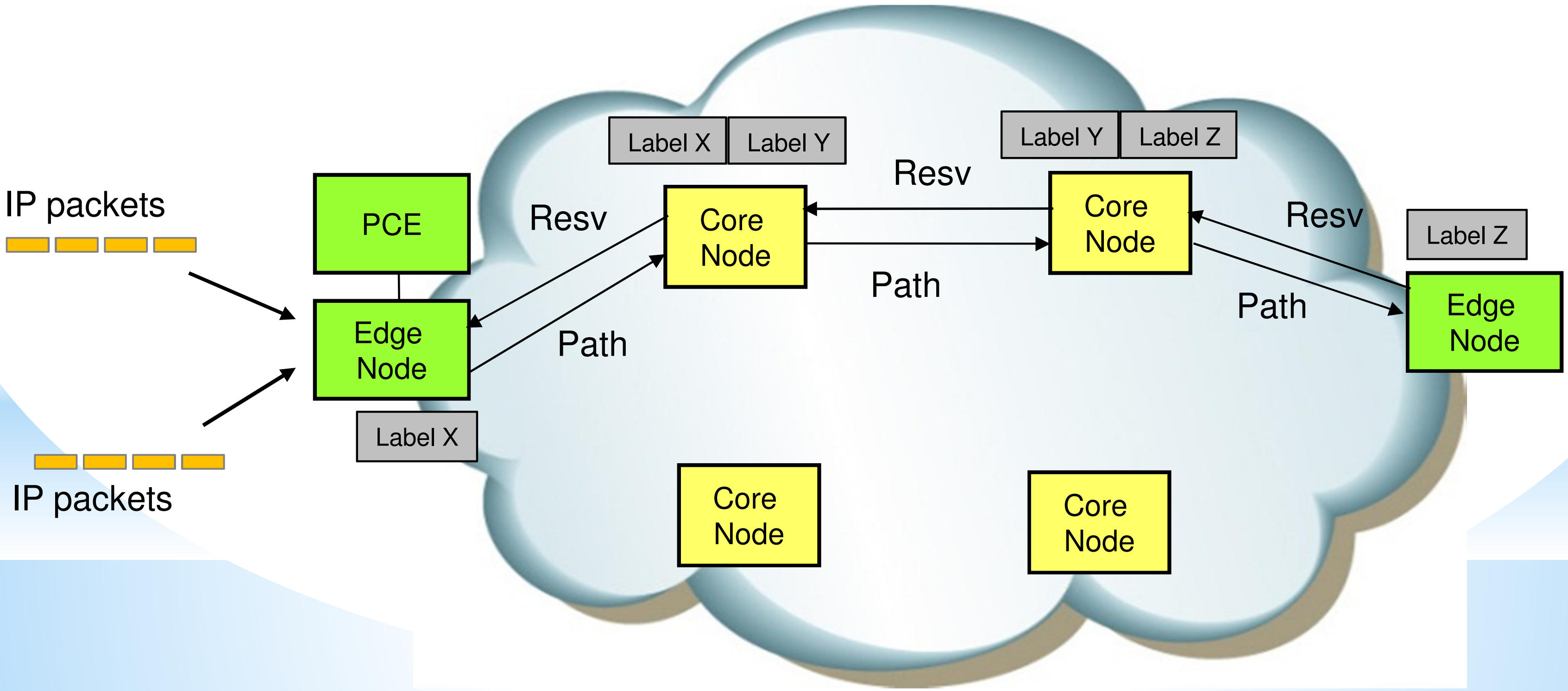
➔ Establishes and maintains the Label Switched Paths (LSP)
➔ Protocols: RSVP with TE extension or CR-LDP

- Link Management:

➔ Link provisioning, fault isolation, maintenance of the associations between link and labels
➔Protocols: LMP

GMPLS

- The edge node performs IP lookup and assigns each packet to a Forwarding Equivalence Class (FEC)
- Path Computation Engine (PCE) determines the path toward the destination basing on the information collected by the routing protocol
- If a LSP toward the destination exists and has enough bandwidth, data is transmitted through this LSP; Otherwise a new LSP is created using the signaling protocol (es. RSVP-TE)



HOS Cont

- The HOS control plane performs resource reservation and data scheduling
  - Circuits:
    - Two-way reservation mechanism
    - High priority
  - Bursts:
    - One-way reservation mechanism (JIT or JET)
    - Scheduling algorithm (Horizon, FFUC-VF, BF-VF)
    - Different level of priority basing on the offset time
  - Packets:
    - Best effort
    - Core nodes can fill unused slots of circuits with optical packets with the same destination
- Coding technique: in-band or out-of-band reservation mechanism

Electronic

Juniper T series
TX Matrix Plus
6.4 Tbps

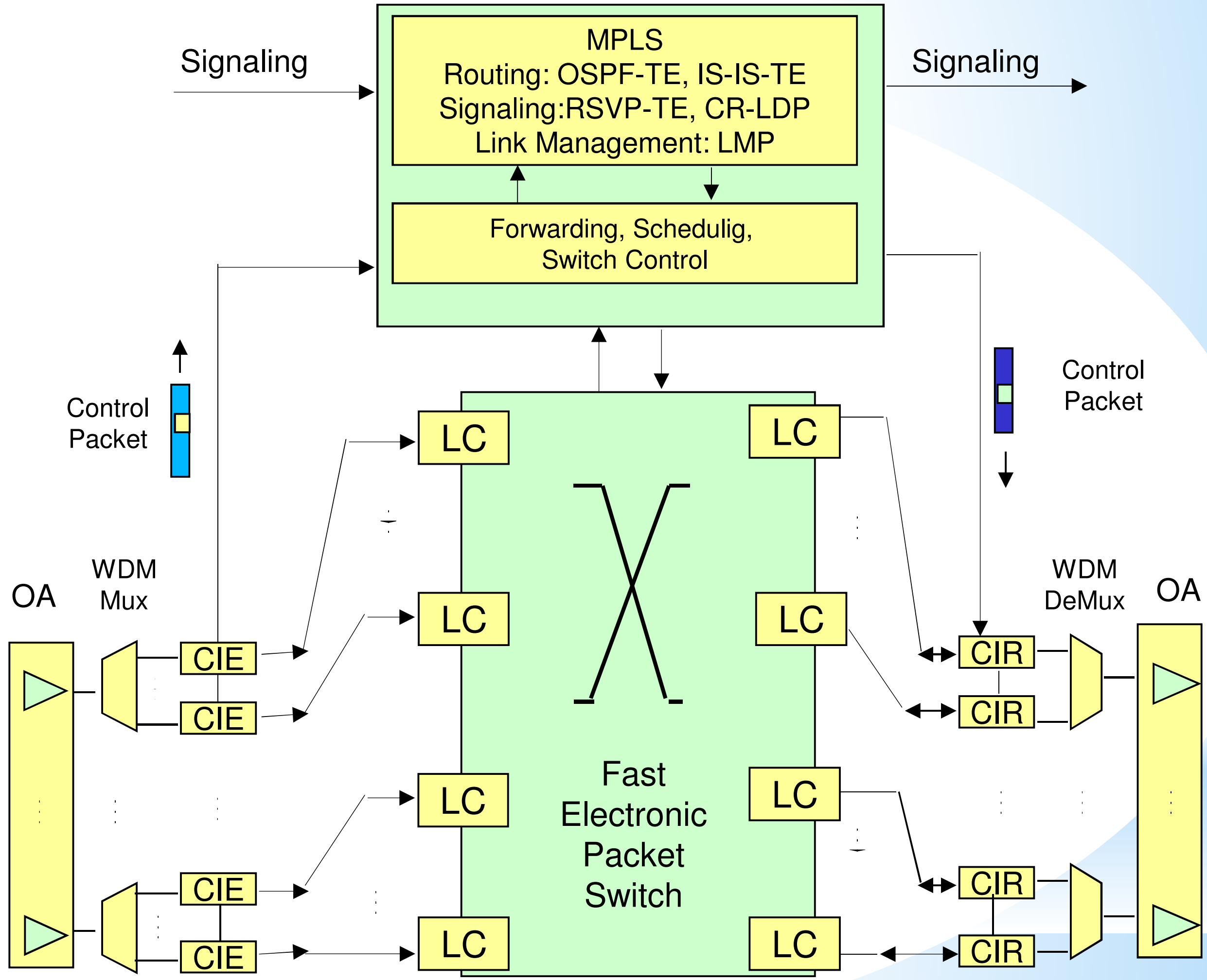
Alcatel-Lucent
1870 Transport Tera Switch
8 Tbps

Cisco CRS (Carrier Routing System) - 3
Up to 322 Tbps

“The Cisco CRS-3 triples the capacity of its predecessor, the Cisco CRS-1 Carrier Routing System, with up to 322 Terabits per second, which enables the entire printed collection of the Library of Congress to be downloaded in just over one second; every man, woman and child in China to make a video call, simultaneously; and every motion picture ever created to be streamed in less than four minutes”

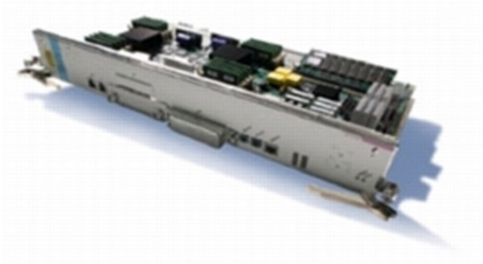
Electronic r

- Building blocks:
  - Control logic
  - Switching fabric
  - Optical WDM interface



Electronic

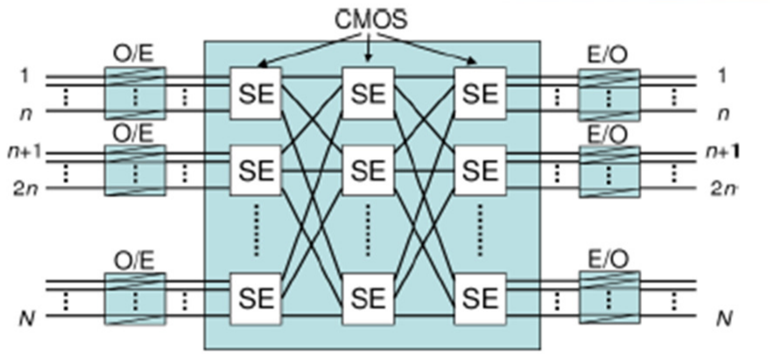
- Control logic:
  - ➔ MPLS control plane functionalities
    - ▪ Off-line operation: Routing (OSPF-TE, IS-IS-TE), Signaling (RSVP-TE, CR-LDP), Link Management (LMP)
    - ▪ On-line operation: label processing, table lookup and forwarding
  - ➔ Switch control
    - ▪ Setup the path through switch
  - ➔ Route processor card
    - ▪ One route processor card every 16 wavelength channels



Cisco CRS-1 16-Slot Line Card Chassis Route Processor

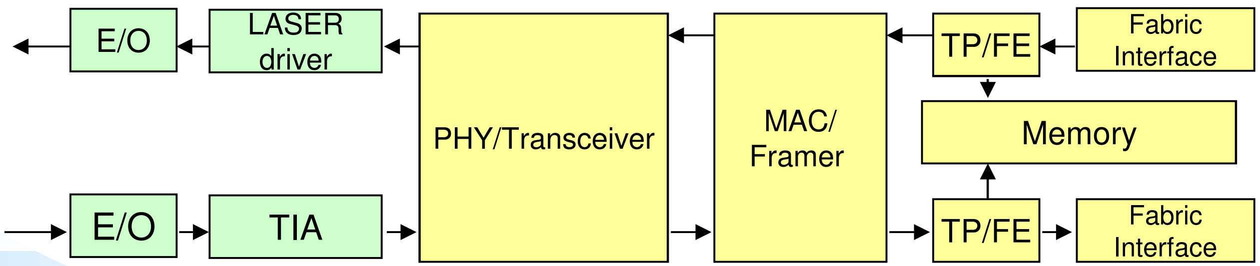
Electronic

- Switching Fabric:
  - Fast CMOS-based electronic switch
    - Switching time in the order of nanoseconds
    - Multi-stage architecture



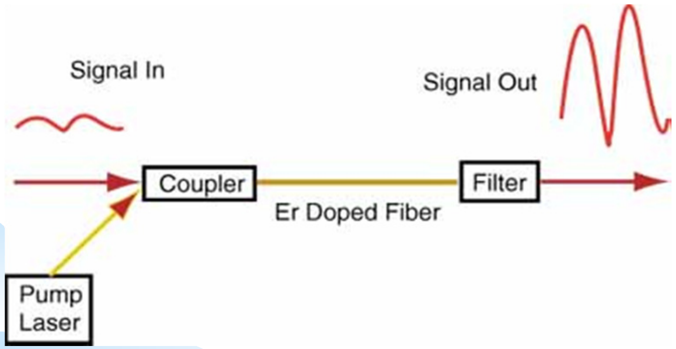
- Electronic line card

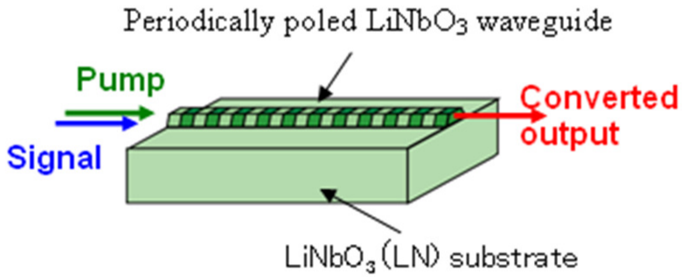
WDM transceivers, PHY (physical layer) devices, framers/mappers, MAC chips, a traffic processor/forwarding, engine (TP/FE), memory devices, and fabric interfaces.



Optical WD

- WDM channel multiplexer and demultiplexer
- Optical amplifiers (OA)
  - Two optical amplifiers per fiber channel
  - Compensate the loss introduced by the core node
  - Erbium Doped Fiber Amplifier (EDFA)
- Control information extraction and re-insertion (CIE/R)
- Tunable Wavelength Converter (TWC)
  - One TWC per wavelength channel



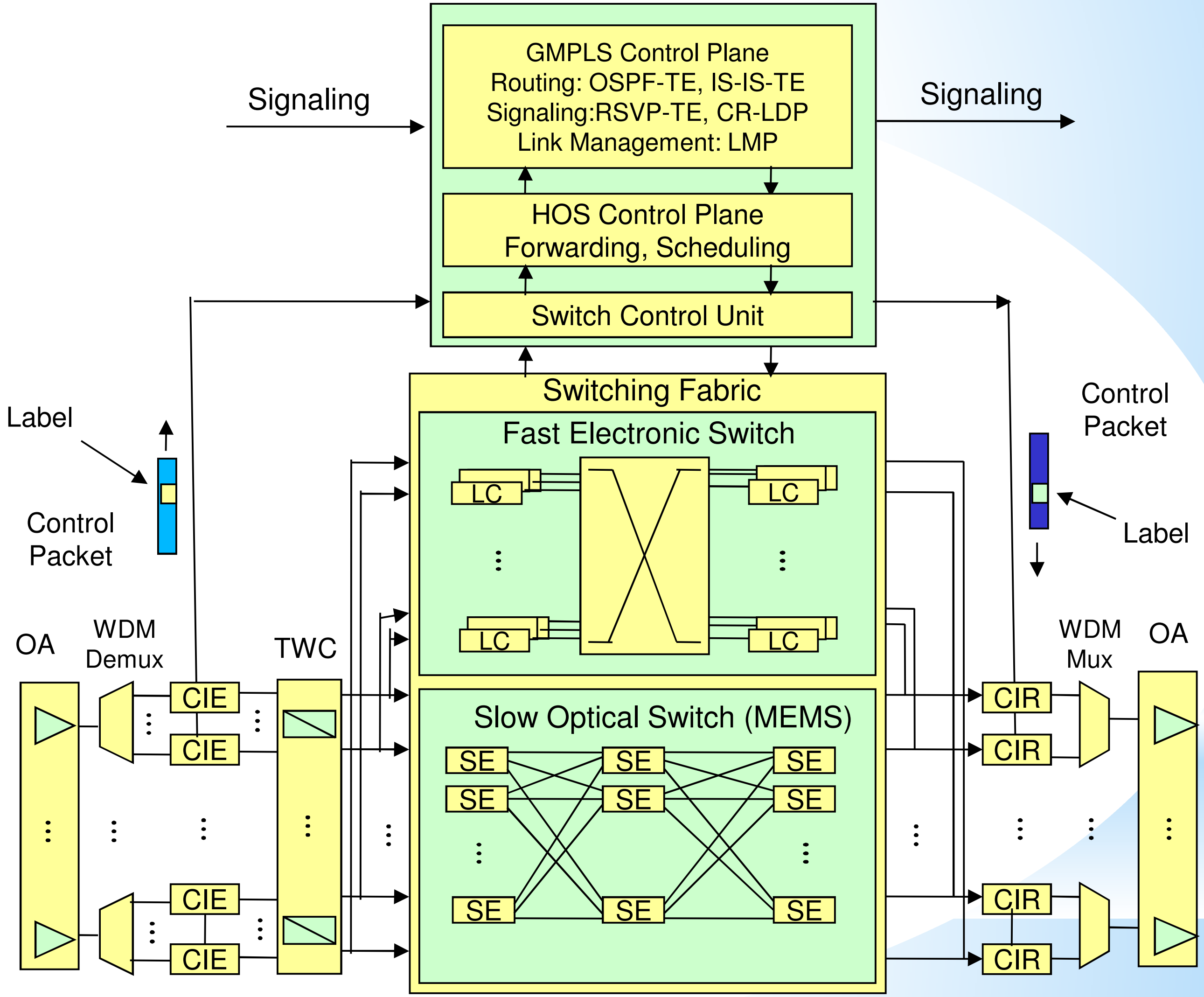


Hybrid node

- Building blocks:
  - Control logic
  - Switching fabric
  - Optical WDM interface

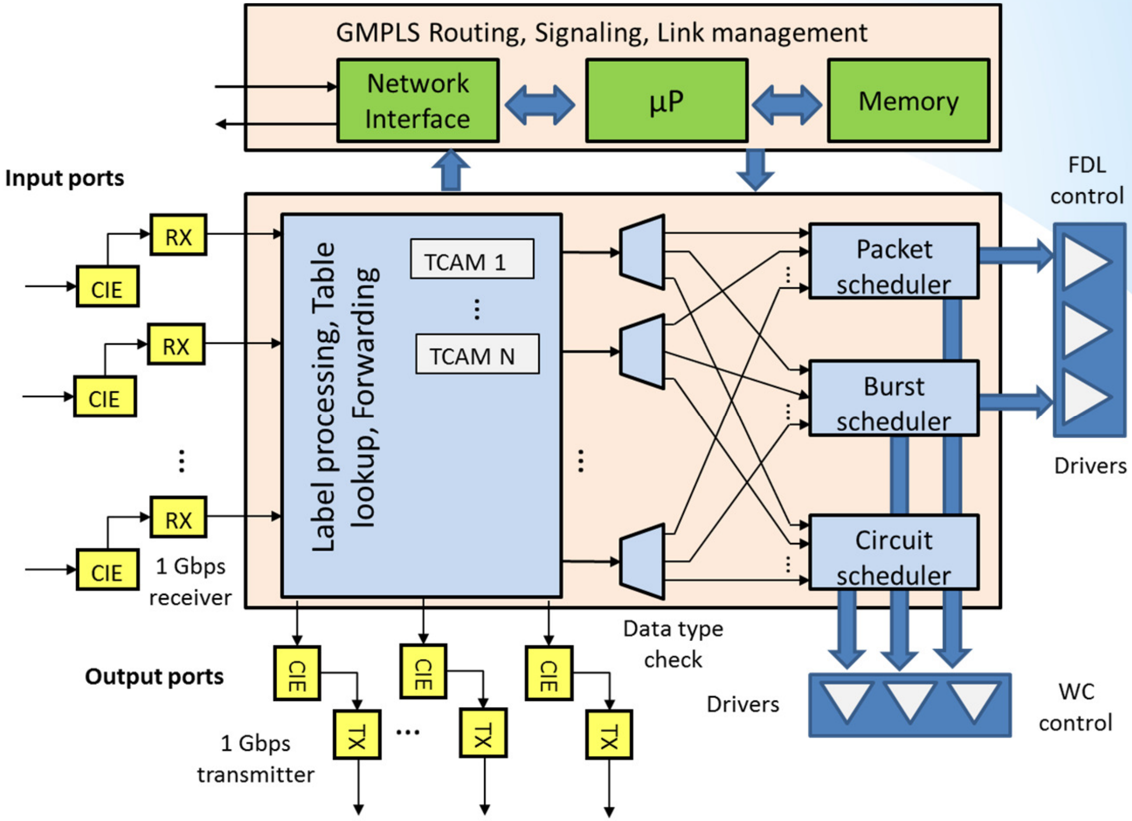
- Switching fabric:
  - Slow optical switch
  - Fast electronic switch

- Tunable Wavelength Converter (TWC)



Hybrid node

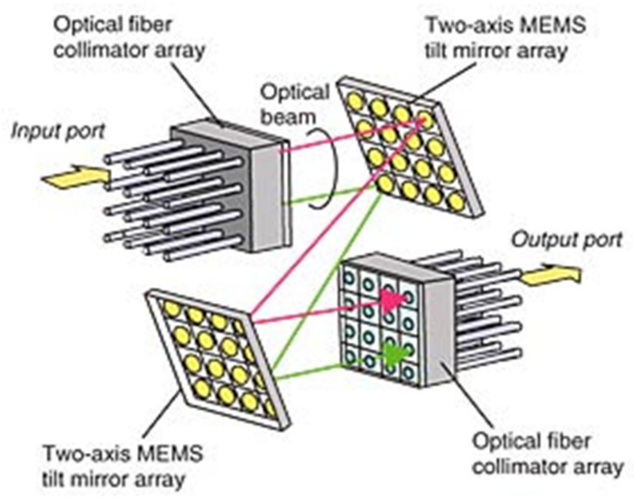
- GMPLS control plane:
  - Off-line operation
  - On-line operation
- Scheduler:
  - Large programmable logic device (FPGA)
- Search engine:
  - Ternary content addressable memory (TCAM)



- Switch control
  - Setup the path through either the slow optical switch or the fast electronic switch

Hybrid node

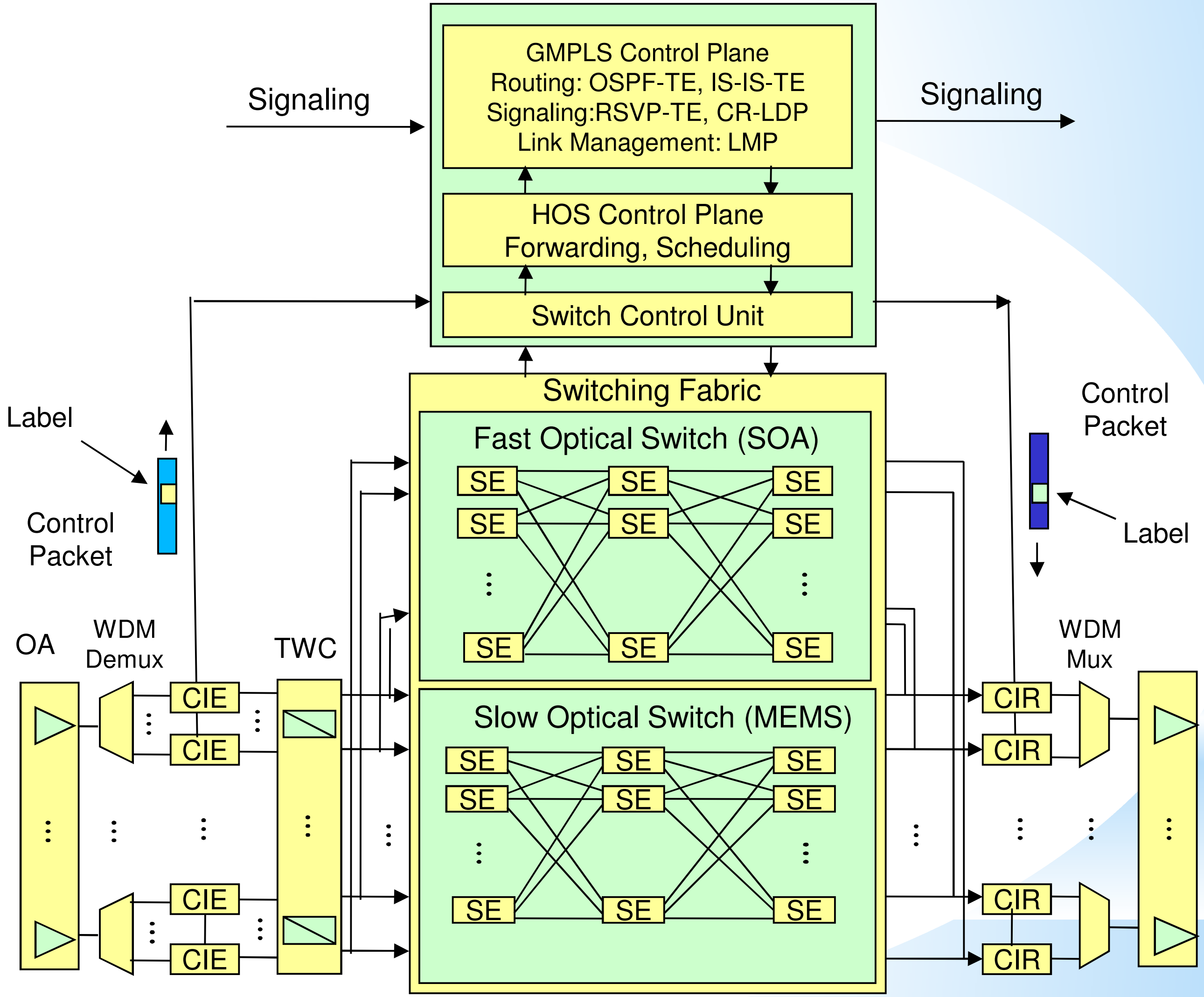
- Switching fabric:
  - The fast electronic switch is used to forward packets and short bursts
  - The slow optical switch is used to forward circuits and long bursts
  - MEMS – Micro electro-mechanical systems
    - Miniature movable mirrors made in silicon
    - Transmit or deflect optical signal depending on the position
  - Why MEMS:
    - It is possible to build switching fabrics of large size (up to 1000×1000)
    - Low power consumption
  - Drawback of MEMS:
    - Switching time is in the order of milliseconds



Optical node

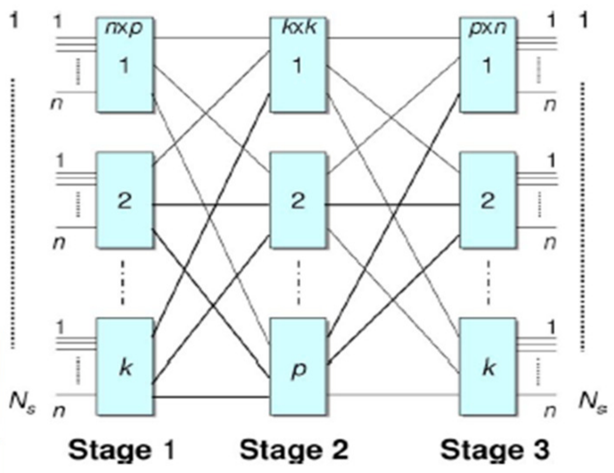
- Building blocks:
  - Control logic
  - Switching fabric
  - Optical WDM interface

- Control logic:
  - The scheduler relies on optical buffers



Optical nod

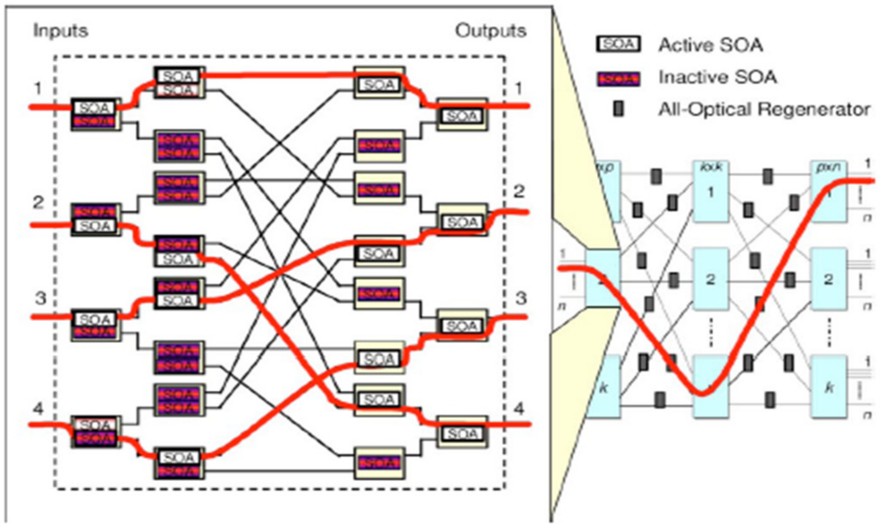
- Switching fabric:
  - The slow optical switch is used to forward circuits and long bursts
  - The fast optical switch is used to forward packets and short bursts
  - SOA – Semiconductor Optical Amplifiers
    - Switching capacity in the order of nanoseconds
  - Drawback of SOAs →small size
    - SOA must be organized in complex multi-stages networks



- Three-stages Clos network
  - Each element of one stage is connected to each element of the next stage
  - Strictly non-blocking if: p ≥ 2n - 1

Optical nod

- Each element of the Clos network is organized in a Spanke architecture
- Each element of the Spanke network is a 1×2 SOA switch



- This architecture require also:
  - 1 Temperature Stabilization Circuit (TEC) every switching elements of the Clos network (Total number of TECs: 2k+p)
  - 1 3R-Regenerator after 9 SOAs (OSNR > -20 dB)

Power Cons

- Consider a core node with N input/output fibers and W wavelengths per fiber
- Power consumption of the core node P_{Node} :

$$P_{Node} = P_{CL} + P_{SF} + P_{OI}$$

P_{CL} = Power consumption of the control logic
P_{SF} = Power consumption of switching fabric
P_{OI} = Power consumption of the optical WDM interface

Control logic

- Electronic

$$P_{CL} = \frac{N \cdot W}{16} \cdot P_{RP}$$

P_{RP} = Power consumption a route processor card = 200 W

- Hybrid and Optical:

$$P_{CL} = P_{GMPLS} + P_{Scheduler} + N \cdot W \cdot P_{Transceiver}$$

$P_{Scheduler}$ = One large programmable logic device (FPGA) per data type = 40 W
$P_{Transceiver}$ = Long reach WDM transceiver = 1.25 W

$$P_{CL} = P_{Offline} + N \cdot P_{online} + N \cdot W \cdot P_{SearchEngine}$$

$P_{Offline}$ = Microprocessor, network interface, DRMA = 150 W
P_{Online} = Large programmable logic device (FPGA) = 40 W
$P_{SearchEngine}$ = Ternary Content Addressable Memory (TCAM) = 4.5 W

Switching F

- Electronic SF

$$P_{SFperPort} = P_{LC} + P_{Switch}$$

P_{LC} = Power consumption of a line card = 298.3 W
P_{Switch} = Power consumption of the CMOS switch per port = 8 W

- MEMS:

$$P_{SFperPort} = P_{MEMS}$$

P_{MEMS} = Power consumption of a 3D MEMS = 0.1 W

- SOA:

$$P_{SFperPort} = N_{SOA} \cdot P_{SOA} + N_{TEC} \cdot P_{TEC} + N_{3Rreg} \cdot P_{3Rreg}$$

$P_{SFperPort}$ = Power consumption of the SOA-based switch = 19.9 W

Optical Inte

$$P_{OI} = 2 \cdot N \cdot P_{OA} + N_{TWC} \cdot P_{TWC} + N \cdot W \cdot P_{CIE/R}$$

P_{OA} =Power consumption of an EDF optical amplifier = 14 W
P_{TWC} = Power consumption of an all-optical tunable wavelength converter = 1.69 W
$P_{CIE/R}$ = Power consumption of the control information extraction and re-insertion block = 17 W

→ WDM Mux and WDM Demux do not consume power