The Seventh Advanced International Conference
on Telecommunications

AICT 2011

March 20-25, 2011 - St. Maarten, The Netherlands Antilles

Tutorial 1
Optical Communications: Status and Trends

Prof. Dr. Djafar K. Mynbaev

City University of New York,

USA

Sunday, March 20

14:30 – 17:30 pm

Optical Communications: Status and Trends

Djafar K. Mynbaev
New York City College of Technology of the City University of New York
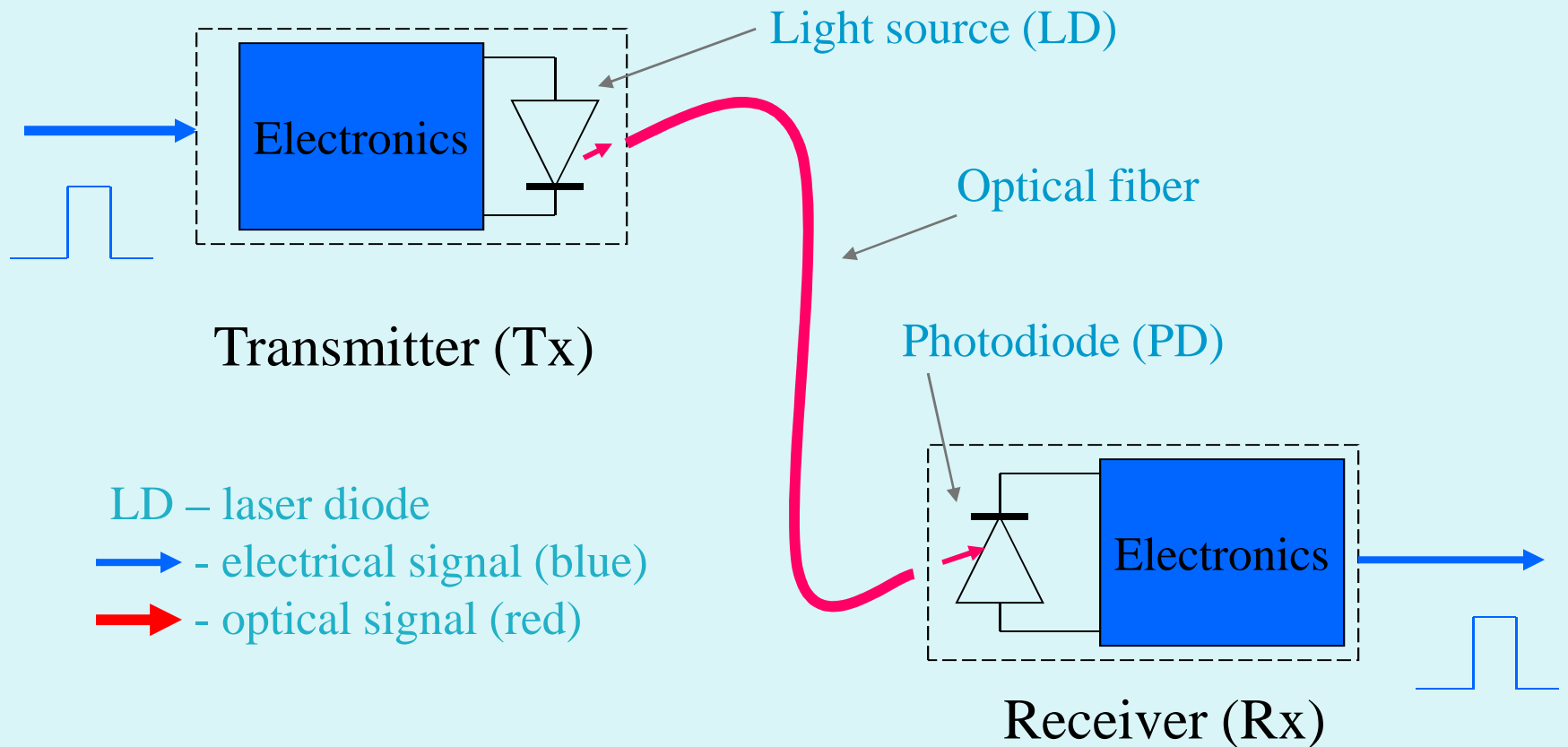dmynbaev@citytech.cuny.edu

Outline

- Where we are today – current status and problems of optical communications
  - In space, in time and in spectrum
  - Network and its components
  - PON
- Trends
  - Components
  - Networks
- Conclusion

Outline

- The goal of this tutorial is to picture the current status of optical communications, to stress its achievements and emphasize its needs and to discuss how the newest developments in in this field would help in solving the problems accumulated in optical communications:
  - To achieve this goal, I'll first present a brief review of the current status of optical communications by not reporting some specific results, but rather exhibiting a general picture that would—along with a better understanding of the situation in the field—stimulate some thoughts and new questions.
  - Second part of my tutorial will concentrate at the trends in the future developments in this filed from both component and network standpoints.
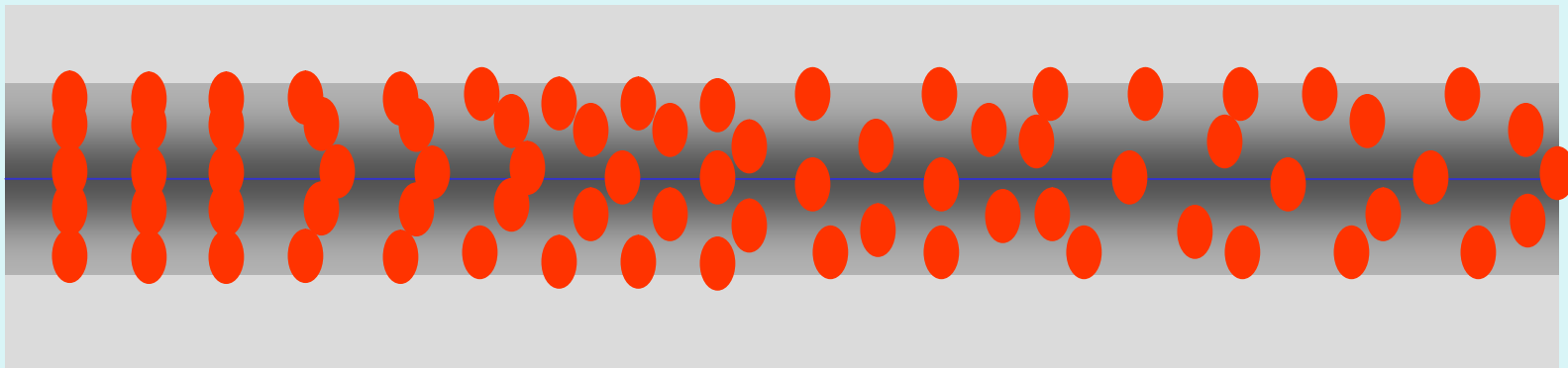
Optical communications

What it is - basic fiber-optic communications system (link)

Light source (LD)

Electronics

Optical fiber

Transmitter (Tx)

Photodiode (PD)

Electronics

LD – laser diode
- electrical signal (blue)
- optical signal (red)

Receiver (Rx)

Optical communications

- Comment 1 on the block diagram:
  - Tx – transmitter; in general, Tx is a device that allows launching an electrical signal into an optical waveguide.
  - Optical fiber; in general, an optical waveguide, a conductor of an optical signal.
  - Rx – receiver; in general, Rx is a device that allows for extracting information from an optical conductor in a suitable form.
- Comment 2:
  - The goal is delivering information, not light. Here the light is delivered, but information is not!

0 1 0 1 0 1 0 1 0 1 0 1 ? ? ? ? ? ? ? ? ? ? ? ? ➔ High DMD = High ISI

Optical communications, telecommunications and electronics

- Optical communications is the linchpin of the telecommunications industry: The vast majority (by some estimates > 98%) of global telecommunications traffic in the Untied States and in other developed countries today is delivered optically. Why?

- Two speeds: Propagation speed and transmission speeds:
  - Propagation speed becomes the area of interest today as related to optical interconnects.
  - Transmission speed (capacity, or bandwidth) is proportional to the frequency of a carrier, f_C. Light has the highest f_C (hundreds of THz) among practical signal carriers ➜ Optical communications systems can achieve the highest transmission capacity and BW x L value.

Optical communications and telecommunications:
There are satellites, RF, and copper-wire links, but most of the traffic is delivered optically.
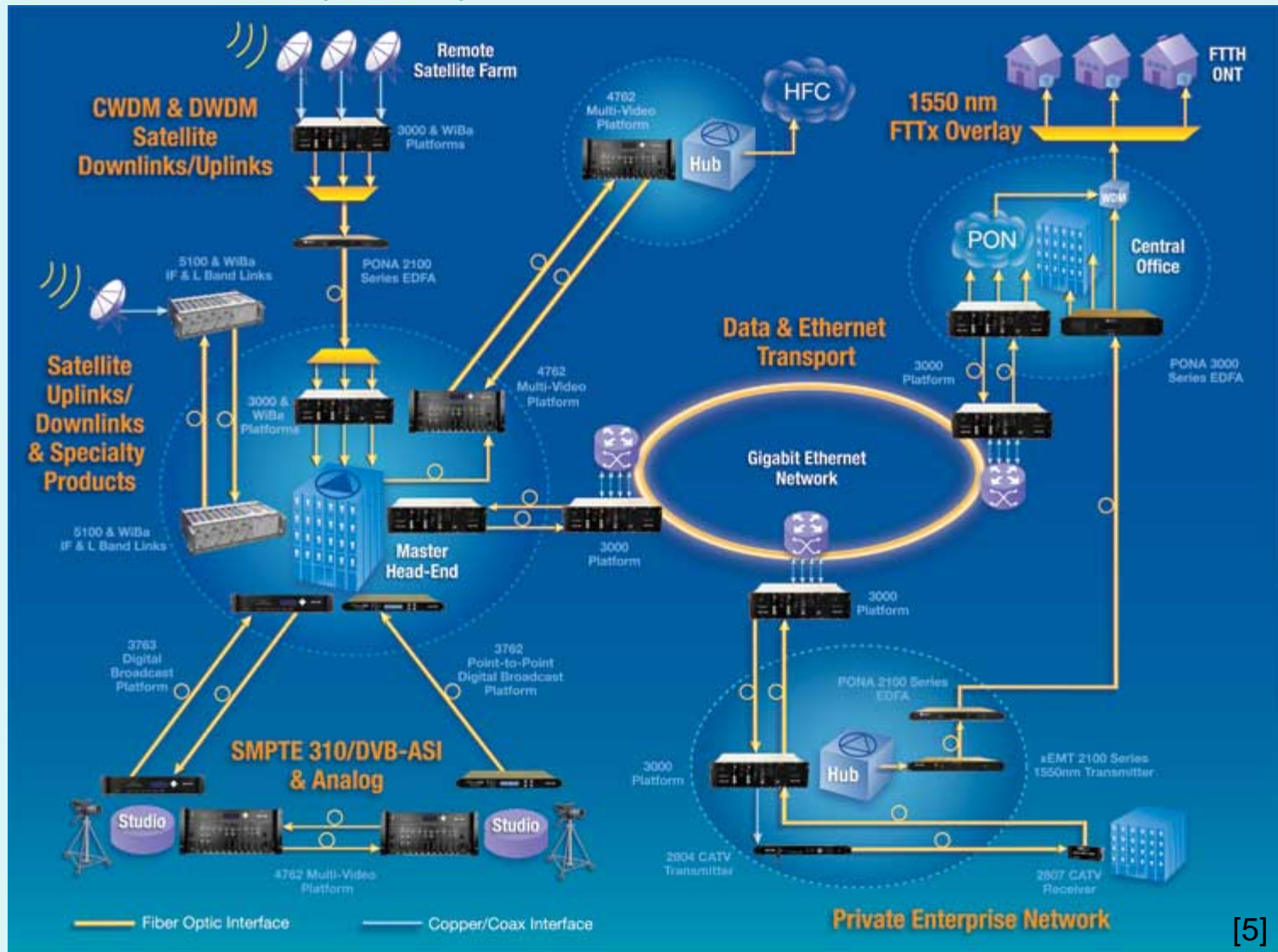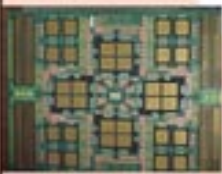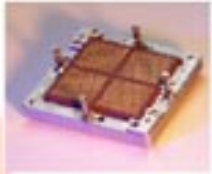

[5]

Optical communications in three dimensions

- Optical communications today widely spreads in three dimensions: in space (length), in time (bit rate) and in frequency (spectrum).

- In space (actually, in length), optical communications stretches from tens of thousands of kilometers in intercontinental links to nanometers in optical interconnects.
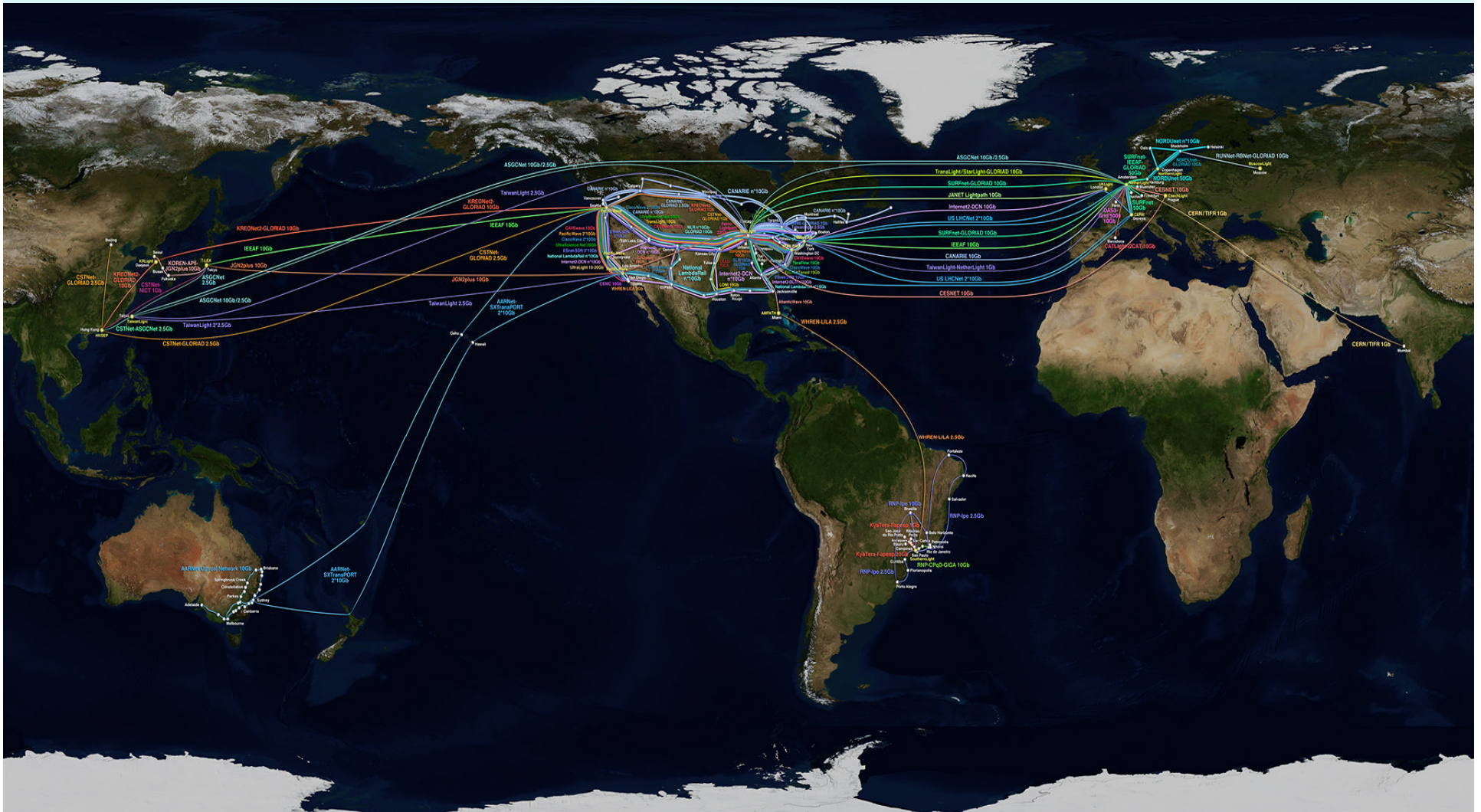
The scale of operations in optical communications

	Internet, Wide Area Network	Local Area Network	Rack-to-Rack	Card-to-Card	On-Card	On- MCM	On-Chip
Distance	multi-km	10 - 2000 m	30+ m	1 m	0.1 - 0.3 m	5 - 100 mm	0.1 - 10 mm
Number of lines	1	1 – 10	~100	~100-1000	~1000	~10'000	~100'000
Use of optics	Since the 80s and the early 90s	Since the late 90s	Now	2010+	2010-2015	Probably after 2015	Later, if ever

[2]

The trend in scale of operations in optical communications

- The *cost/performance curve* of optics is much steeper than that of electronics.

- This is why optical communications has effectively replaced the electrical systems in long distance and metro scales; optical network is replacing the copper in the access scale. Also, at the in-room and intra-rack scales the optical fiber has completely replaced the copper wire; at the board-to-board, and chip-to-chip scales the fiber-optics links start to compete with the electrical. The trend in replacing copper at the chip-level communications is forced by increasing the bit rate at the system (e.g., computer) and a board level.

- The movement in a system's architecture from parallel data buses to a high-speed serial I/Os also in concert with the shift to optics. When the data rate changes from 10 Gbit/s to 40 Gbit/s and 100 Gbit/s, move to optical interconnects seems to become inevitable.
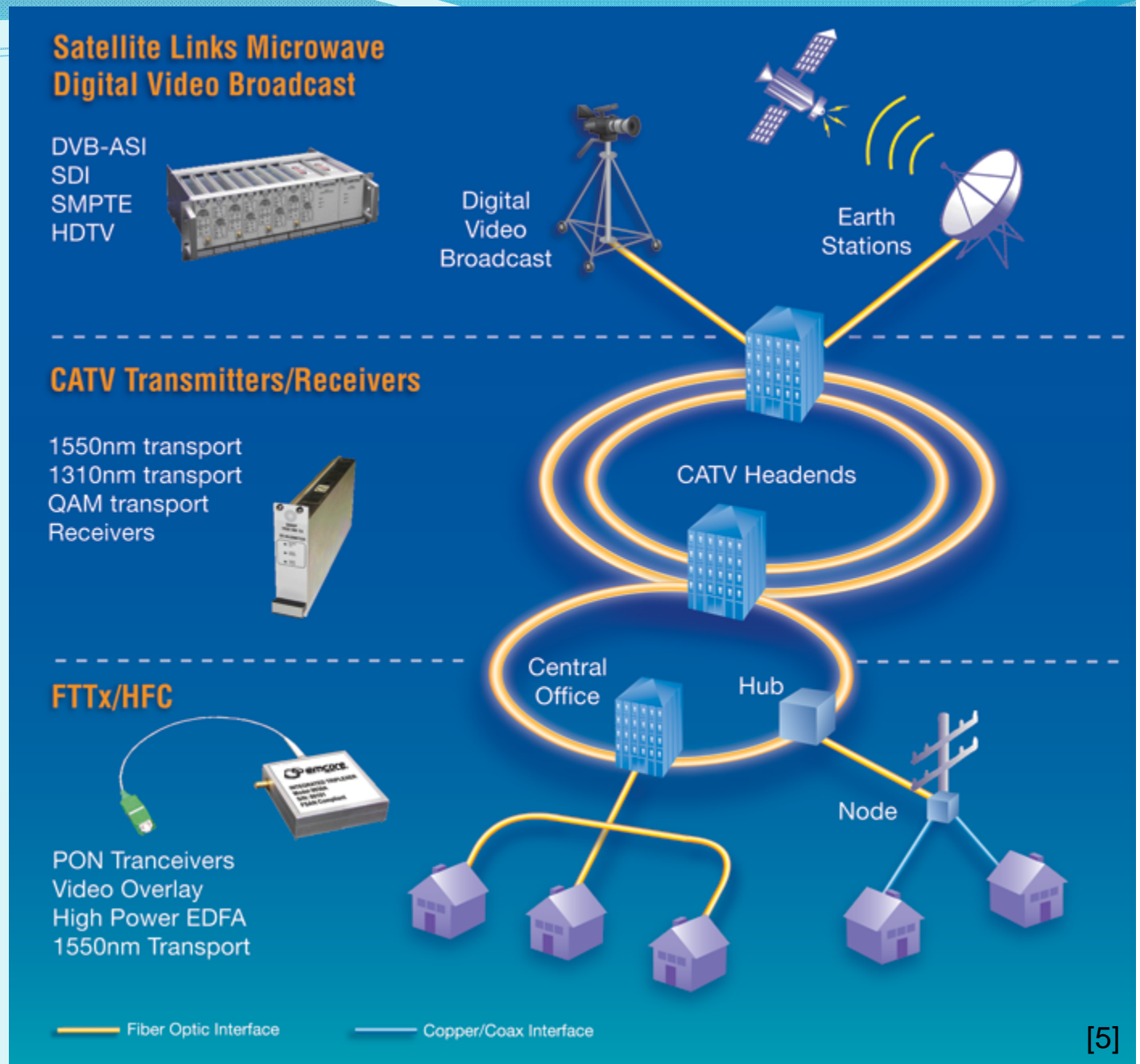
[3]

The map of worldwide optical network (previous slide) doesn't show, of course, all intercontinental, let alone all terrestrial networks; it shows, however, the global scale of optical communications.

New York City

RCN Metro Optical Networks — Fiber ▲ Colocation ■ POP ● CO

Here is the map of New York City optical network, which is built and supported by only one company. [Courtesy of RCN Corporation.] The city is covered by many optical networks (e.g., CUNY).
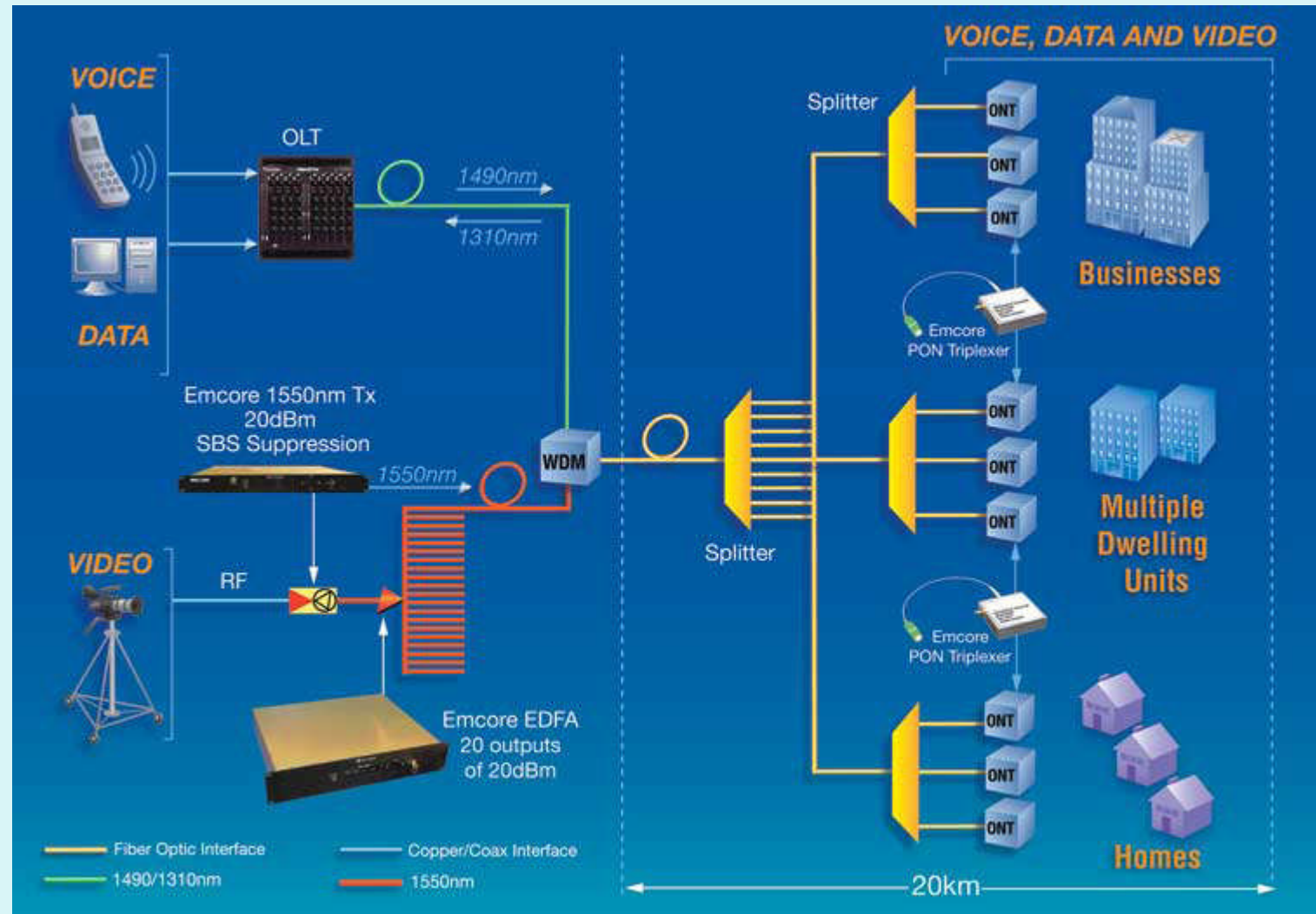
Scale: CATV network – tens of kilometers

CATV network is mostly fiber based; however, there are still segments of coaxial-cable connections.
In the United States, cable-TV network is the primary provider of the broadband access, whereas the rest of the developed world still relies on DSL technology.

Satellite Links Microwave Digital Video Broadcast

DVB-ASI
SDI
SMPTE
HDTV

Digital Video Broadcast

Earth Stations

CATV Transmitters/Receivers

1550nm transport
1310nm transport
QAM transport
Receivers

CATV Headends

FTTx/HFC

PON Tranceivers
Video Overlay
High Power EDFA
1550nm Transport

Central Office

Hub

Node

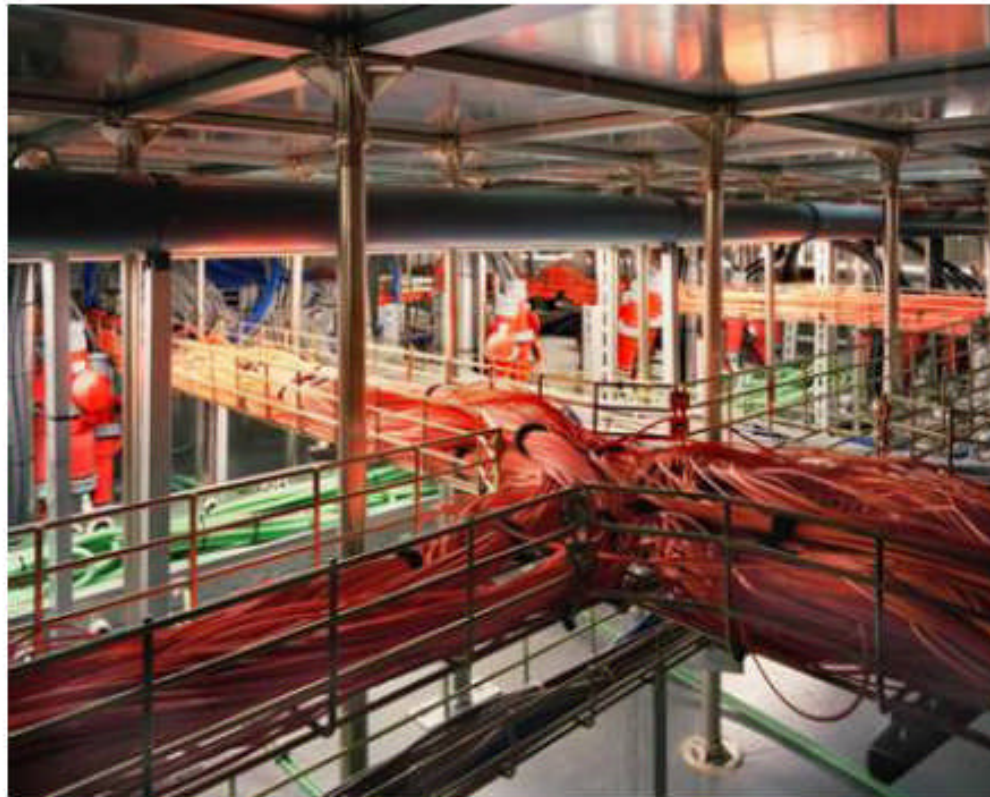Fiber Optic Interface   Copper/Coax Interface

[5]

Scale: PON – tens of kilometers

Passive optical network (PON) replaces the traditional copper-wire telephone connections from a house (apartment) to the central office Installation of PON and other types of optical access networks keeps growing in the United States and other developed countries; e.g., in South Korea and Japan optical access becomes the main type of broadband connection.

VOICE

DATA

VIDEO

OLT

1490nm

1310nm

Emcore 1550nm Tx 20dBm SBS Suppression

1550nm

RF

WDM

Emcore EDFA 20 outputs of 20dBm

Fiber Optic Interface

1490/1310nm

Copper/Coax Interface

1550nm

VOICE, DATA AND VIDEO

Splitter

ONT

Businesses

Emcore PON Triplexer

ONT
ONT
ONT

Multiple Dwelling Units

Splitter

Emcore PON Triplexer

ONT
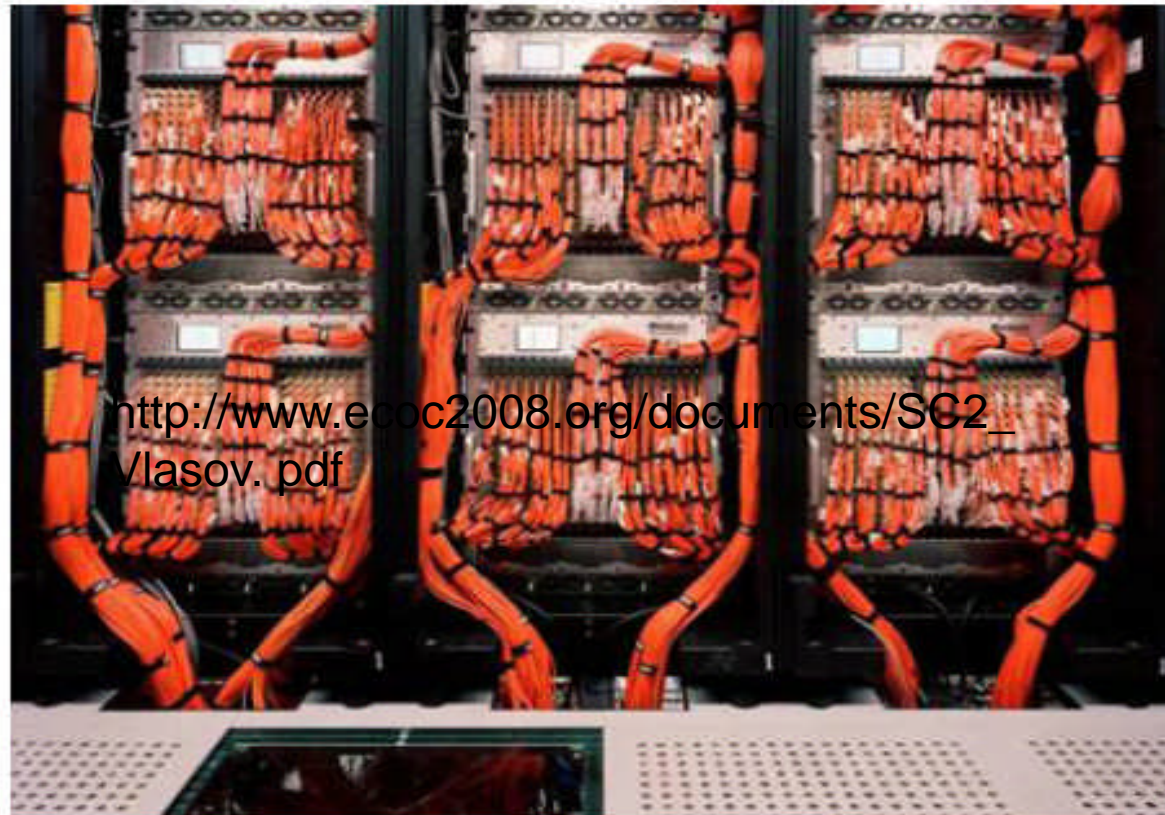ONT
ONT

Homes

20km

[5]

Scale: In-room connections – hundreds of meters

MareNostrum (Barcelona) 62TFlops
About 5000 fiber cables

[34]

Scale: Rack-to-rack connections – tens of meters

http://www.ecoc2008.org/documents/SC2_Vlasov.pdf

MareNostrum central switch racks:
About 1700 fiber cables/rack today

[34]

Scale: Optical interconnects between cards – tens of centimeters

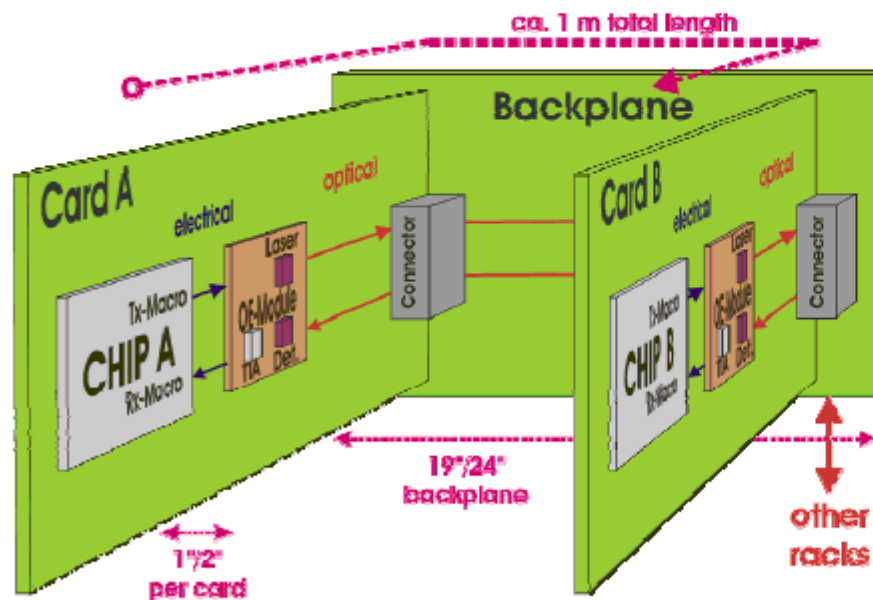Optics between cards: Optical backplane

Length: ~50cm
links: ~10K
BW: ~10Gbps/link
Power: ~10mW/Gb/s/link

Price: <1$ per Gbps
Reliability!!

- **Electronics**
  - Fast CMOS designs with low power consumption
- **Opto-electronics**
  - Separate from processor to avoid heat/lifetime issues
  - VCSEL/PD: *2D-arrays* (cost)
- **Optical channel**
  - Fibers, fiber flexes
  - PCB embedded waveguides
- **Coupling**
  - Passive alignment and positioning

Courtesy of IBM ZRL – Christoph Berger, Bert Jan Offrein, Martin Schmatz

[34]

Scale: Intra-card optical interconnects – tens of millimeters

Chip-to-chip link.

Length: ~1cm
links: ~100K
BW: ~1Tbps/link
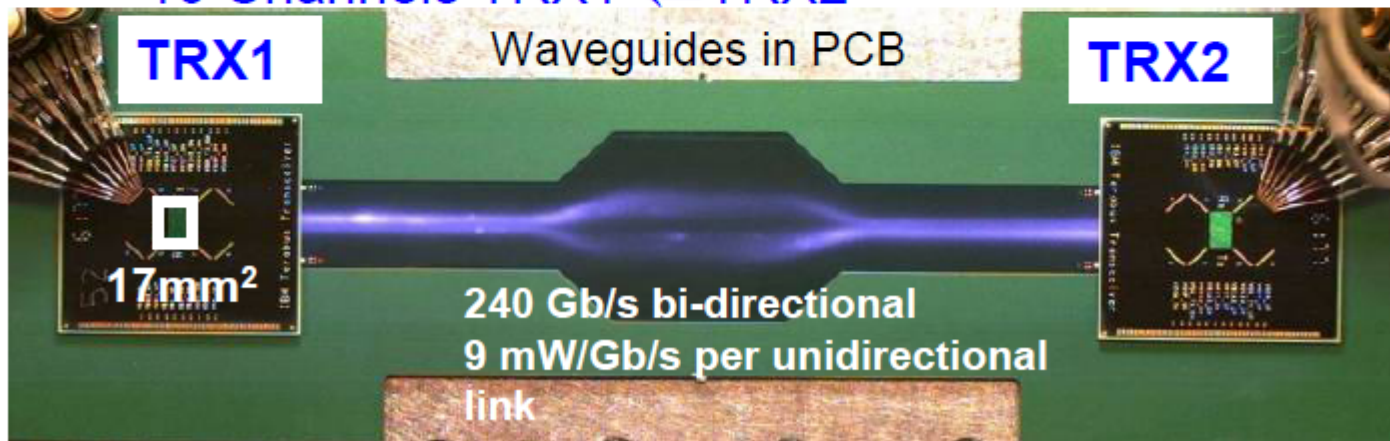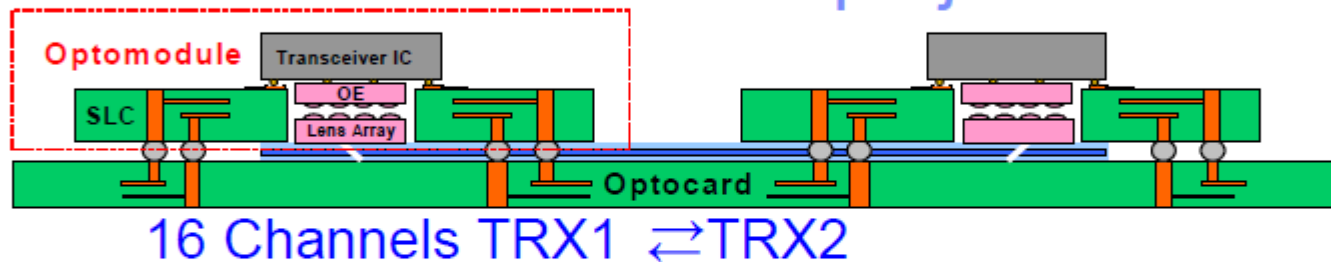Power: <10mW/Gb/s/link

Price: <0.1$ per Gbps
Reliability !!!

IBM Terabus project

16 Channels TRX1 ⇄ TRX2

Waveguides in PCB

TRX1

TRX2

17mm²

240 Gb/s bi-directional
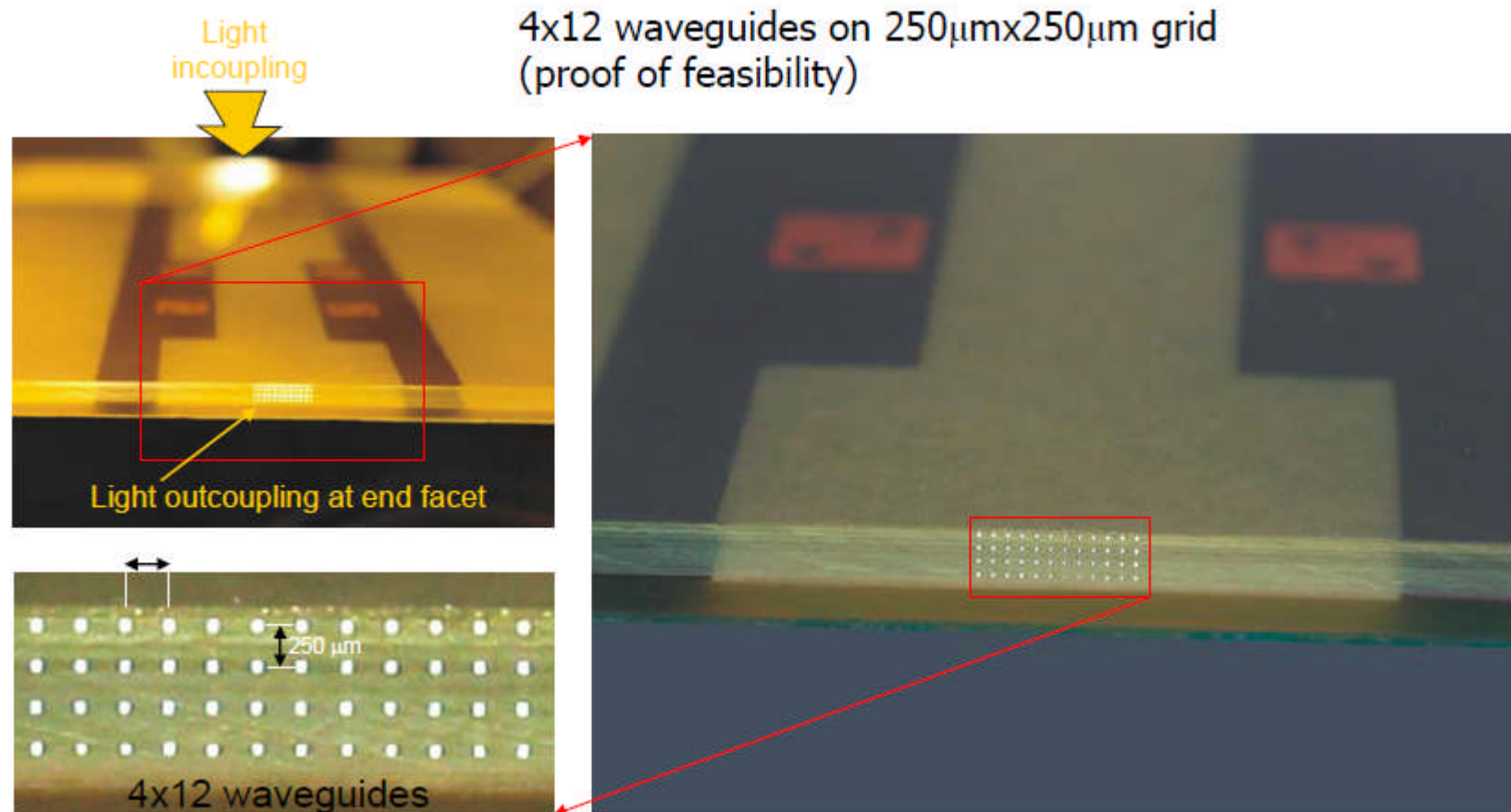9 mW/Gb/s per unidirectional link

Courtesy of IBM Terabus team – Jeff Kash, Clint Schow, Fuad Doany et al   [34]

Scale: Intra-card waveguides hundreds of micrometers

Multilayer optical waveguides in PCB

Light incoupling

4x12 waveguides on 250μm x 250μm grid (proof of feasibility)

Light outcoupling at end facet

250 μm

4x12 waveguides

Y. Vlasov, IBM Research Division

Courtesy of IBM ZRL – Roger Dangel, Folkert Horst, Bert Offrein   [34]

Scale: Optical interconnects on chip – micro- and nanometers
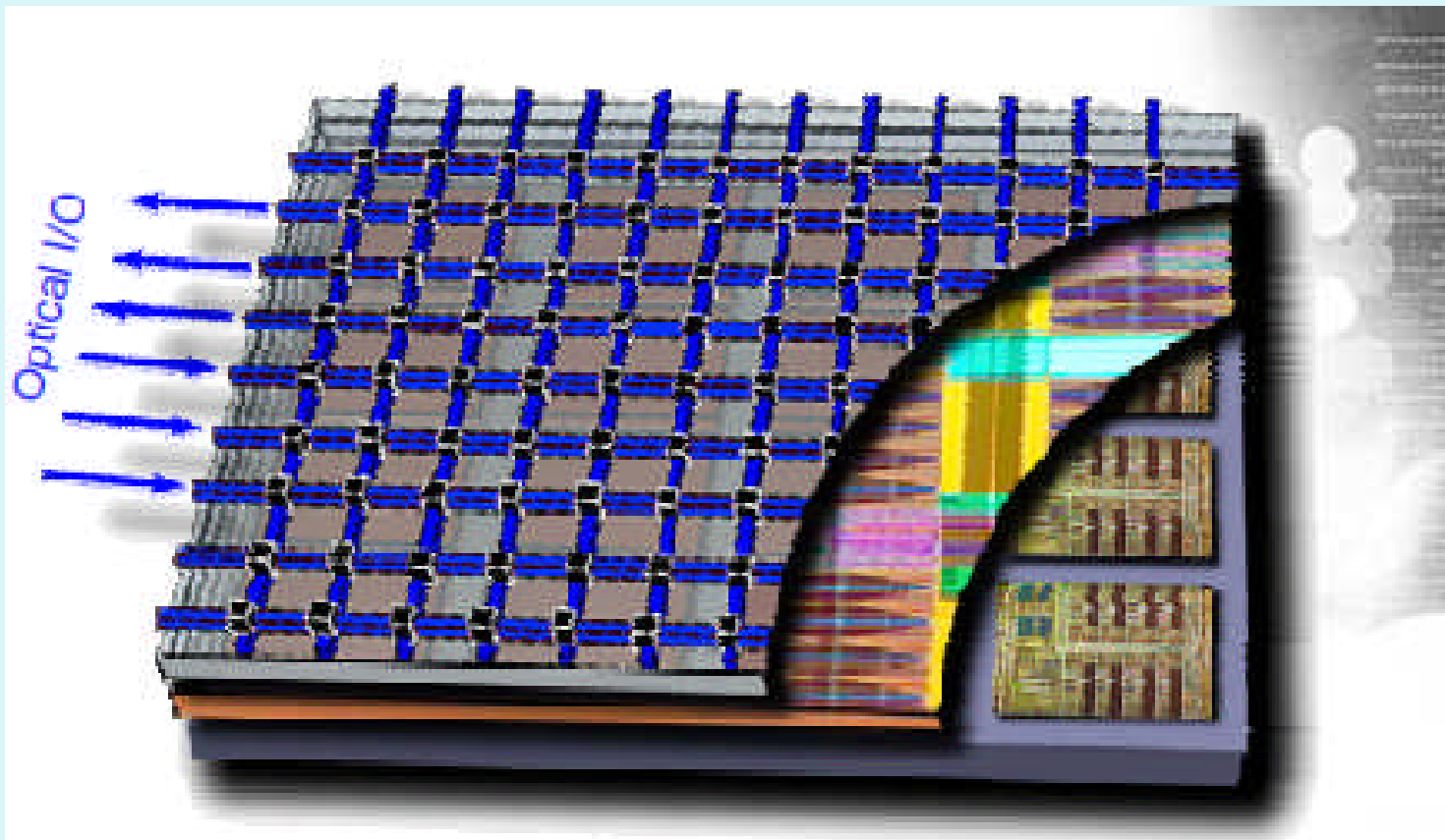
[34]

The trend in the scale of operation in optical communications

- Optical communications consistently outperforms electronics counterpart over the shorter and shorter distances.

- For last twenty plus years, optical communications has replaced the electronics in scale ranging from ultra-long-haul to rack-to-rack links.

- These replacements occur mainly in point-to-point topologies; this is why some researchers refer to optical interconnections rather than networks.

- The trend is clear: Optical interconnections penetrate closer and closer to chips.

|	Internet, Wide Area Network	Local Area Network	Rack-to-Rack	Card-to-Card	On-Card	On- MCM	On-Chip
Distance	multi-km	10 - 2000 m	30+ m	1 m	0.1 - 0.3 m	5 - 100 mm	0.1 - 10 mm
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Our Focus

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  - PON
- Trends
  - Components
  - Networks
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Optical communications in time – bit rates

- Main advantage of optical fiber over any other transmission medium is greater bandwidth (transmission capacity).

- This is why the first quest in using optical communications has been and still is the increase of signal bit rate.

- We need to distinguish between the bit rate of a single channel (wavelength) achieved by time-division multiplexing (TDM) and data rate transmitted over a fiber achieved by wavelength-division multiplexing (WDM).
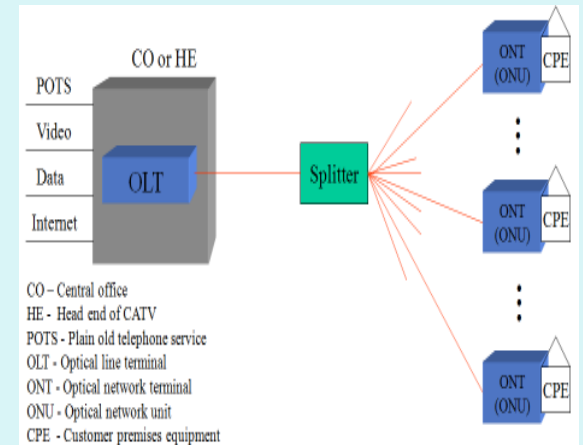
Optical communications in time - bit rates
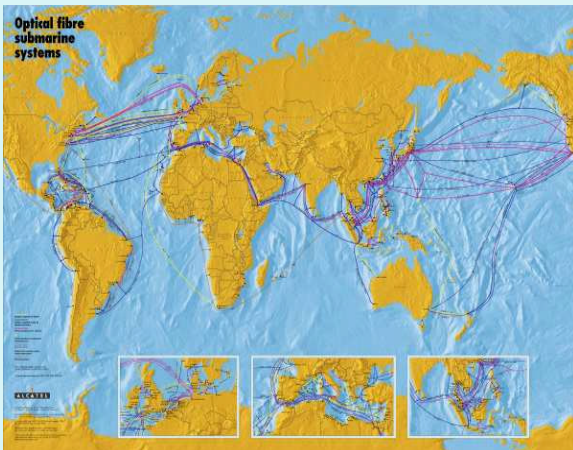
Long-distance optical networks operate at Tb/s bit rate.
(World-wide submarine links by Alcatel.)
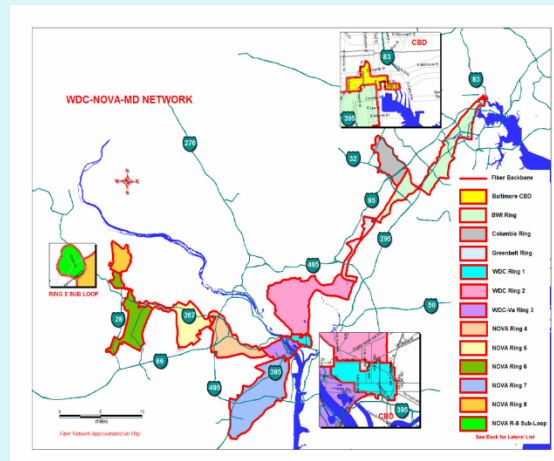
Metro optical networks operate at hundreds of Gb/s bit rate.
(Washington DC metro network by FiberLight.)

Access optical networks operate at units of Gb/s and hundreds of Mb/s bit rate.
(Schematic diagram of PON, aka FiOs.)

TDM bit rate

- Single wavelength (channel) link now routinely achieves 40 Gb/s bit rate.

- It is done by improvement of performance of individual Tx and Rx and combining (multiplexing) several low-rate signals in one stream (e.g., 4 x 10 Gbit/s).

- 100 Gbit/s bit rate is approaching, as recent trials show. Industry considers two versions: 4 x 25 Gb/s or 10 x 10 Gb/s.

- 160 Gbit/s has been consistently demonstrated.

- New modulation schemes allowing for reduction of bit-error rate have been introduced.

- (We can achieve the better signal transmission by not only improving the quality of the components but also by other means, including the work at the network's logical layer.)

Bit rates - TDM and WDM

- We need to realize that at the bit rate of 1 Tbit/s the bit time is equal to 10^{-12} s = 1 ps. There is no optoelectronics (LDs, modulators and PDs) that can operate at this speed.

- Today's electronics (Tx and Rx) mainly operates at 10 Gbit/s; modulation at 40 Gbit/s has achieved and modulation at 100 Gbit/s is on the horizon.

- However, theoretically an optical fiber can carry 100 Tbit/s at a single channel (wavelength), which means that an optical fiber can carry a thousand of 100Gbit/s channels.

- Thus, the need for WDM!

Optical fiber's transmission capacity

Single wavelength's transmission capacity
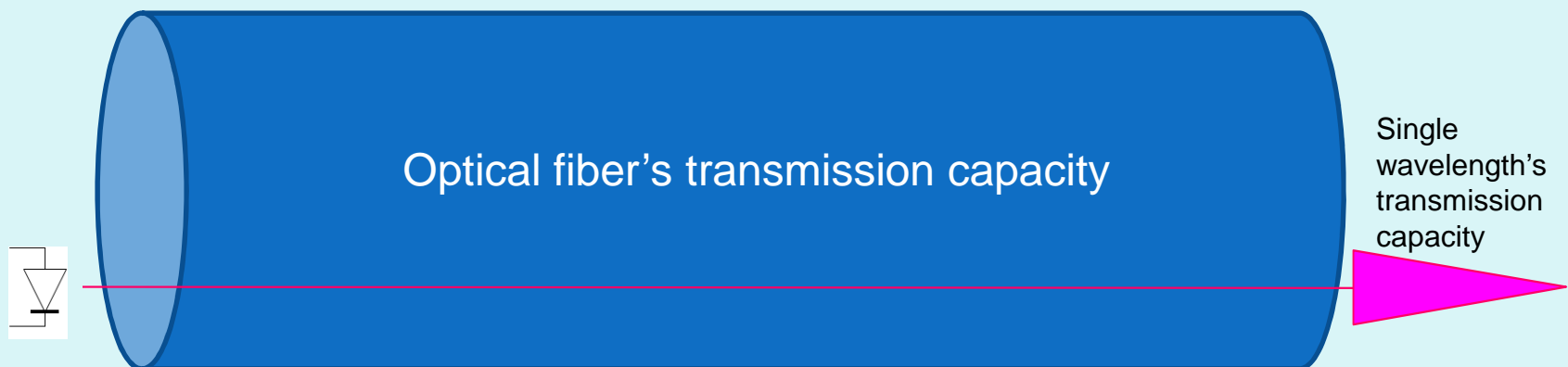
Bit rate - WDM

WDM concept and the frequency spectrum are shown at right.

WDM allows for N-times increase of data rate transmitted by optical fiber, where N is the number of wavelengths.
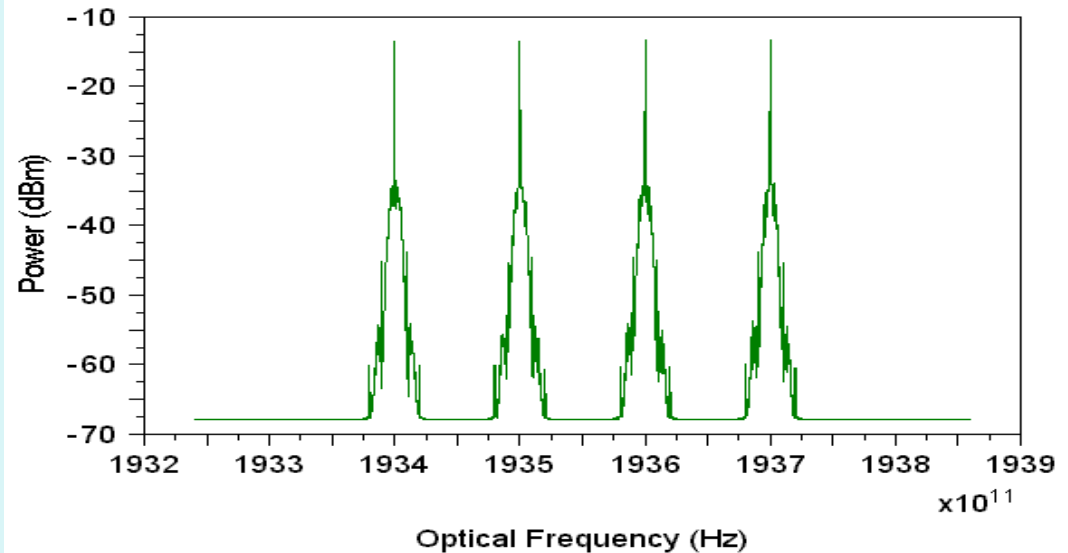
There are two types of WDM today: Dense WDM (DWDM) and Coarse WDM (CWDM). They differ in channel (λ) spacing: DWDM operates at spacing ranging from 1.6 nm (200 GHz) to 0.2 nm (25 GHz); CDWM works at 20-nm spacing.
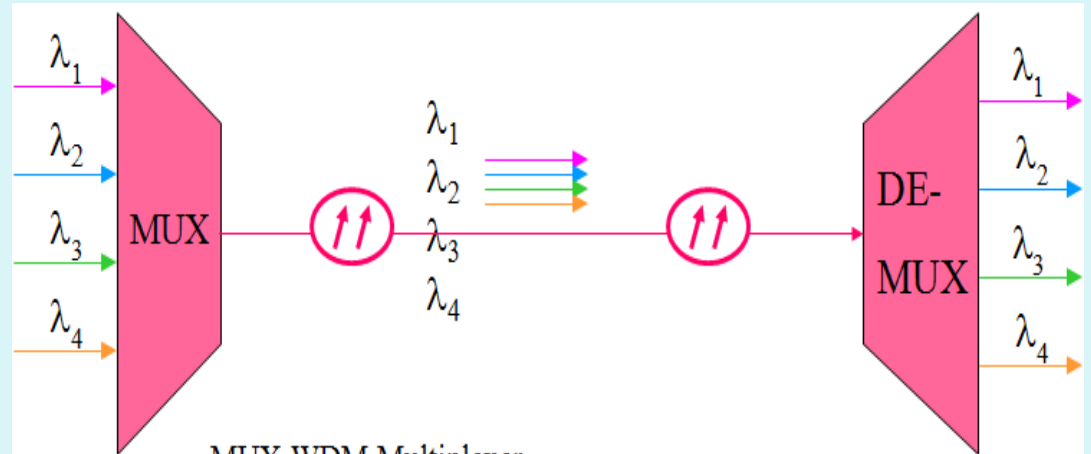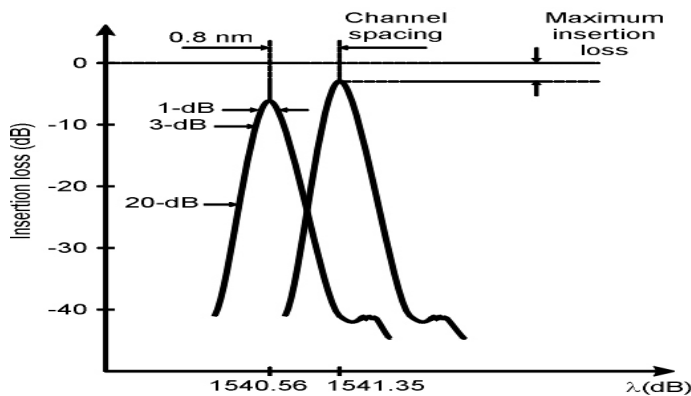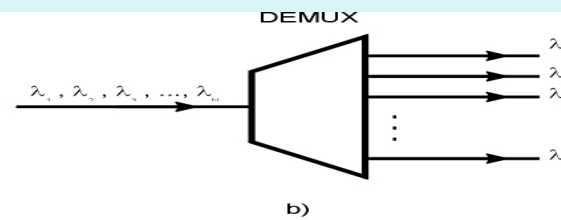

MUX-WDM Multiplexer

DEMUX-WDM Demultiplxer

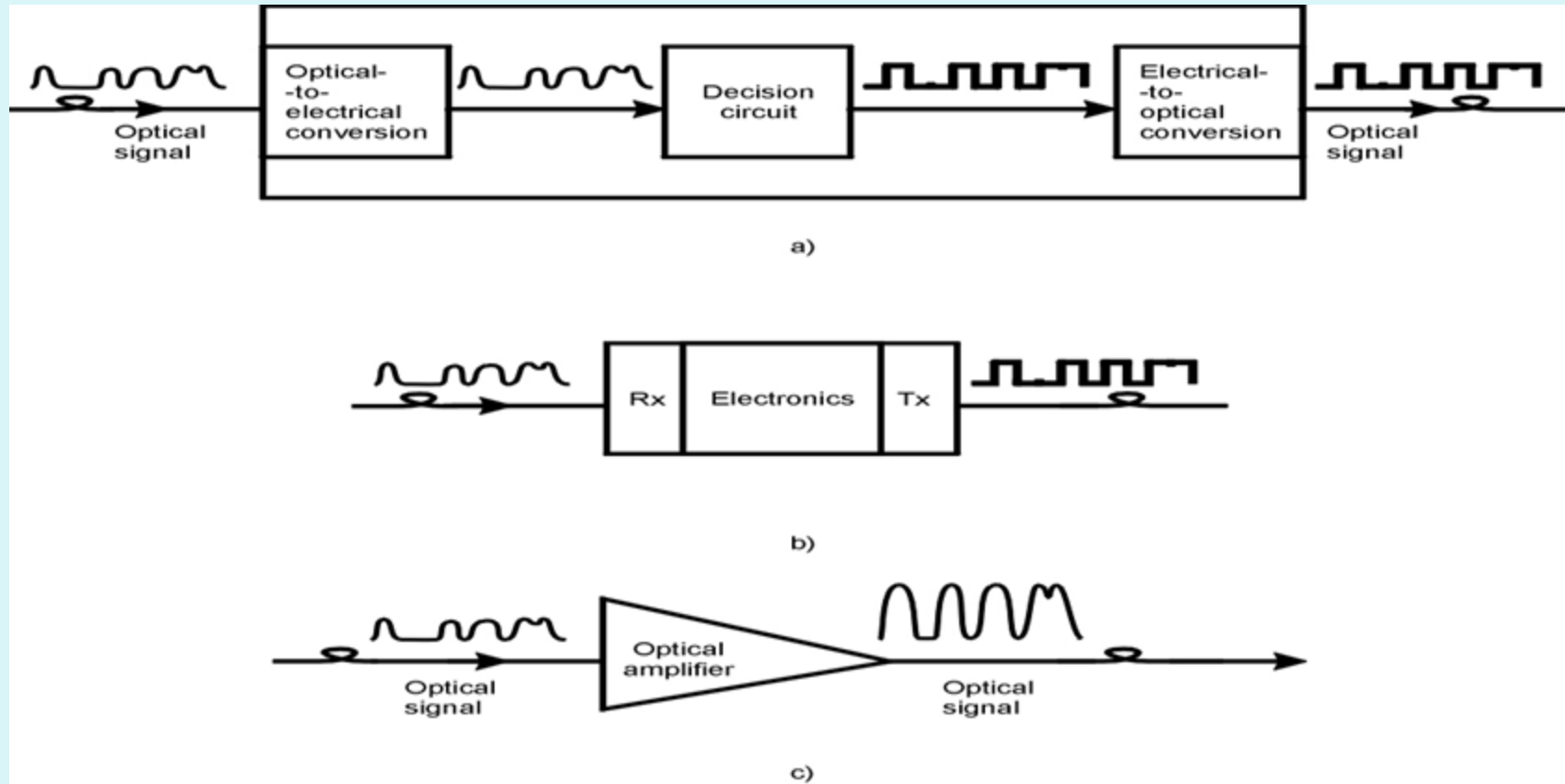Istmpspectraout Optical Frequency Spectrum

Bit rate – WDM components
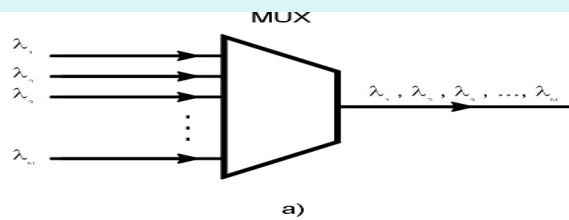
WDM MUXs and DEMUXs are the special splitters and couplers:
thus, they are passive devices.

[1]

WDM – the need for amplification

Regenerator and optical amplifier [1].

Figure 7.6: Repeaters and optical amplifiers:
a) Functional block diagram of a repeater.
b) Simplified diagram of a repeater. c) Optical amplifier.

WDM - regenerators
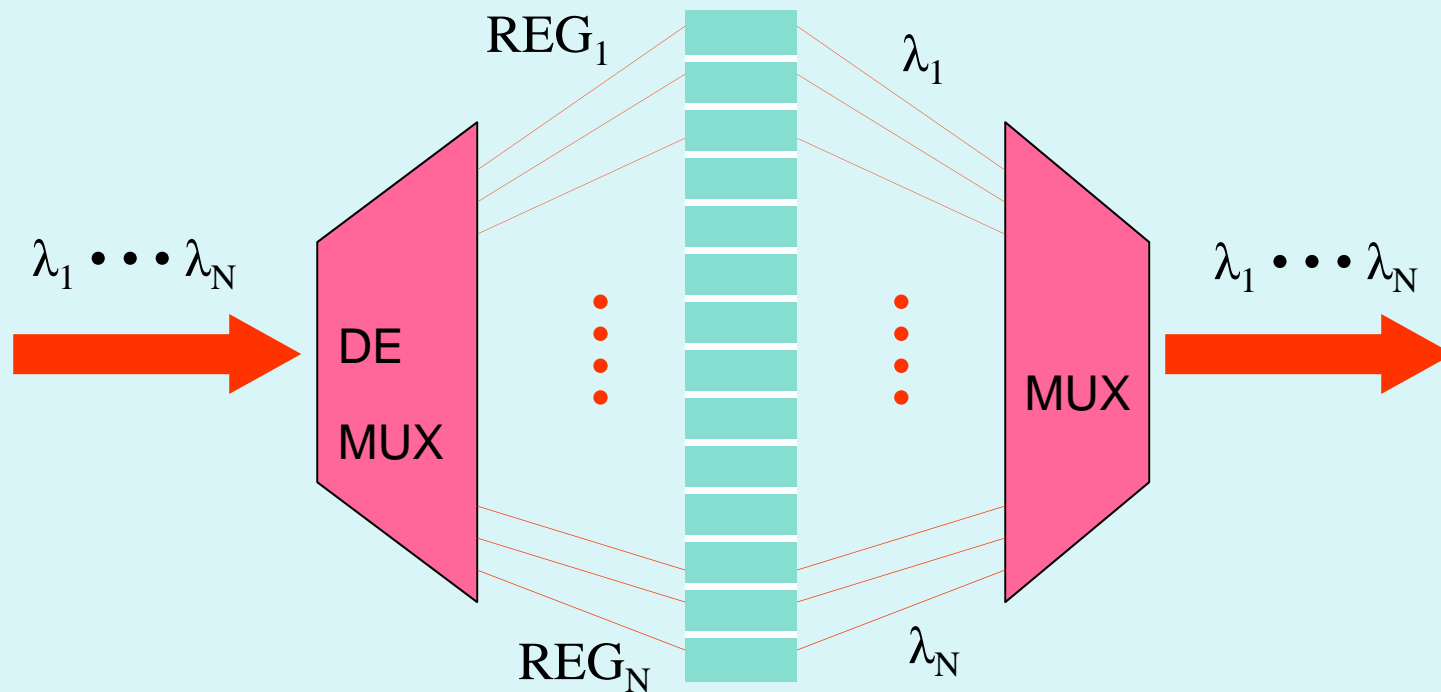
Regenerators are sensitive to the bit rate and format of a signal. Most importantly, a regenerator can work with one wavelength only. Therefore, to use regenerators in WDM network, we need to demultiplex the input optical signal, regenerate every individual wavelength, and multiplex the output signal again. We still need the regenerators to compensate for the bit spread (dispersion).

WDM – optical amplifier

WDM link: introduction of OA

- **WDM became the practical technique for increasing channel capacity only after optical amplifiers (OAs) had been developed.**

- **An optical amplifier can amplify all wavelengths within its band, while a regenerator can work only with one wavelength.**

WDM – optical amplifier
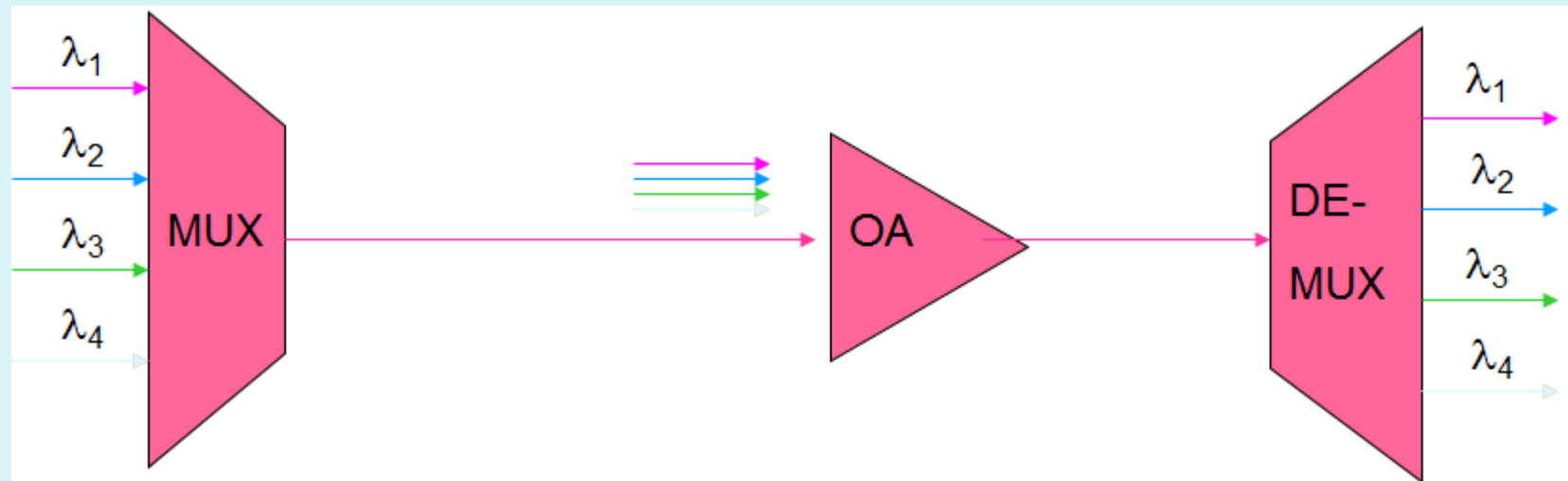
WDM point-to-point link with optical amplifier (OA).

WDM – optical amplifiers

There are several types of optical amplifiers:

- Erbium-doped fiber amplifiers (EDFAs).

- Raman amplifiers.

- Hybrid systems: EDFA + Raman amplification.

- Semiconductor optical amplifiers (SOAs).

WDM - EDFA
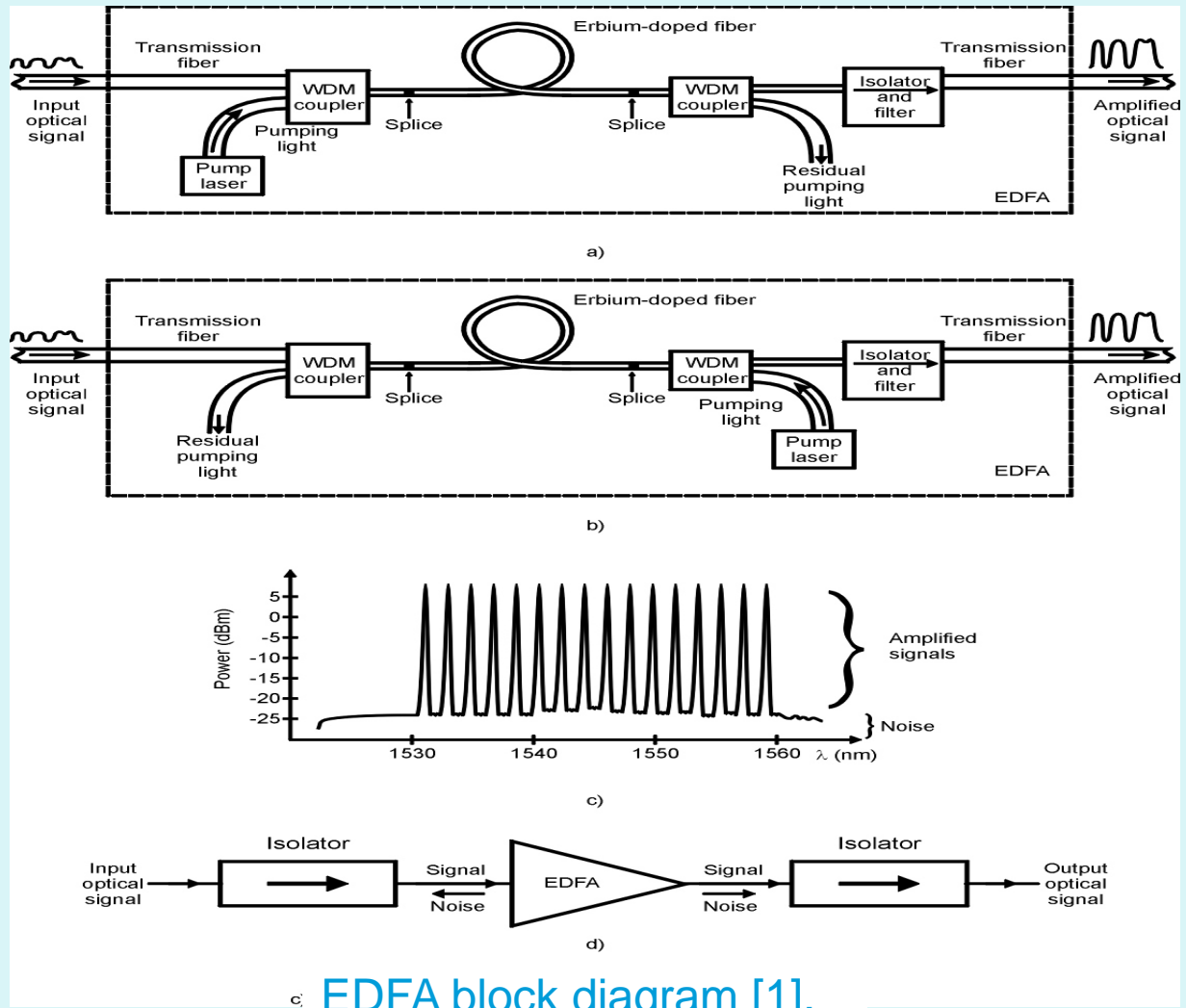
EDFA block diagram [1].

WDM - EDFA

Erbium-doped fiber amplifier (EDFA) is the workhorse of WDM networks.

- **Main advantages:**
    - Cover C band from 1530 to 1565 nm and L band from 1560 to 1610 nm.
    - Can amplify wavelength-division multiplexed signal in any transmission format and bit rate.
    - Excellent performance characteristics: High gain (> 30 dB) and low noise figures (< 6 dB); fiber-based optical amplifiers ➔ easy coupling; Insensitive to signal polarization.

WDM – Raman OA

Raman amplification: block diagram
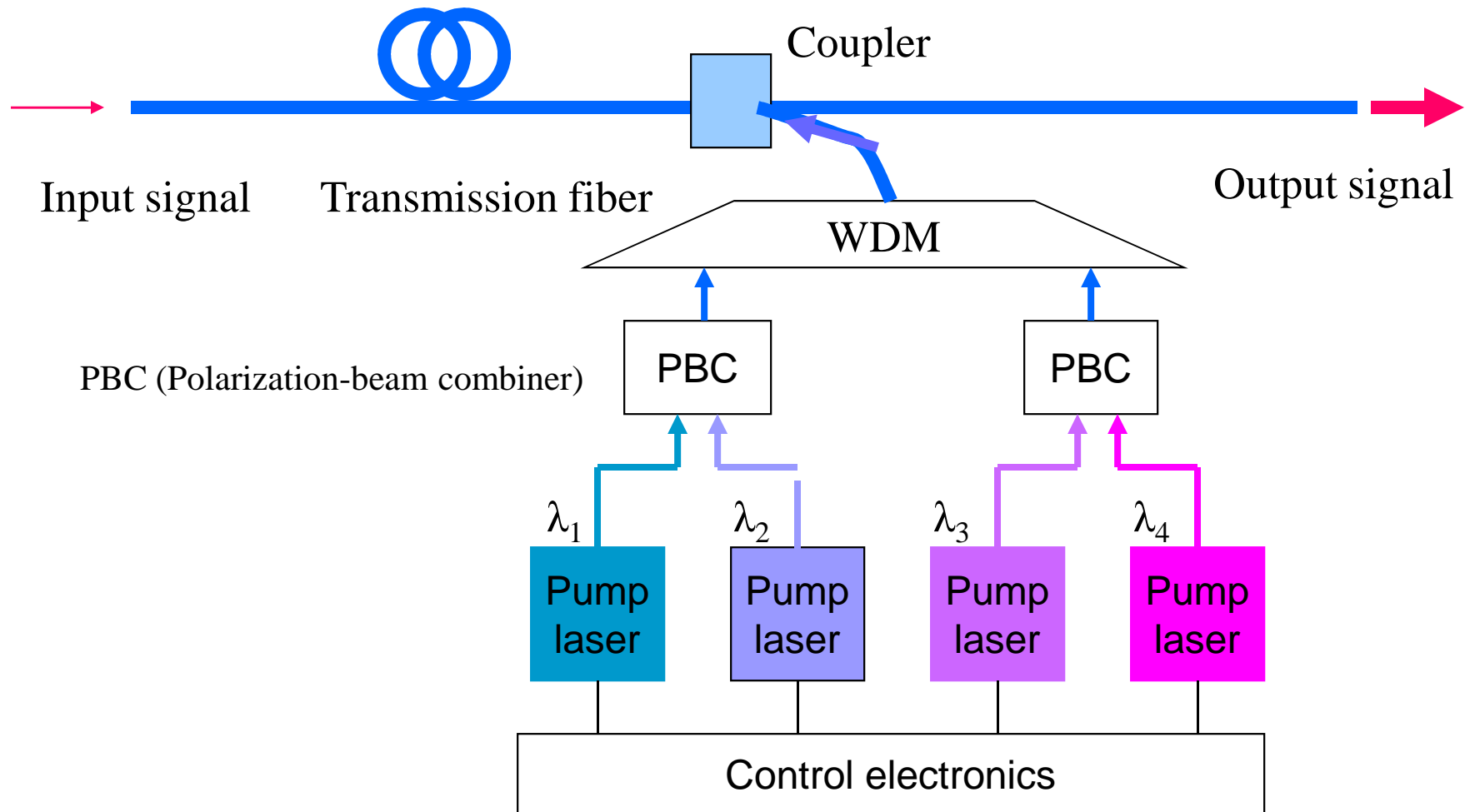
WDM – hybrid amplification

WDM - Spectrum

DWDM occupies wavelengths from ~1530 nm to ~1610 nm. This range is subdivided in two subsections: conventional band [C] between 1560 and 1530 nm and long band [L] between 1560 nm and 1610 nm.

DWDM - spectral efficiency

- Spectral efficiency
  - Spectral efficiency is equal to channel rate (CR) divided by the spectral width (spectral bandwidth, SBW) necessary to transmit this signal; i.e., CR (bit/s)/SBW(Hz). This obviously is reduced to
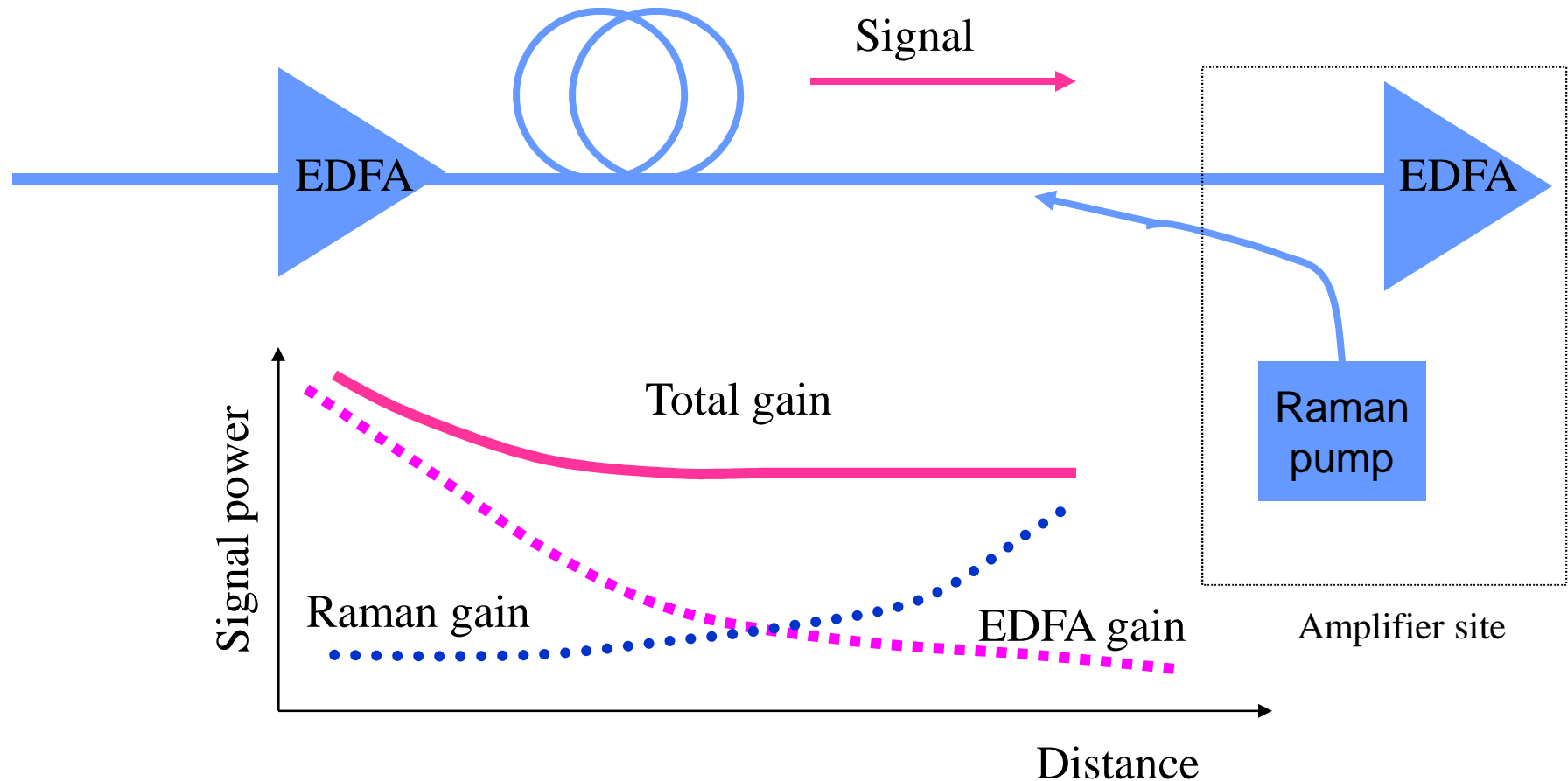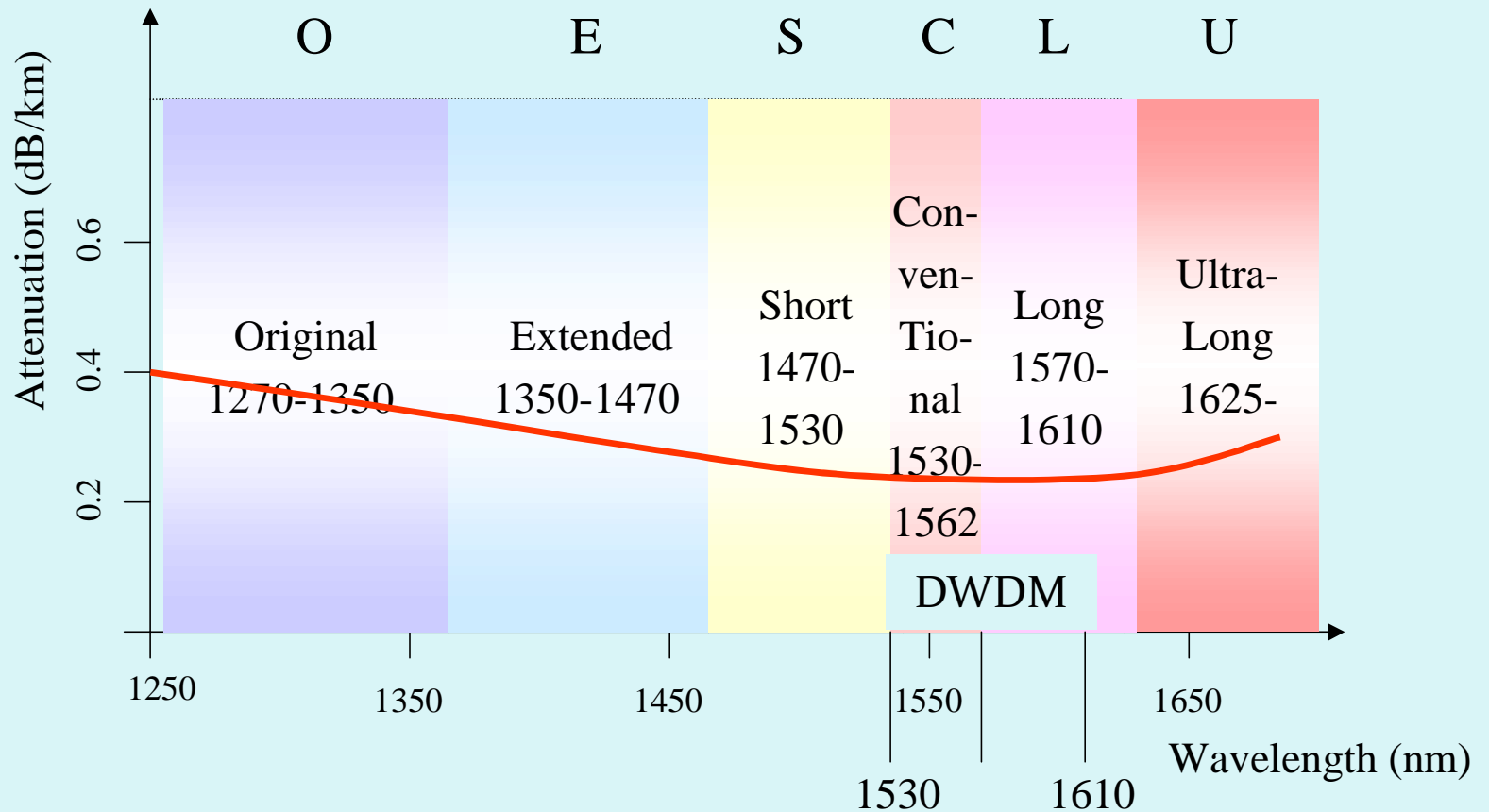
    Bit rate (bit/s)/Channel spacing (Hz)

    For example, 10 Gbit/s/100 GHz = 0.1 bit/s/Hz (very low)

    100 Gbit/s/100 GHz = 1 bit/s/Hz (high)

  - The same definition can be done in generalized way as follows:

    $$\text{Spectral efficiency, SE (b/s/Hz)} = \frac{Information\ bit\ rate\ (\frac{b}{s})}{Total\ bandwidth\ c\ onsumed\ (Hz)}$$

  - The goal is increasing spectral efficiency as much as possible; the value as high as 1.32 bit/s/Hz has been achieved in a trial.

- Importance of this characteristic is clearly emphasized by its title: It shows how efficiently we use the available spectrum for transmission.

DWDM

DWDM: ITU-T Recommendation G.694.1 (06/2002) specifies the frequency grid anchored to 193.1 THz (1552.52 nm). This grid starts from 196.1 THz (1528.77 nm) and supports a variety of channel spacings ranging from 12.5 GHz (~0.1 nm) to 100 GHz (~0.8 nm) and wider. The pictures below show wavelength comb and its detail on the screen of an optical spectrum analyzer.
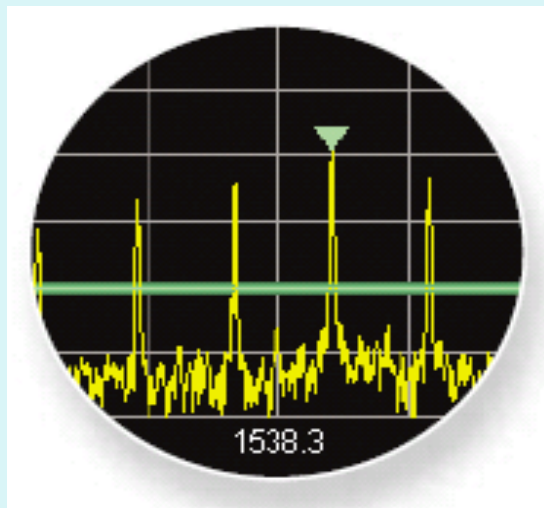
DWDM and EDFA

• It is a gift of nature that EDFAs operate in the range (1530 nm to 1600 nm), where standard singlemode fiber (SMF) exhibits minimum attenuation. Thus, EDFAs can be used to compensate for transmission losses. This fortunate coincidence has triggered the wide use of DWDM technology.

• DWDM technology increases network transmission capacity but it is a costly solution because cooled lasers and other expensive components are required ➔ Applications: long-haul and ultra-long-haul networks.

WDM – DWDM and CWDM

Wavelength-division multiplexing

Dense wavelength-division multiplexing (DWDM)

Coarse wavelength-division Multiplexing (CWDM)

Ultra-dense wavelength-division multiplexing (U-DWDM)
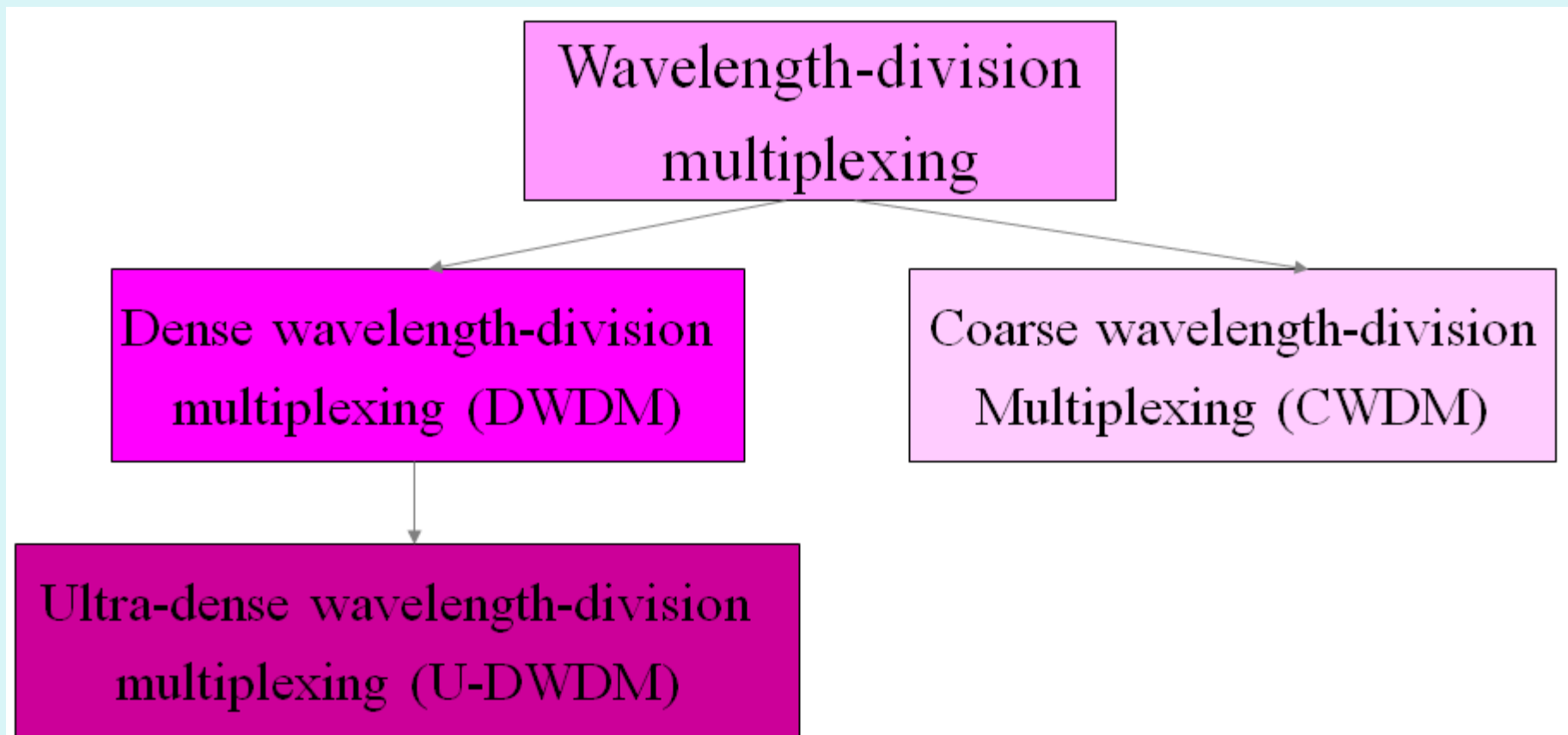
DWDM and CDWM

The frequency grid for CWDM ranges from 1271 nm to 1611 nm with 20-nm channel spacing.
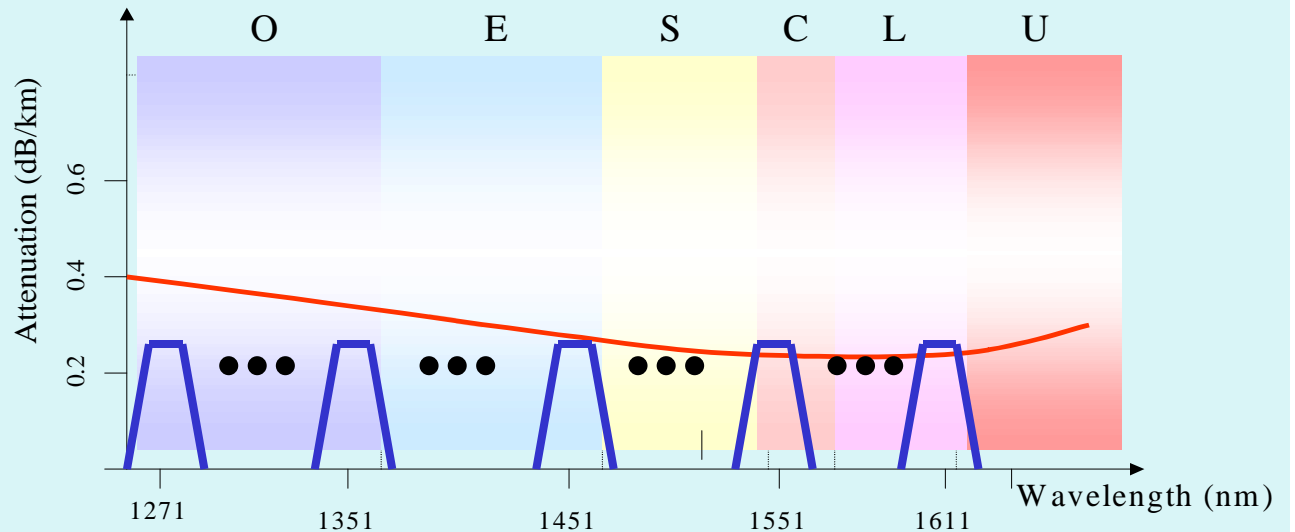
Relative spectra of DWDM and CWDM.

CWDM and DWDM in one scale
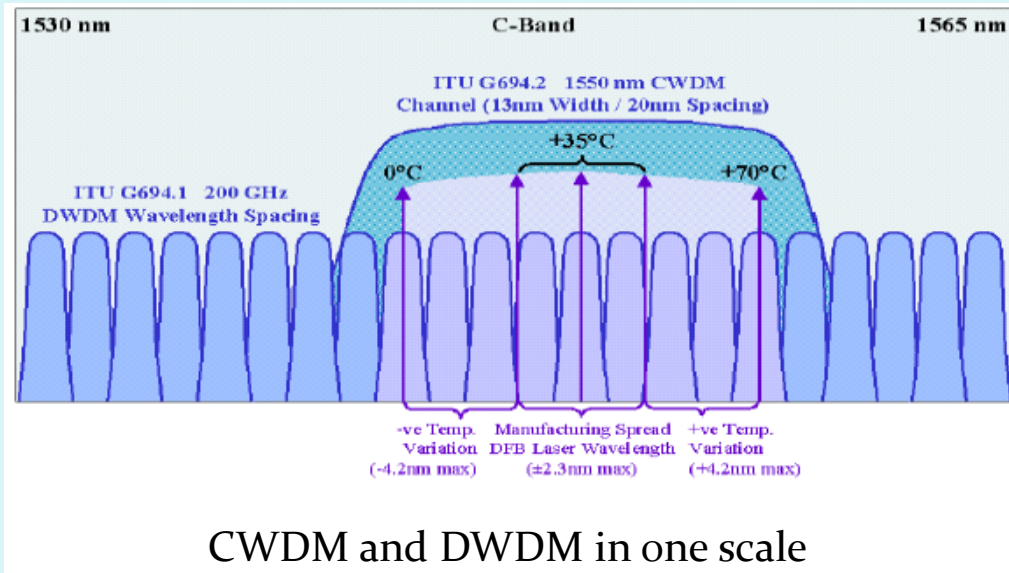
DWDM vs. CWDM

DWDM

↓

Dense channel spacing ➔
more bandwidth ➔more expensive

↓
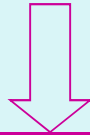
Long-haul networks
and now –
metro and access networks

⟶ Hybrid
networks ⟵

CWDM

↓

Wide channel spacing ➔
less bandwidth ➔less expensive

↓

Metro core and access
networks

WDM - summary

- **Types of WDM**
  - DWDM
  - CWDM
- **Transporting flexibility**
  - Every wavelength is a huge transporting vehicle ➔ theoretically can carry any information in any format
  - Granularity at wavelength and subwavelength levels ➔ bandwidth on demand with fixed network physical topology
  - Wavelength provides Layer 1 optical functionality, while channel provides a Layer 2 link that is mapped onto a wavelength ➔ separation the physical and logical aspects
- **Switching ➔ flexible logical topology over fixed physical topology**
  - Broadcast and select
  - Wavelength routing
- **WDM technology**

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Network

- Network differs from a point-to-point link by its ability to deliver a signal to every node out of many nodes (customers) ➔ need for switching and transmission protocols.

- Network: A network is the symbiosis of the physical and logical (intelligent) layers, very much the same as a computer is the symbiosis of hardware and software.

- Physical layer – transmission and switching.

- Logical (intelligent) layer – protocols.

- Relationship between physical and logical layers: The better the components, the better the network, but even ideal components cannot convert circuit-switching network into packet-switching (routing) one.

Network and components

Network at a physical layer is a set of nodes connected by links:

- Nodes:
    - Systems: switches/routers, optical cross-connects (OXCs), optical add/drop multiplexers (OADM), optical amplifiers, regenerators, etc. They include
        - Modules: Transmitters (Txs), Receivers (Rxs), dispersion-compensation module, wavelength converters, etc. They include
            - Components: Laser diodes, photodiodes, modulators, couplers/splitters, WDM MUXs and DEMUXs, optical filters, attenuators, gratings, etc.

- Links:
    - Optical fiber
    - Waveguides

Core, edge, and access networks
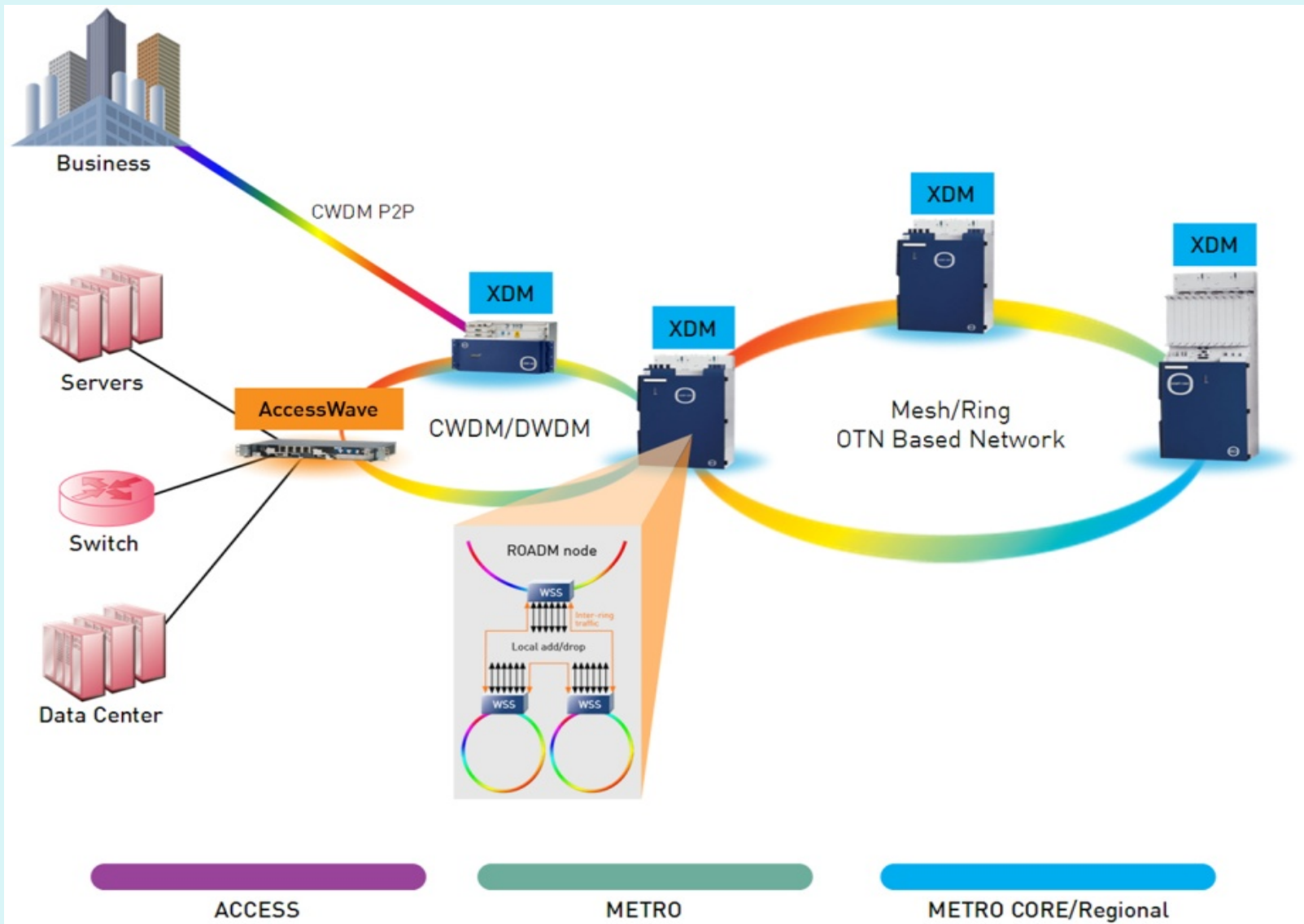
Network – main problems

Network: main problems

Traffic is delivered optically, but routed electronically ➔ all-optical routing.

The cost of switching and transmission equipment, including energy bills, is the today's main barrier for the further growth of the Internet ➔ energy-optimized network design [16], low-power-consumption equipment.

Signal distortions are to be compensated by special systems (optical amplifiers, regenerators, dispersion-compensation devices) ➔ better systems and modules.

Specific problems of PON networks: restricted distance, no switching and resilience ➔ light-controlled-by-light systems.

Components – main problems

Systems and modules:

- Electrical-to-optical (E/O) and optical-to-electrical (O/E) conversion in routers and regenerators ➔ have to be all-optical systems ➔ optical packet switching and all-optical 3R regenerators, integrated systems?

- Switches, OXCs, ROADMs, amplifiers, and other systems are built from individual components with E/O/E conversions ➔ must be miniature, integrated, all-optical modules, integrated with transmission lines?

Optical switch [Gimmerglass]

From link to network

OXC-optical cross-connect, REG-electronic regenerator, OA-optical amplifier, DCM-dispersion-compensated module.
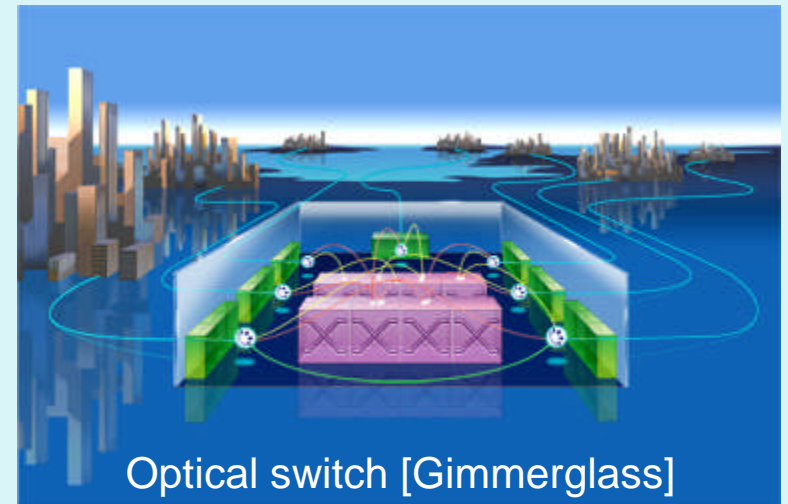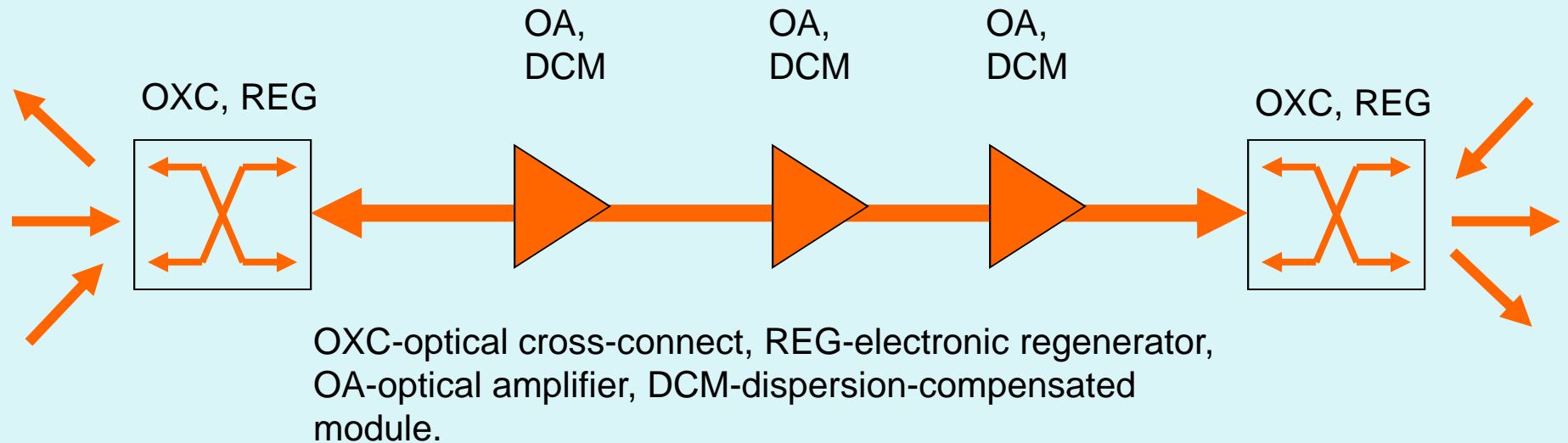
Long-haul link: transmission distances from 100 to 2000 km, OA and DCM every 100 km, bit rate up to 40 Gb/s, signal regeneration every 2000 km. Dispersion management and the use of new fibers and optical amplifiers allows for longer transmission links without regeneration.

Ultra-long-haul link: transmission distances from hundreds of km to thousands of km including both terrestrial and submarine links.

From link to network

ROADM – reconfigurable optical add/drop multiplexer

OXC – optical cross coneect/Switch
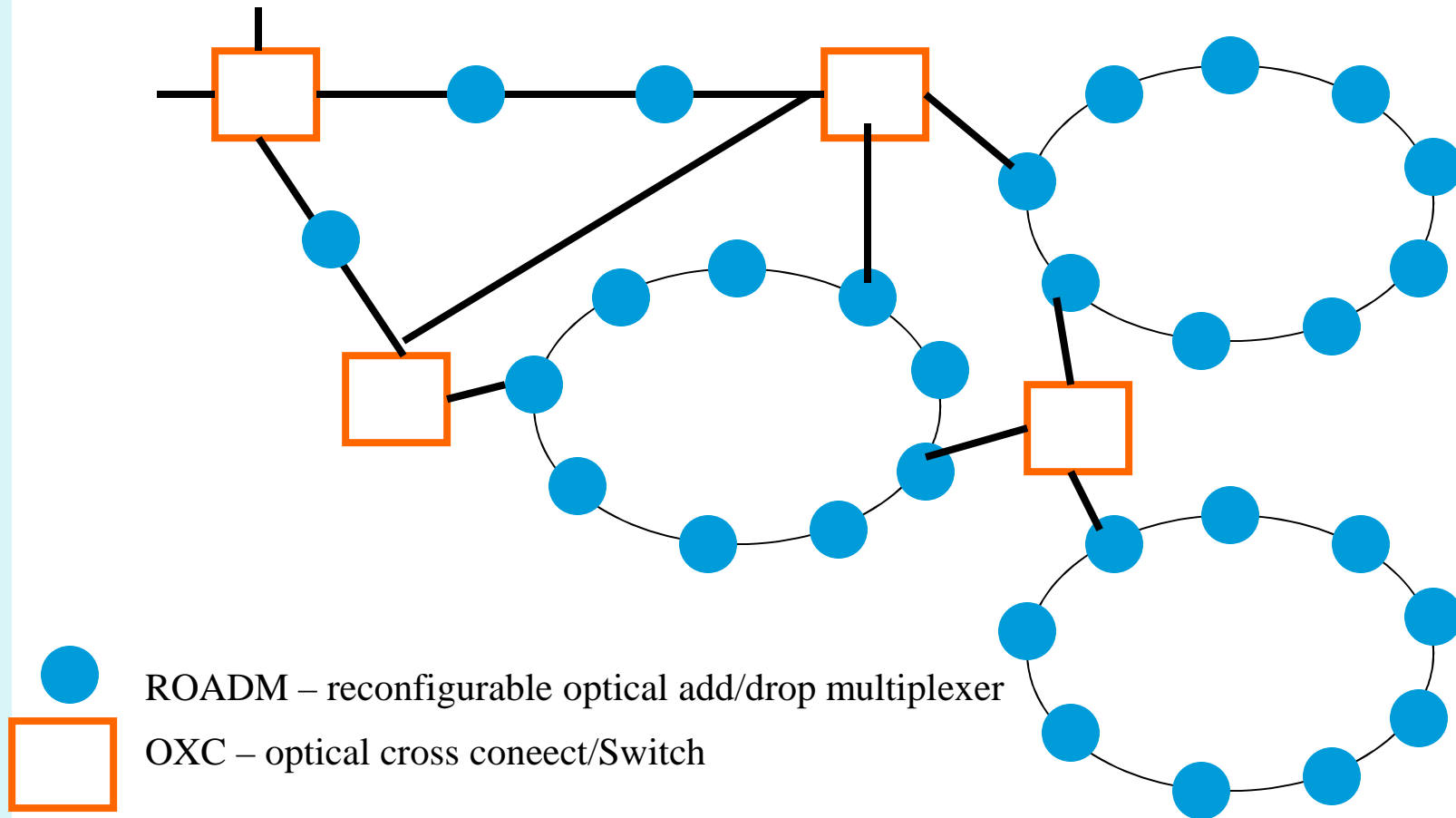
From link to network
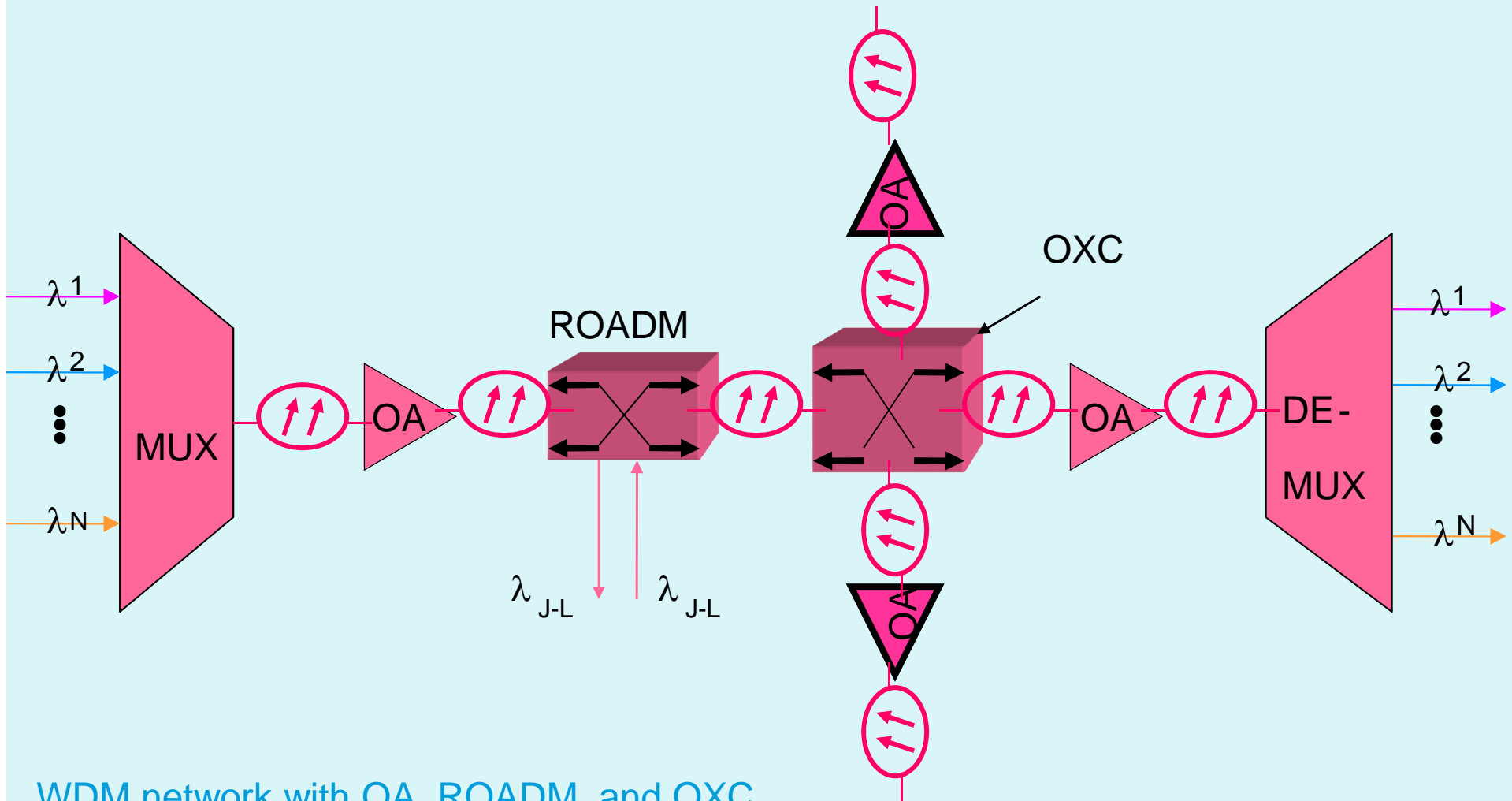
WDM network with OA, ROADM, and OXC

From link to network
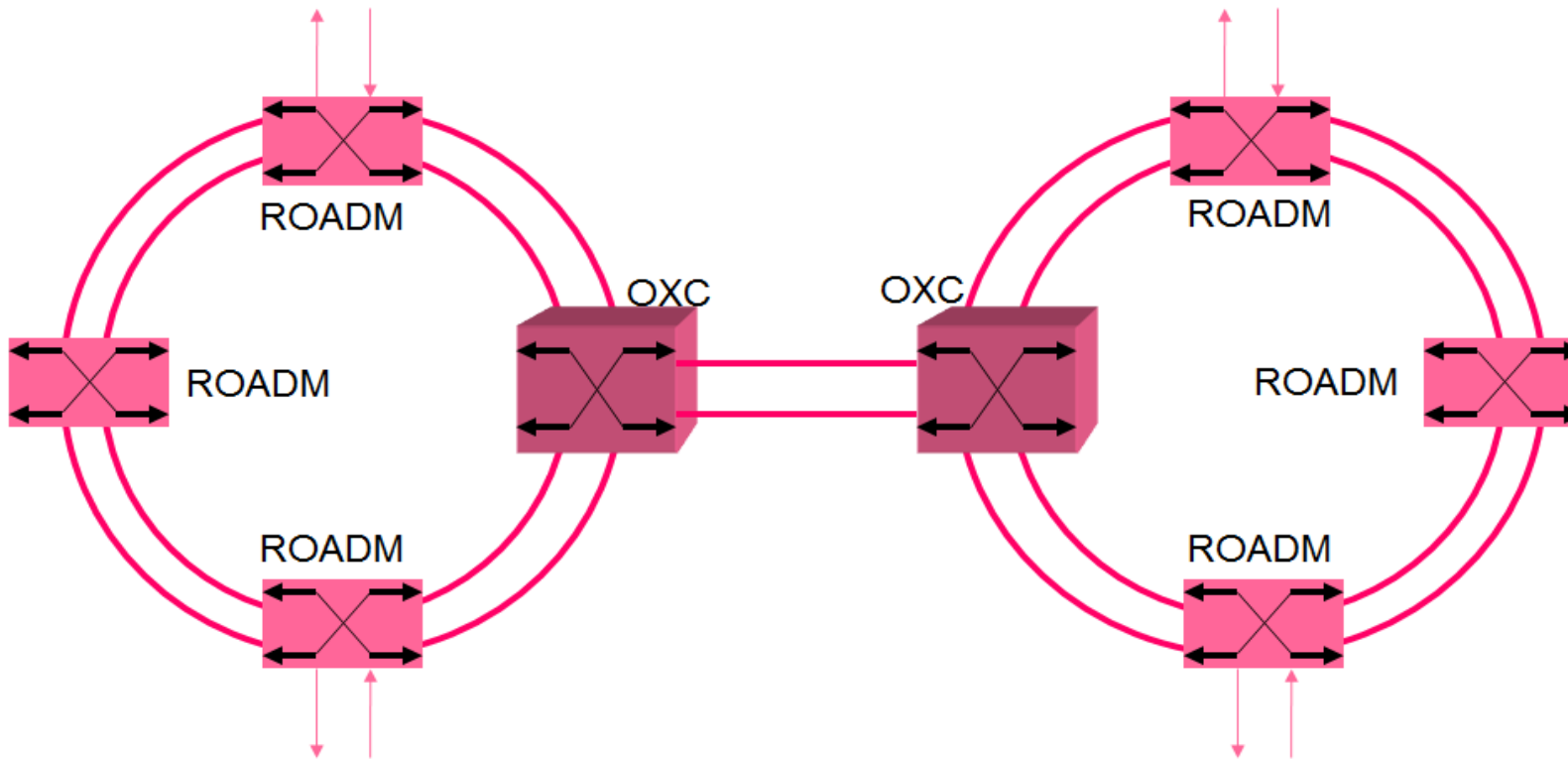
WDM ring network with ROADMs and OXCs.

A key component of the Self-Aware Network, ROADMs are fast becoming the core of every optical node, providing the flexibility to remotely reconfigure any or all wavelengths, thereby reducing time-to-service, simplifying the network and streamlining planning and management.

Network – circuit switching and packet switching/routing

Circuit switching

Switches

Switches

Packet switching

Switch

Internet
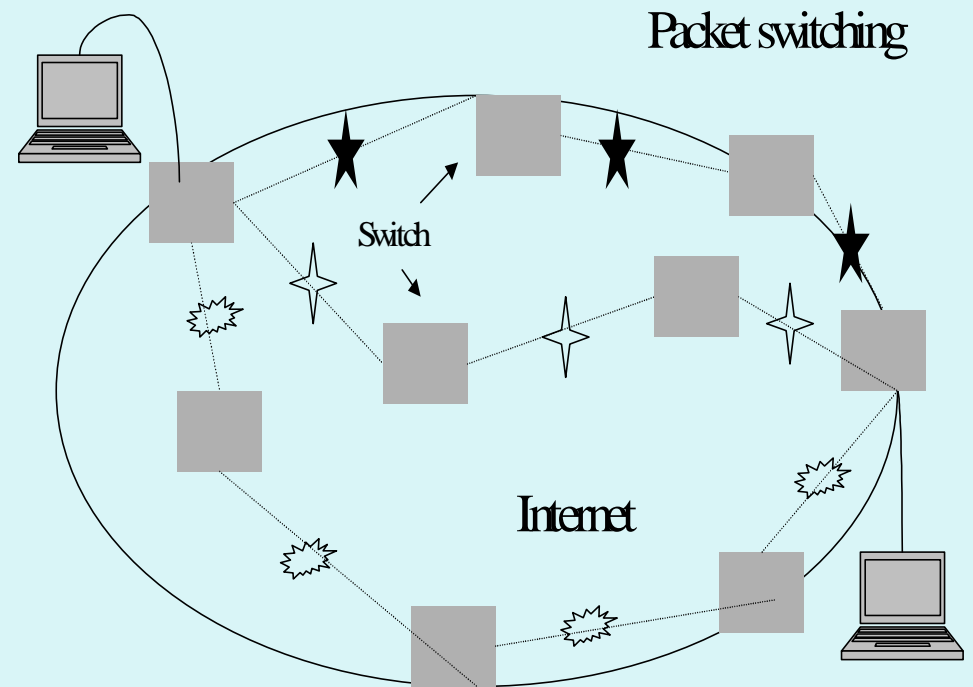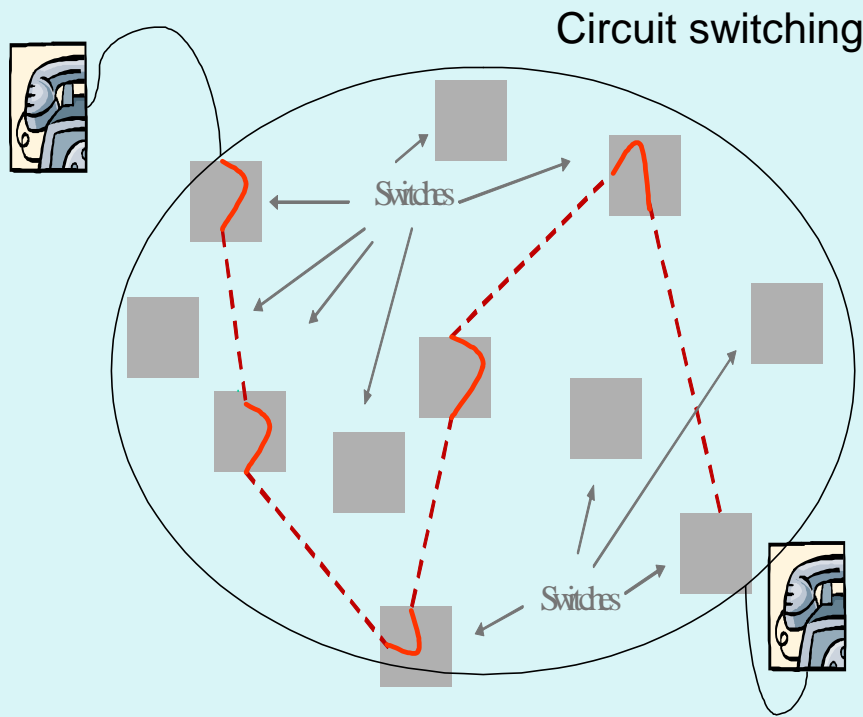
The trend is to replace the circuit-switching approach by the packet-switching/routing (called IP) method.

Optical network and IP transmission

As optical communications has migrated from point-to-point links to optical networks, ➔ switching and routing problems ➔ ideal solution: optical packet switching .

Optical network and IP transmission

Data

Internet

IP router/ MPLS

Optical core

/GMPLS

/GMPLS

IP router/ MPLS

Data
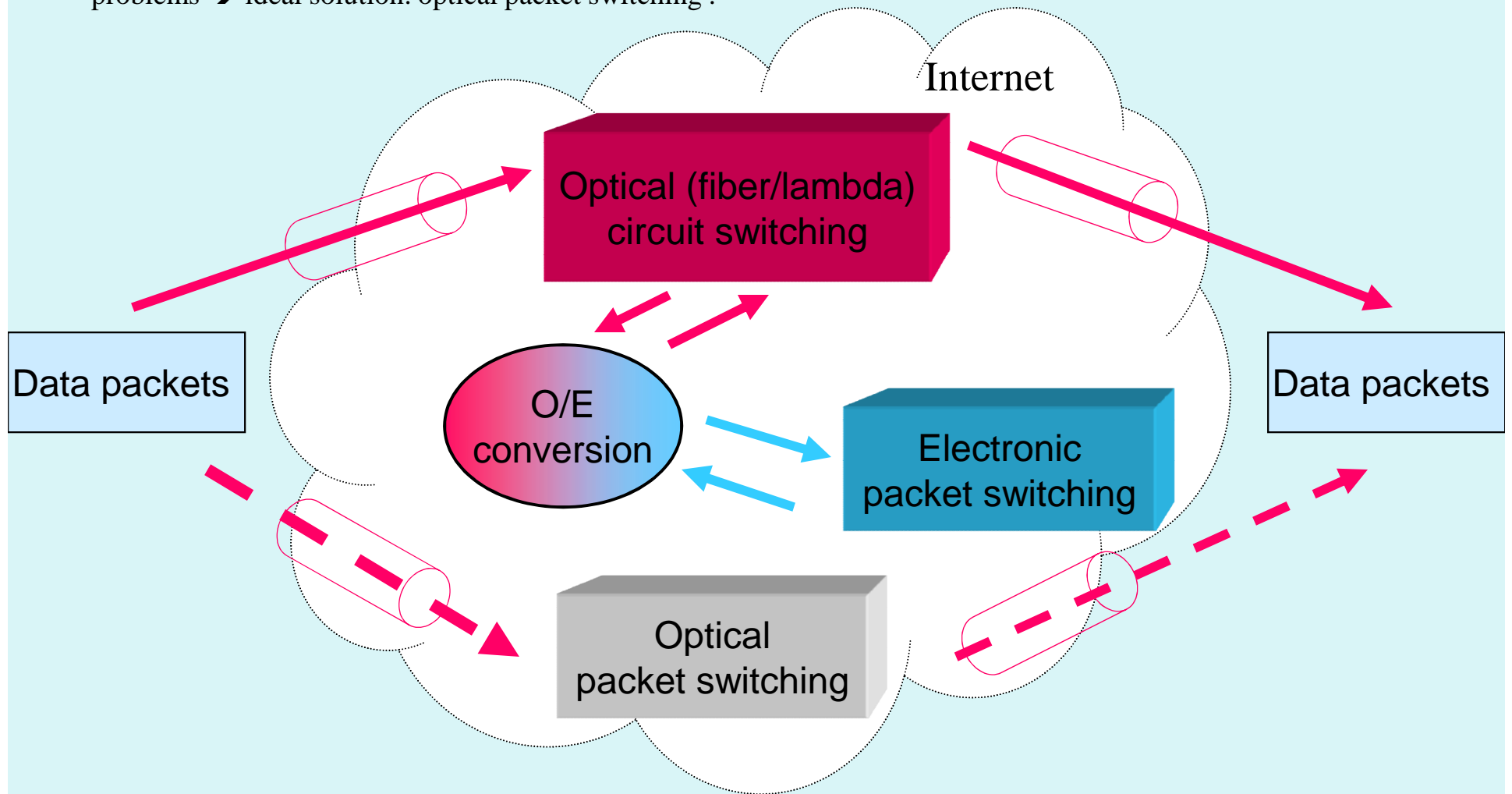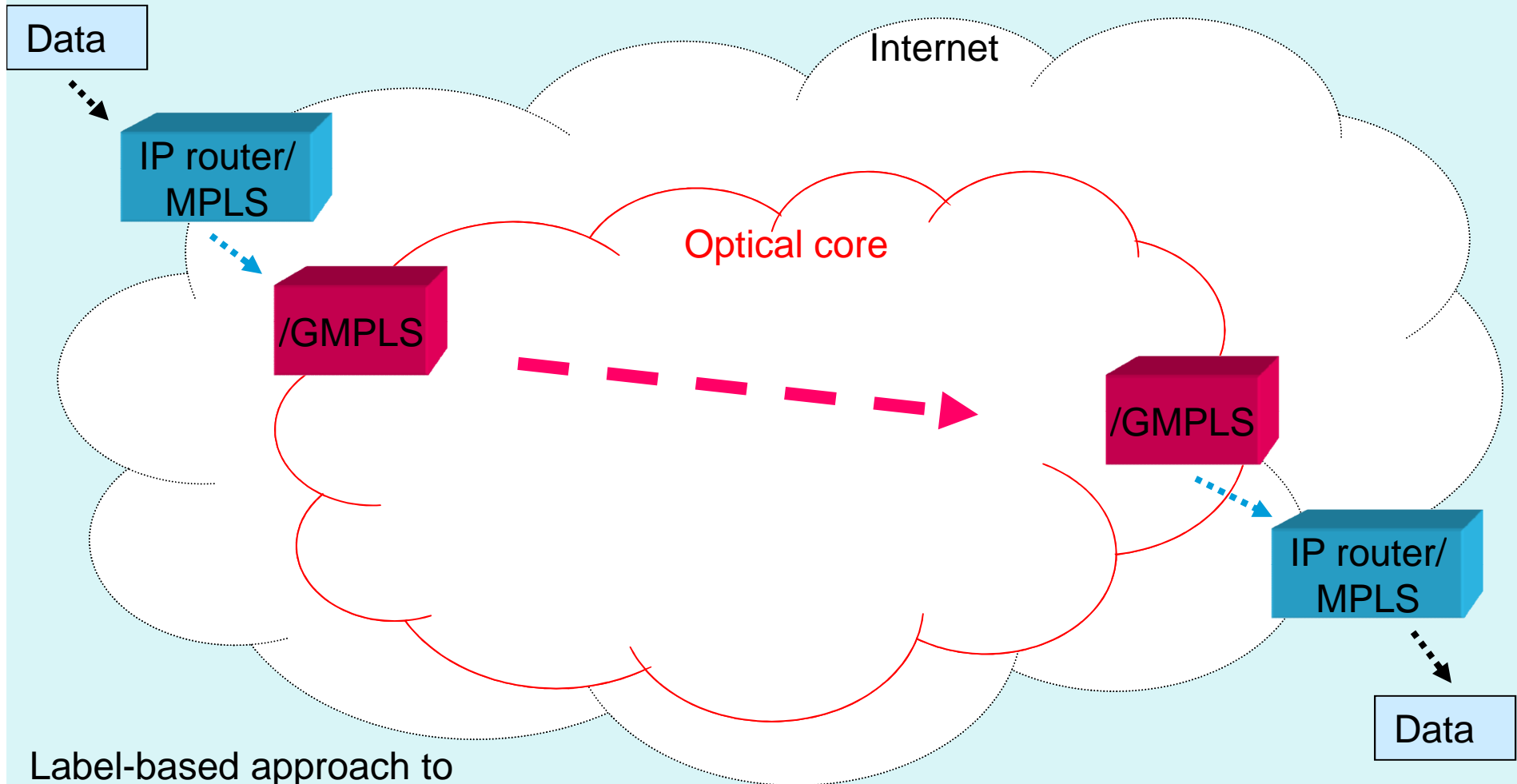
Label-based approach to delivering the Internet traffic.

IP over WDM - example

The set of routers provides IP traffic transmission from edge to edge over optical networks [Cisco].
One of the transmission's problems is granularity – the network's ability to transmit at any required rate, including a sub-wavelength's rate.
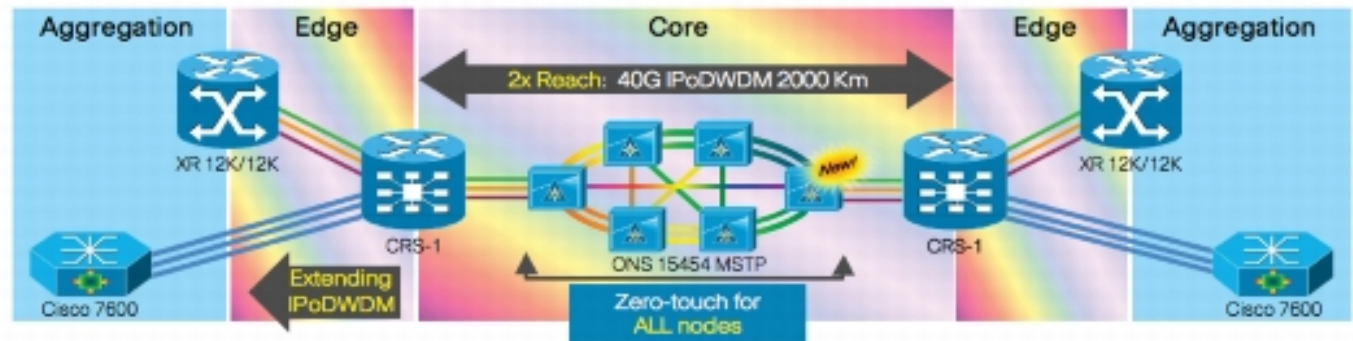
- CRS-1: Doubling Reach to 2000 KM without regeneration
- XR 12K / 12K: Extending IPoDWDM to the Edge
- ONS 15454 MSTP: Omnidirectional and Colorless ROADM
- Proactive Protection: Resetting the standard for superior experiences
- Virtual Transponder: Preserves existing operational models
- Eco-friendly: Reduced space, power and cooling

Cisco Carrier Routing System (CRS)

Cisco 12000 Series Routers

Cisco ONS 15454 Multiservice Transport Platform

Optical network – data plane and control plane
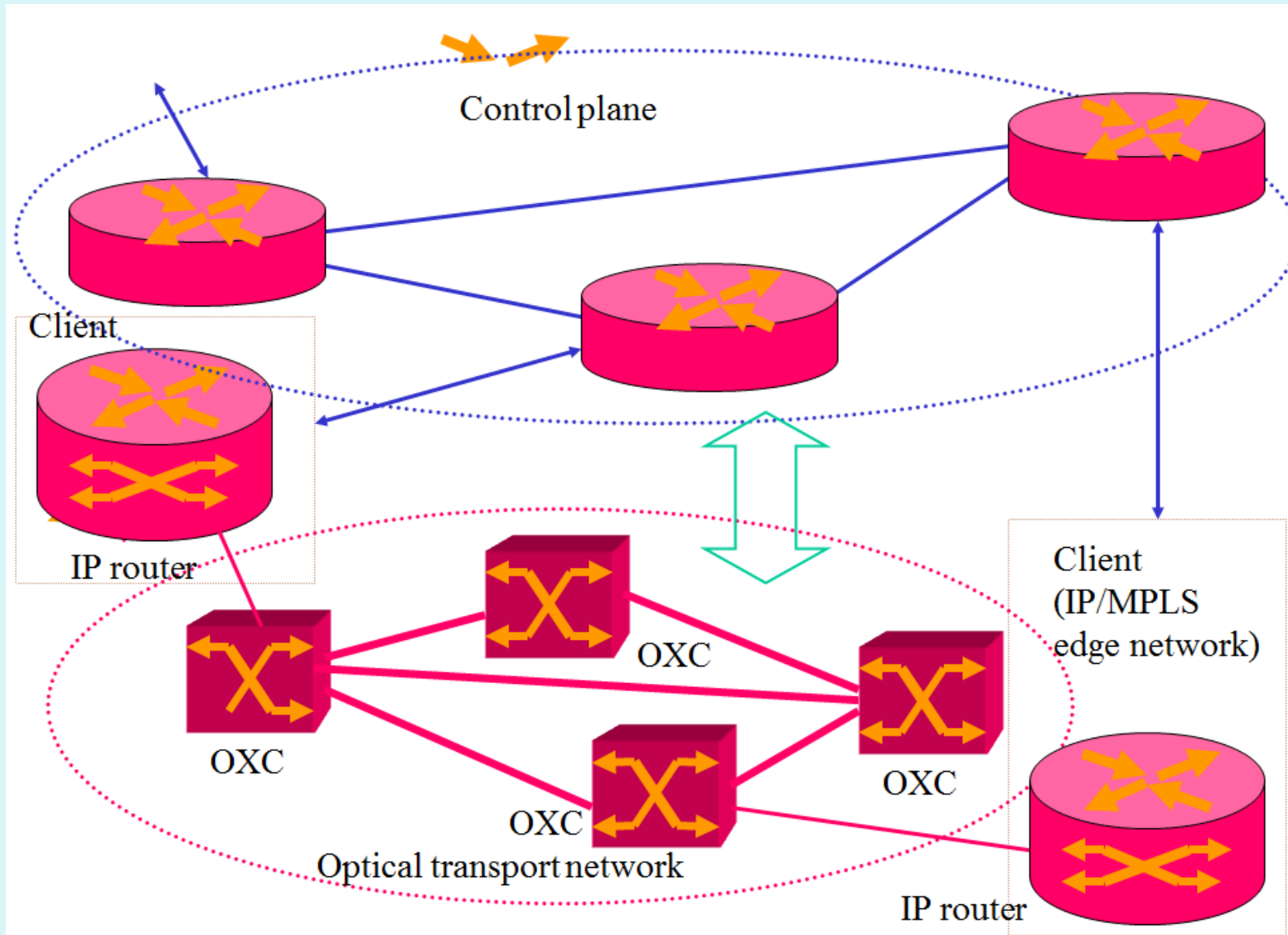
Data plane and control plane

Control plane and data plane: Separation of control and transport functions

Optical network node

Control messages

Control messages

Control plane (router)

Interface

Traffic

Data plane (OXC)

Traffic

Network - OADM

Node B

Node A

Optical through traffic (optical bypass)

Node C

Drop traffic   Add traffic

OADM –optical add/drop multiplexer

Network - ROADM

Port complex

Control plane

Signal monitor

Switch fabric

OADM = switch
with only two ports:
in and out.

Local traffic

Local traffic
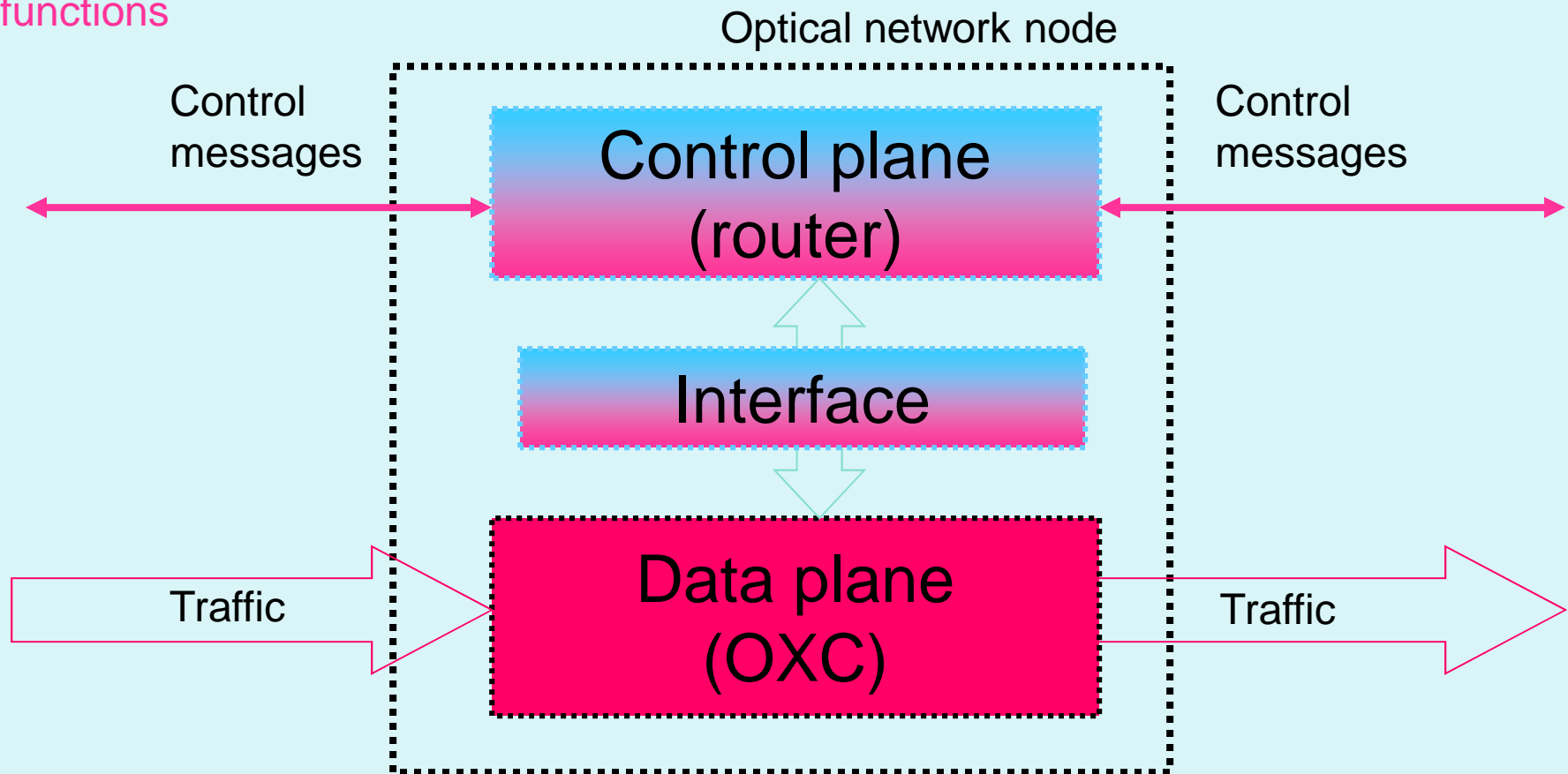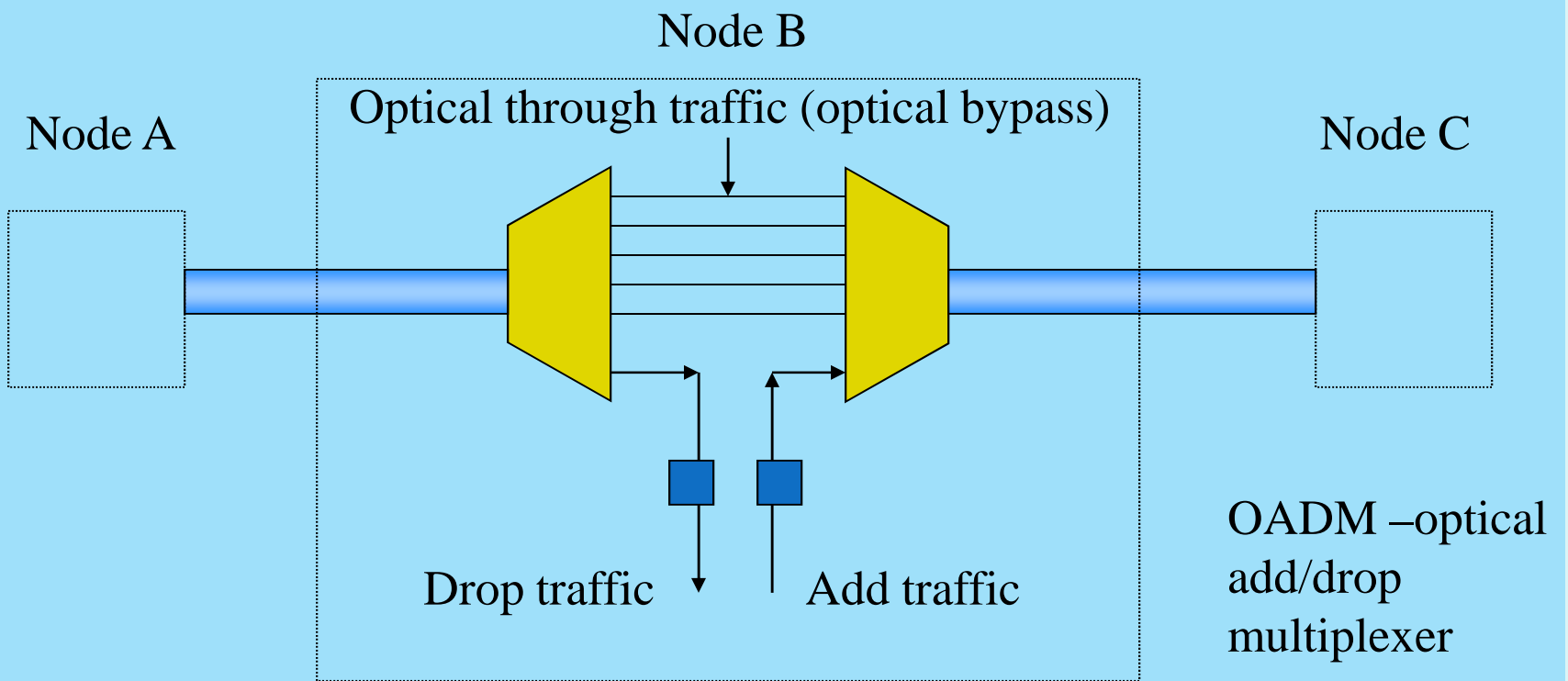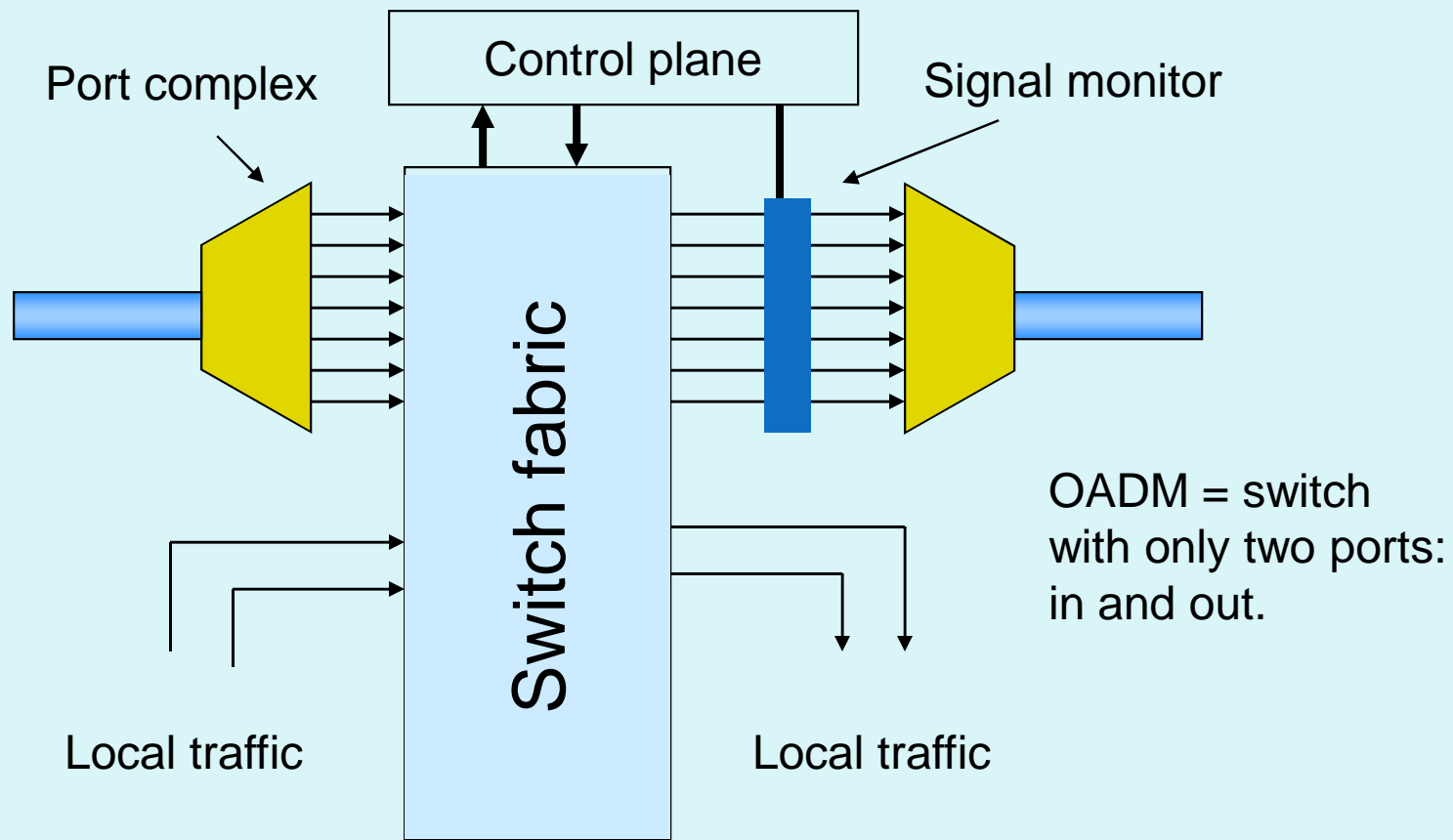
Reconfigurable OADM. (After J. Lacey.)

Network - OXC

Optical cross connect (OXC)

Fiber switch (FXC). (Automated fiber patch panel.)

Wavelength-selective cross-connect (WSXC).

OXC with wavelength conversion. (Wavelength interchanging XC, WIXC.)
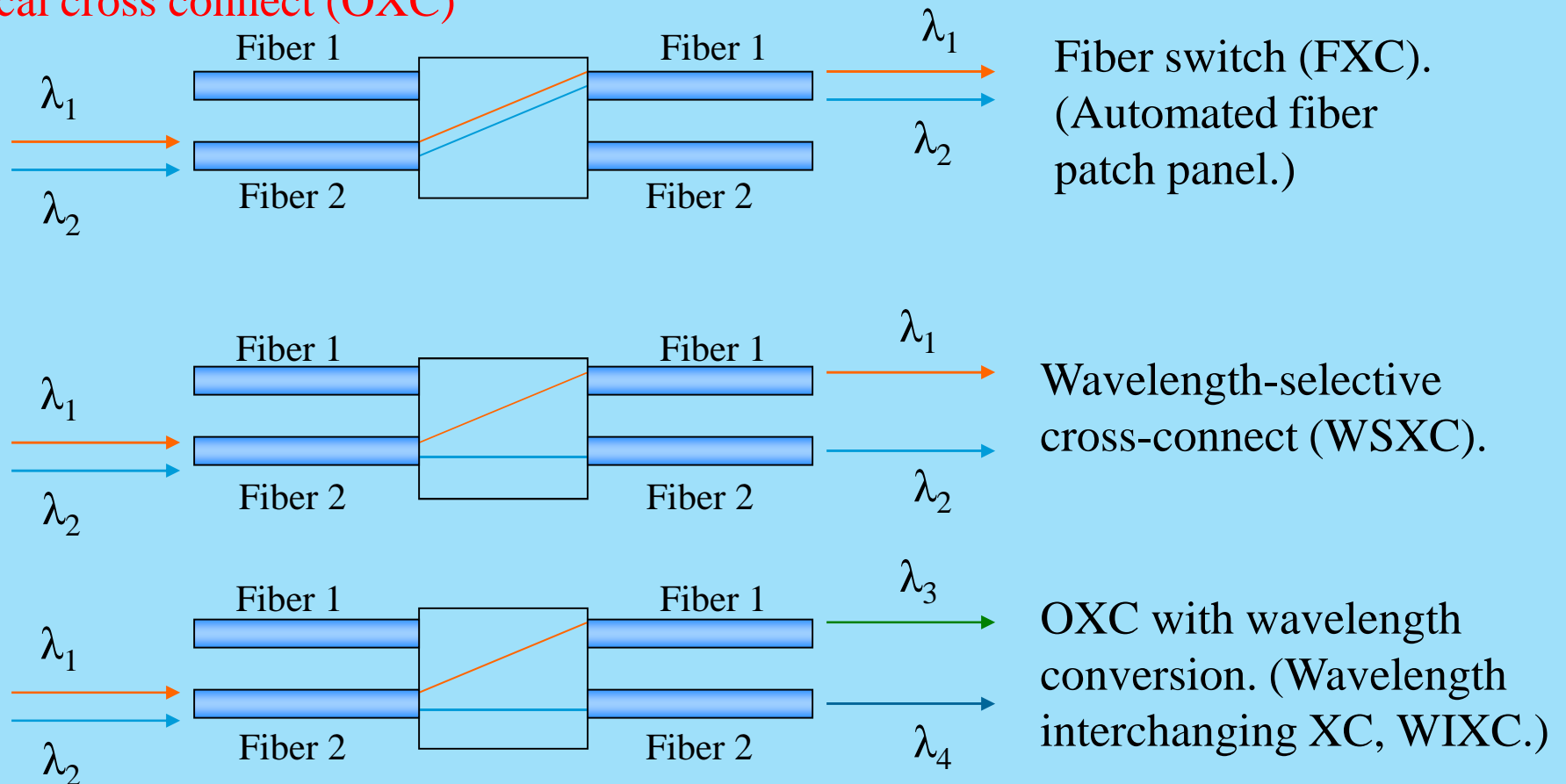
Network - OXC
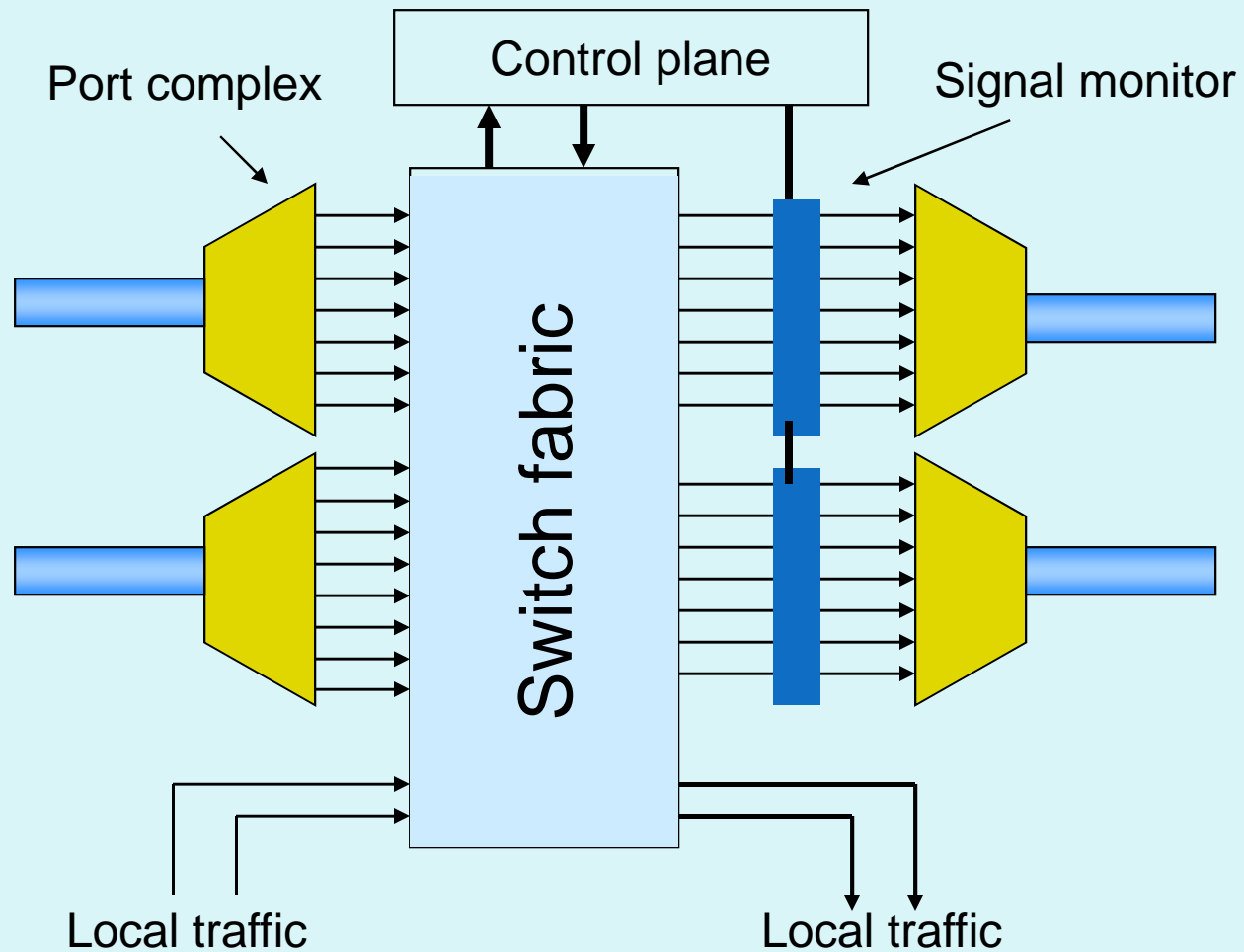
OXC general architecture. (After J. Lacey.)

Network – MEMS optical switch

3D MEMS optical switch concept
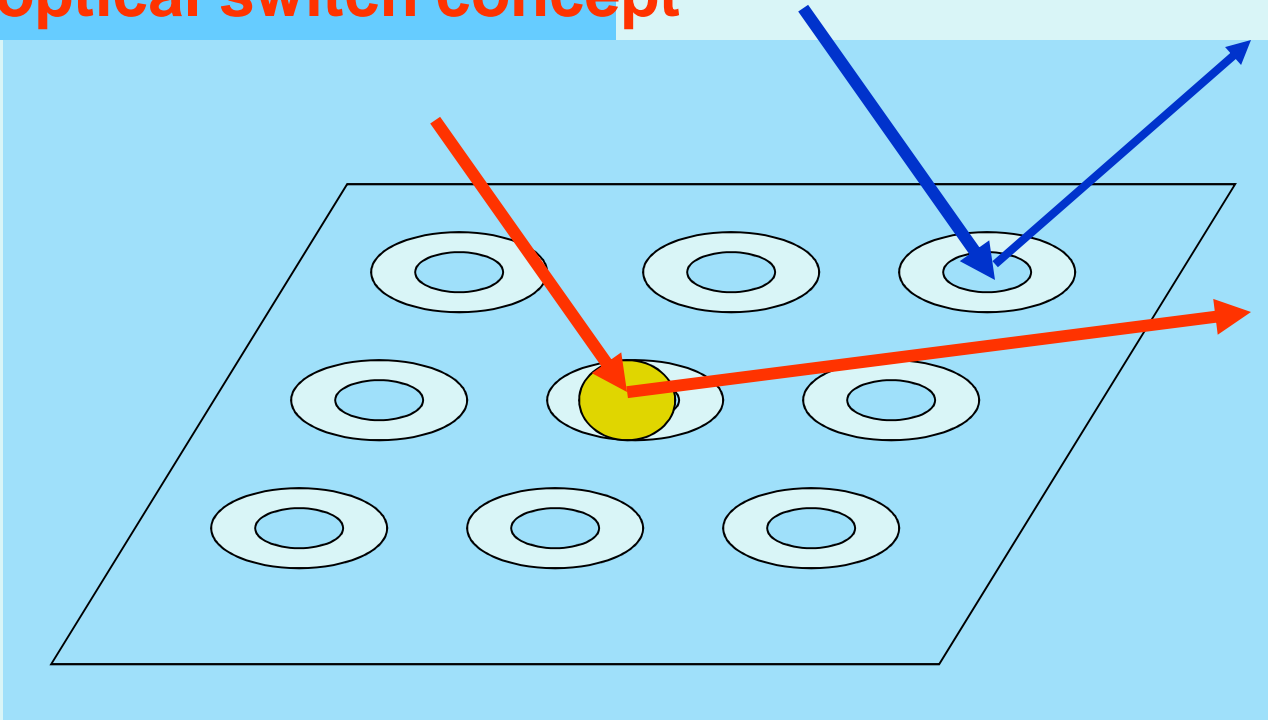
Micromirrors fabricated on a silicon substrate ⬅ semiconductor manufacturing technology. 2D and 3D mirrors. Precise analog electrical control. Large number of ports.

Network types and traffic aggregation
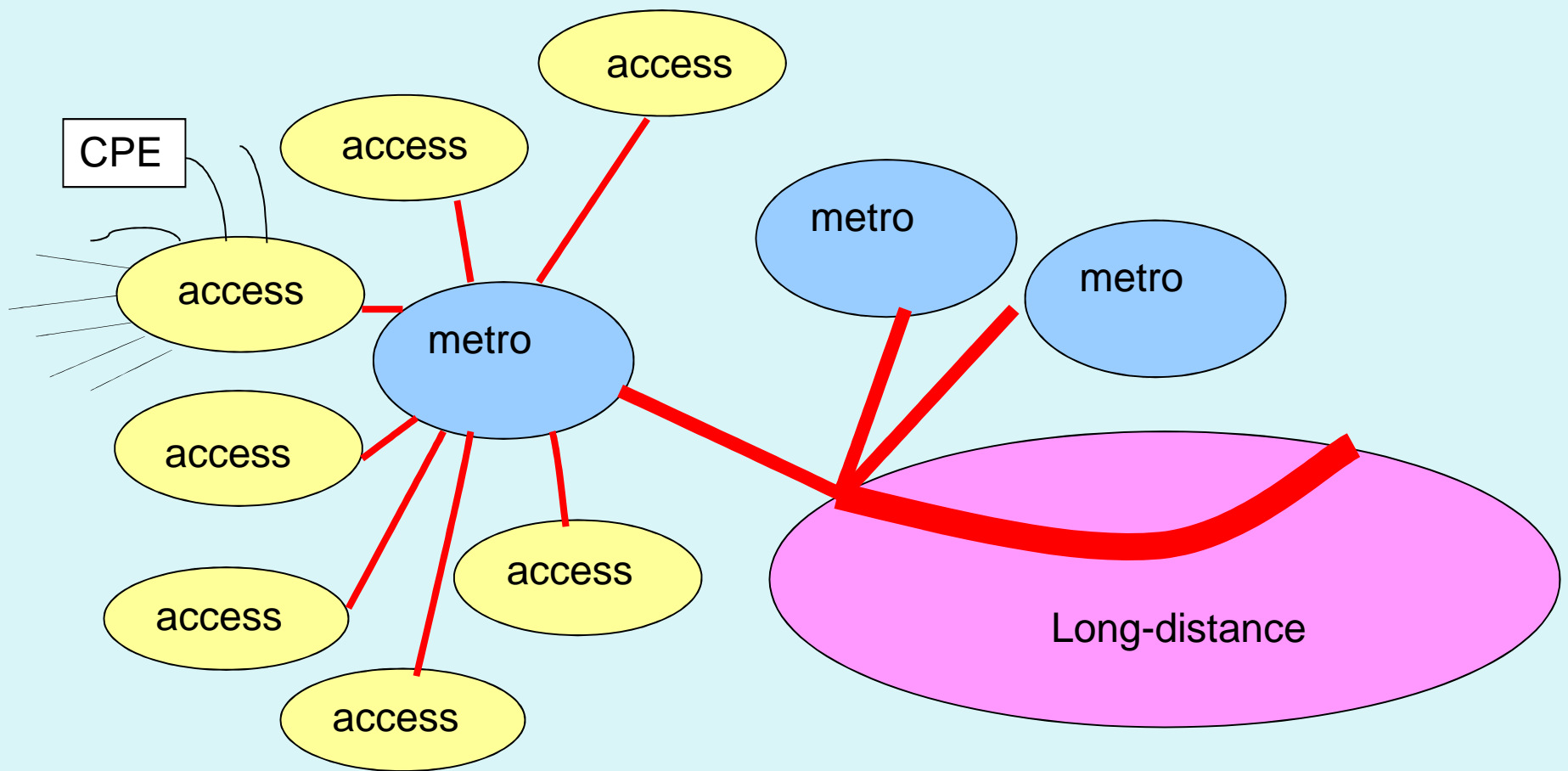
Three types of networks: traffic aggregation

Key issues for optical networks
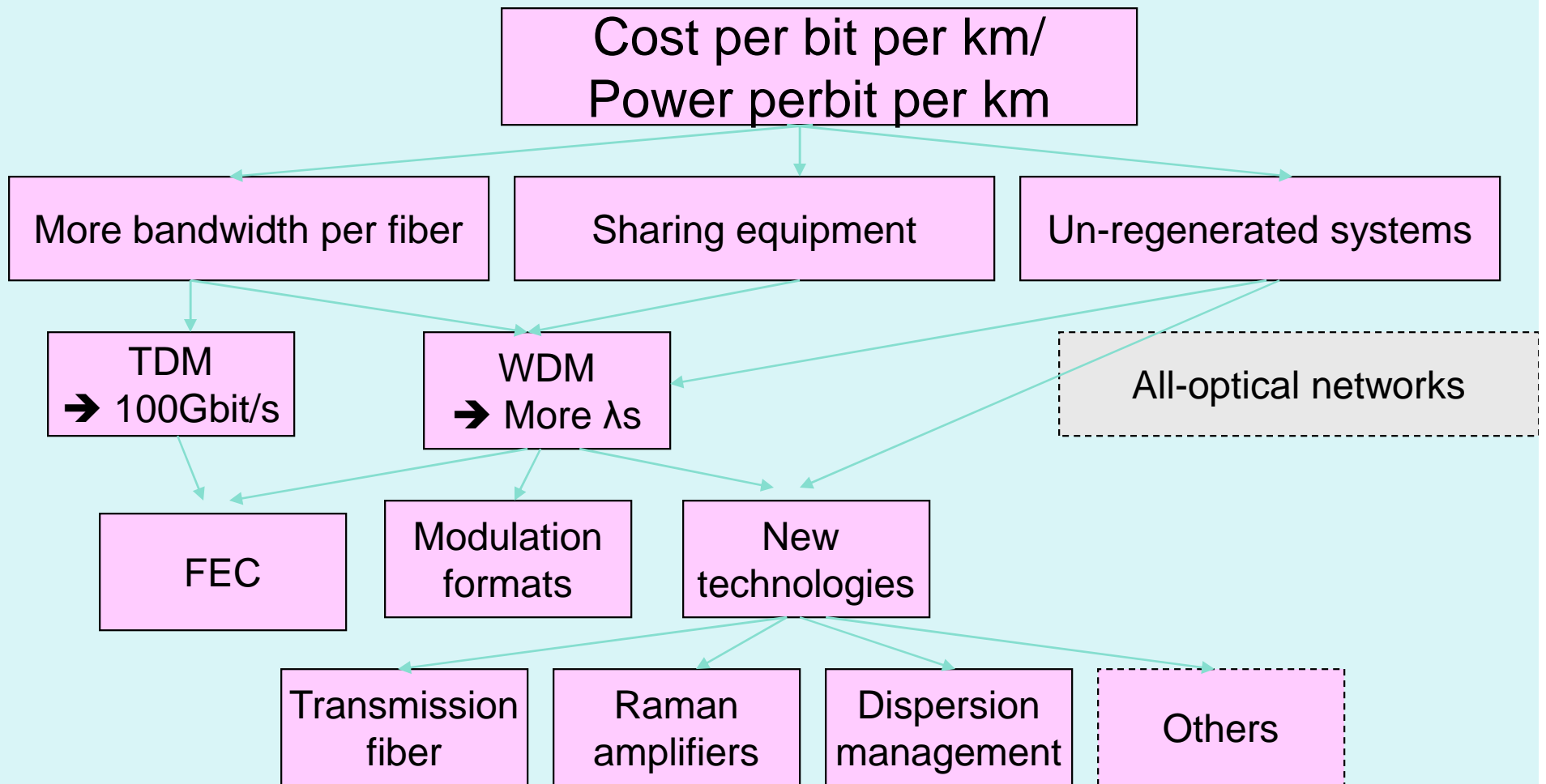
Cost per bit per km/
Power perbit per km

More bandwidth per fiber

Sharing equipment

Un-regenerated systems

TDM
➔ 100Gbit/s

WDM
➔ More λs

All-optical networks

FEC

Modulation formats

New technologies

Transmission fiber

Raman amplifiers

Dispersion management

Others

Outline

- Where we are today – current status and problems of optical communications
  - In space, in time and in spectrum
  - Network and its components
  - PON
- Trends
  - Components
  - Networks
- Conclusion

PON - passive optical network

CO or HE

POTS
Video
Data
Internet

OLT

Splitter

ONT (ONU) — CPE
ONT (ONU) — CPE
ONT (ONU) — CPE

CO – Central office
HE - Head end of CATV
POTS - Plain old telephone service
OLT - Optical line terminal
ONT - Optical network terminal
ONU - Optical network unit
CPE - Customer premises equipment
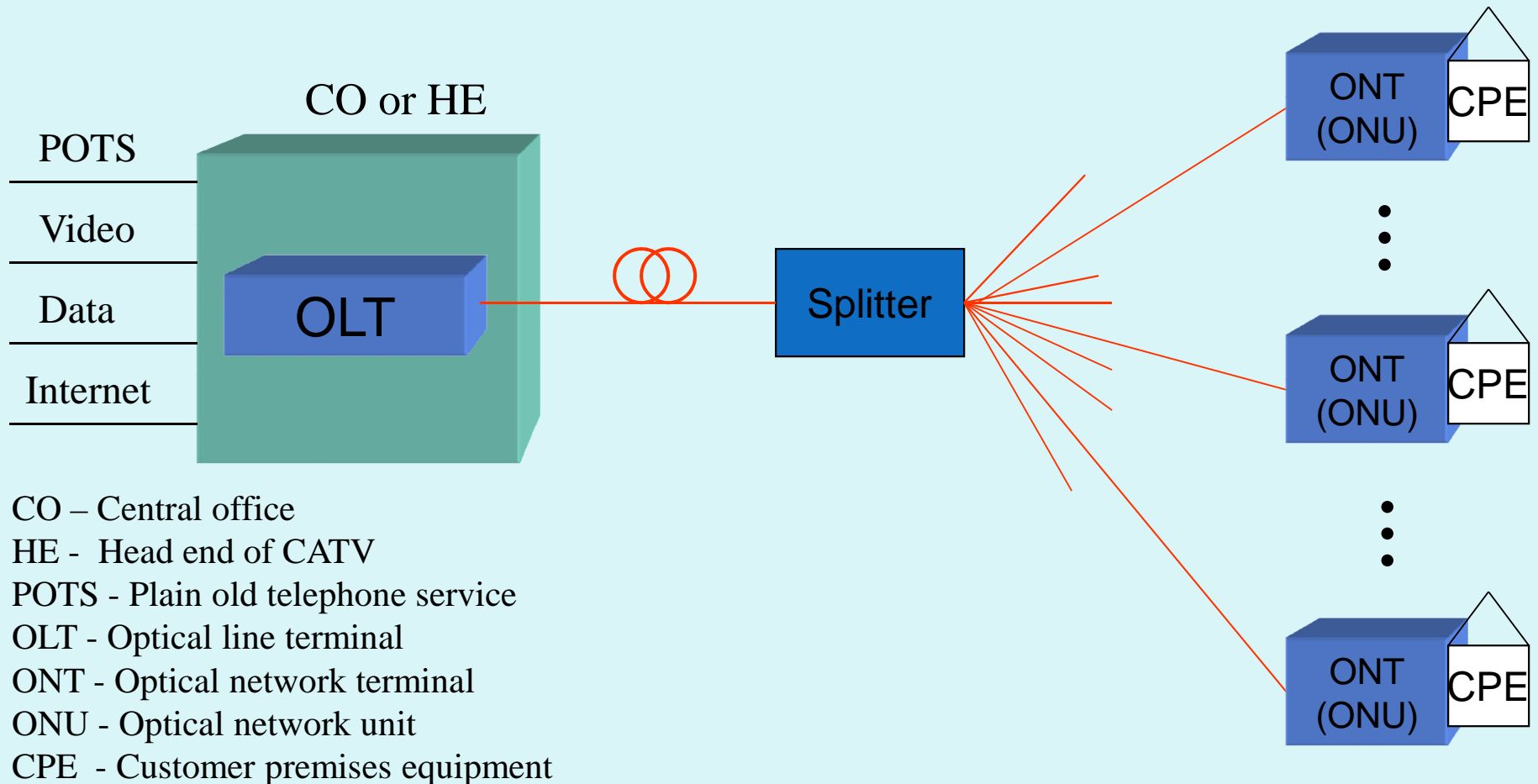
PON basic configuration

PON – passive optical network
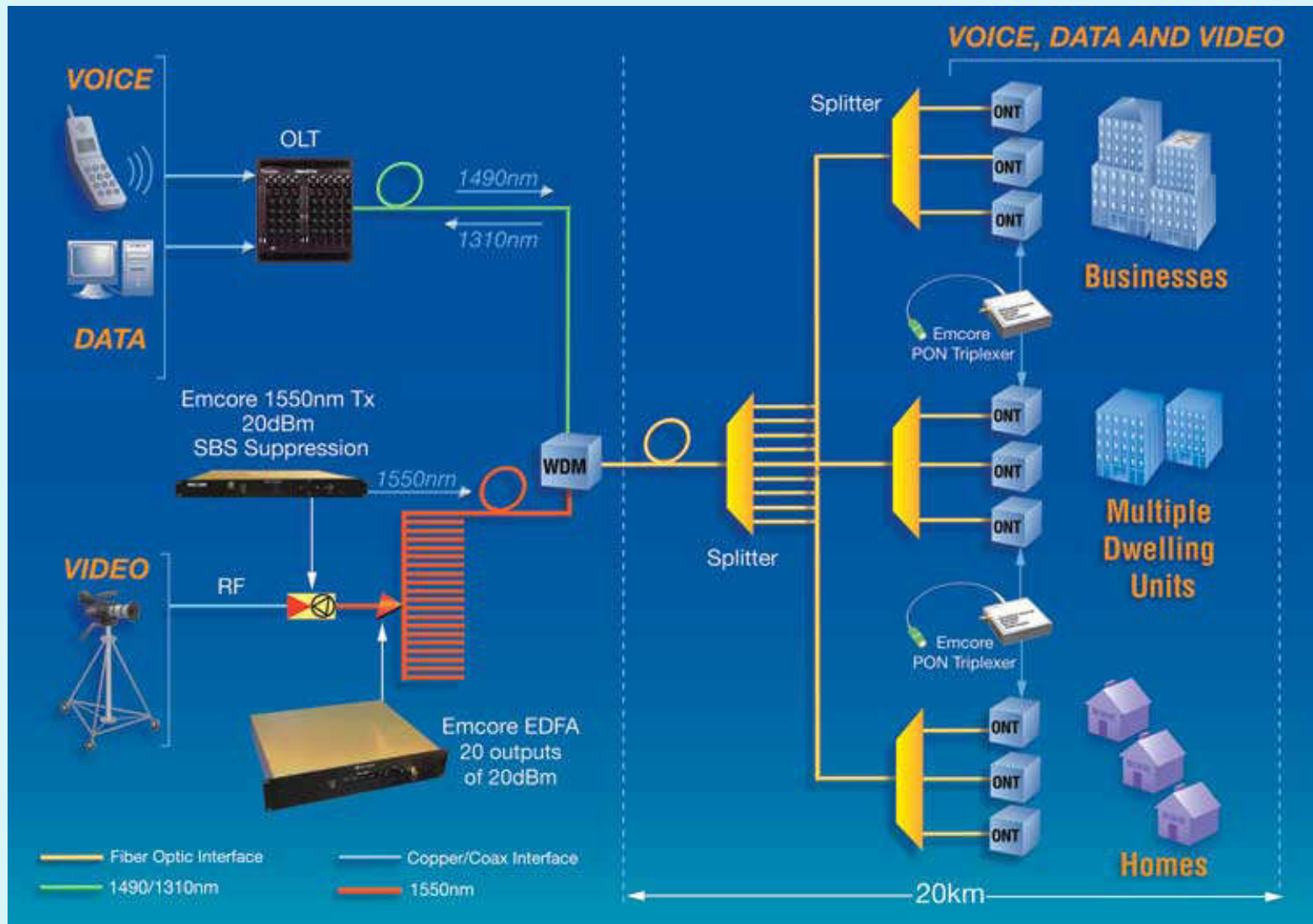
Various architectures of PON

[36]
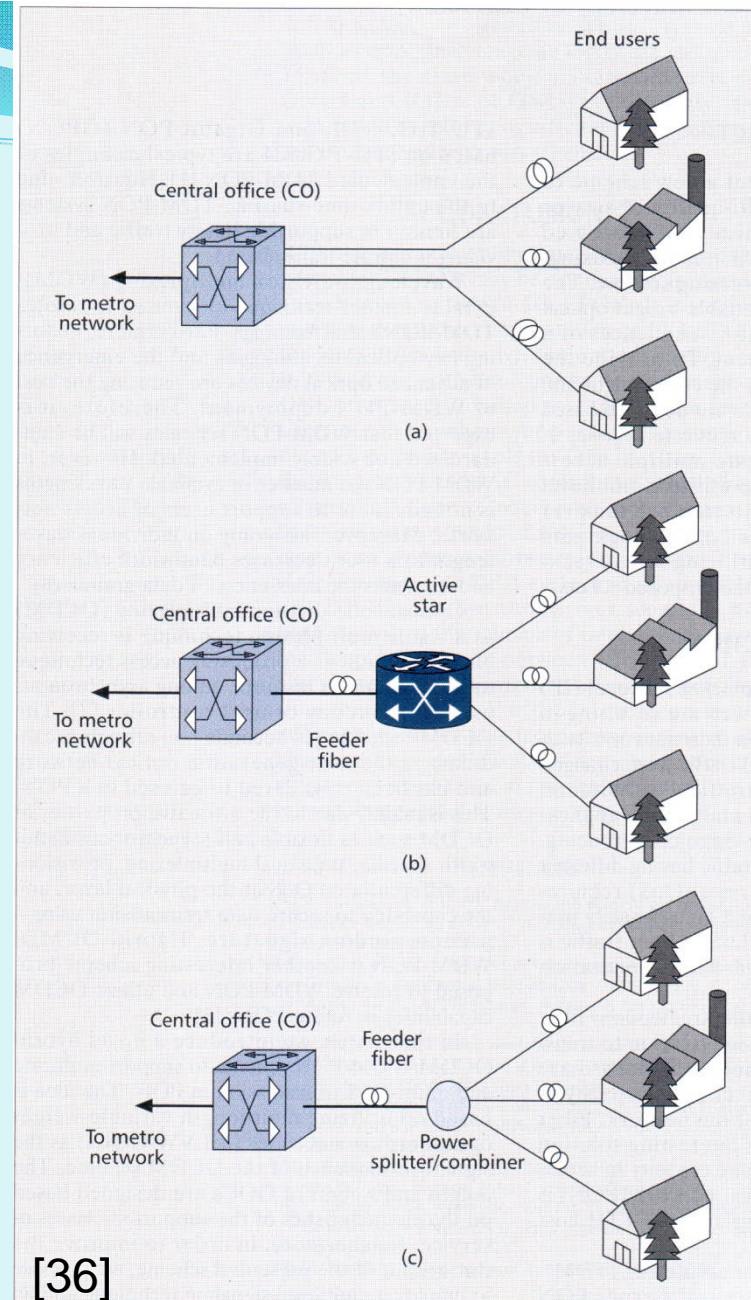
Figure 1. *Different architectures for FTTH: a) point-to-point; b) active star; c) passive star.*

TDM PON – main problems

Lifeline service

↓

Power supply

- **Utility power line**
- **Telco dc power from curb cabinet**
- **Battery in CPE**
- **Low power-consumption components**

Survivability (Resilience)

- **Unprotected PON**
- **Protected PON**

Duplicating feeder fiber and main splitter

Duplicating entire PON network
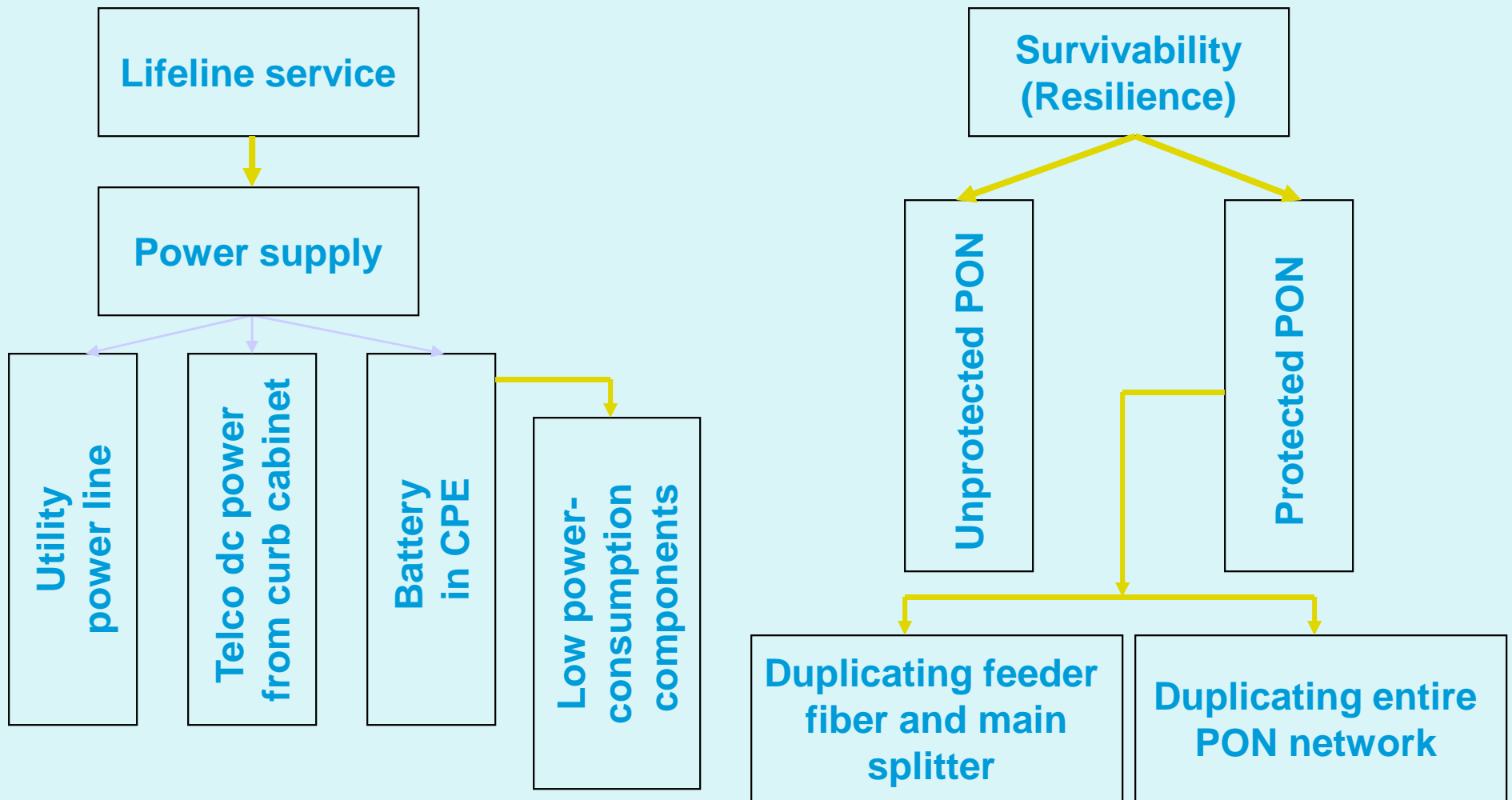
TDM PONs – Physical layer: basic wavelength usage

POTS
(voice)

Data
(Internet,
other)

OLT

$\lambda = 1310$ nm

$\lambda = 1490$ nm

WDM
MUX/DEMUX

Main splitter

$\lambda = 1550$ nm

Video

Optical Video Tx

ONT

ONU

DSL
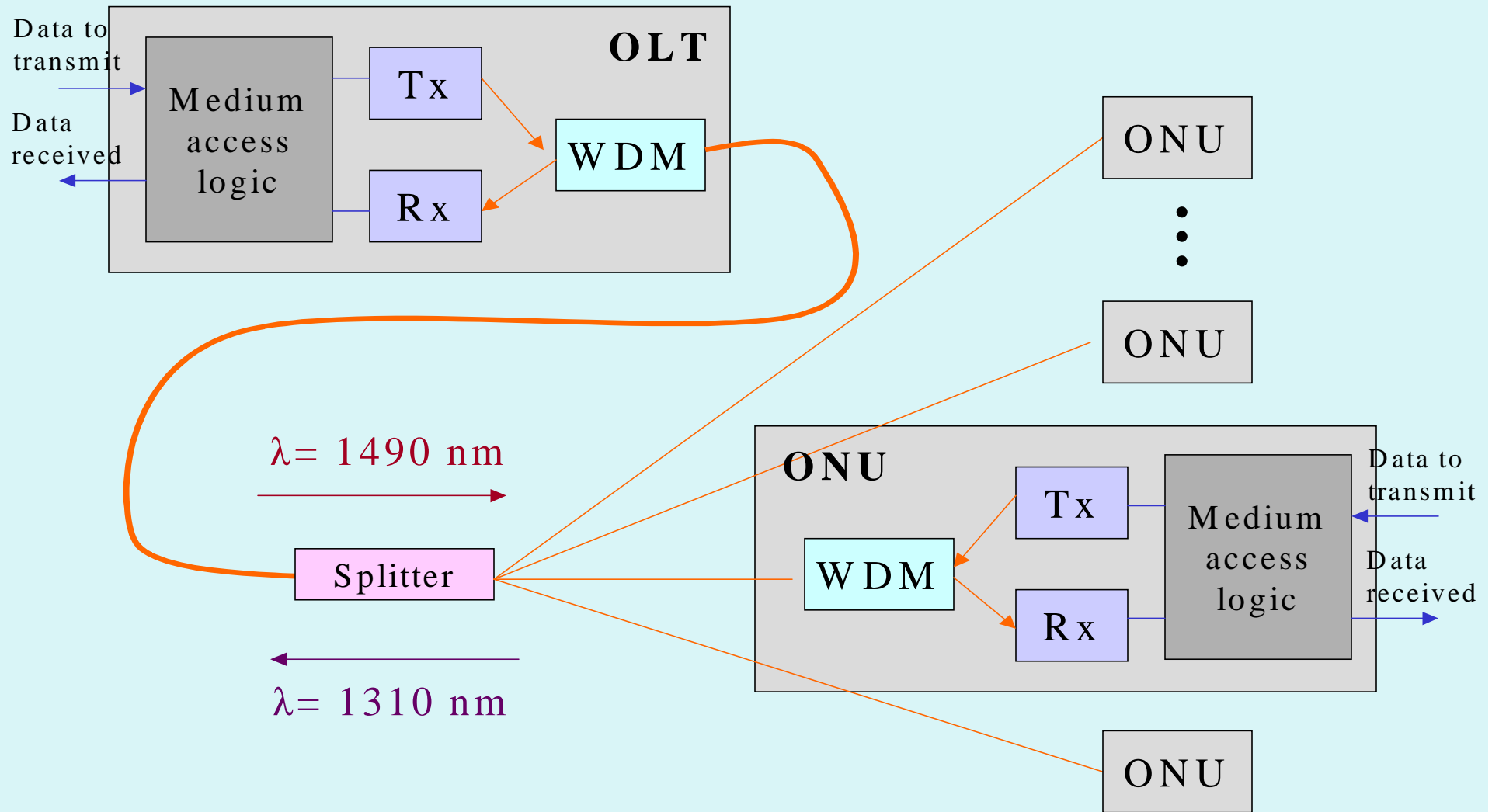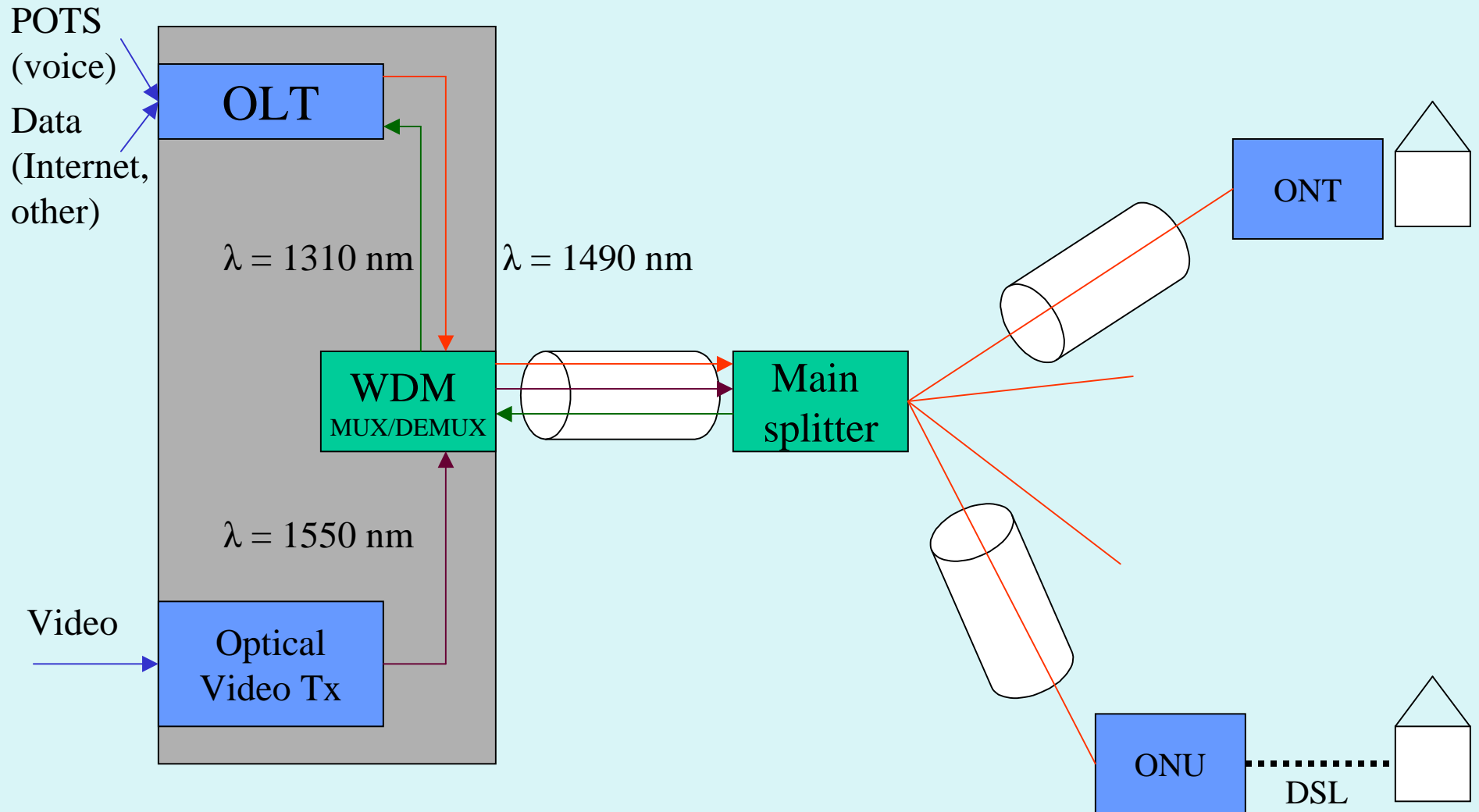
TDM PON – need for ranging

The need for distance and power ranging can be clearly seen from this setup: TDM PON with various distances ➔ need for ranging.
[Z. Belfgih, OWS1, OFC 2007.]
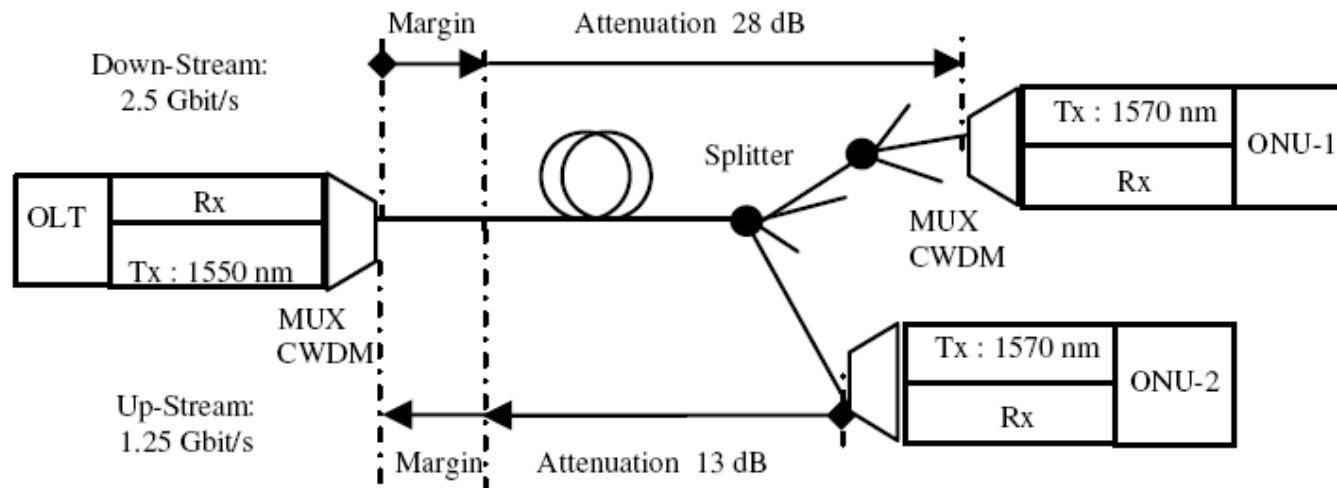
Figure 1. Experimental setup with an optical budget of class B+ GPON architecture.

TDM PON - ranging

Distance ranging	What	Power ranging
↓		↓
Support TDMA operation	Why	Equalize SNR for each link
↓		↓
Equalization of propagation delays	How	Optimization of receiver sensitivity
↓		↓
Measuring individual delays and setting artificial delays	By what means	Measuring individual Power and optimizing sensitivity of each receiver

TDM PON - protocols

ATM-based PONs

Ethernet-based PON

ATM-PON

BPON

G PON

EPON
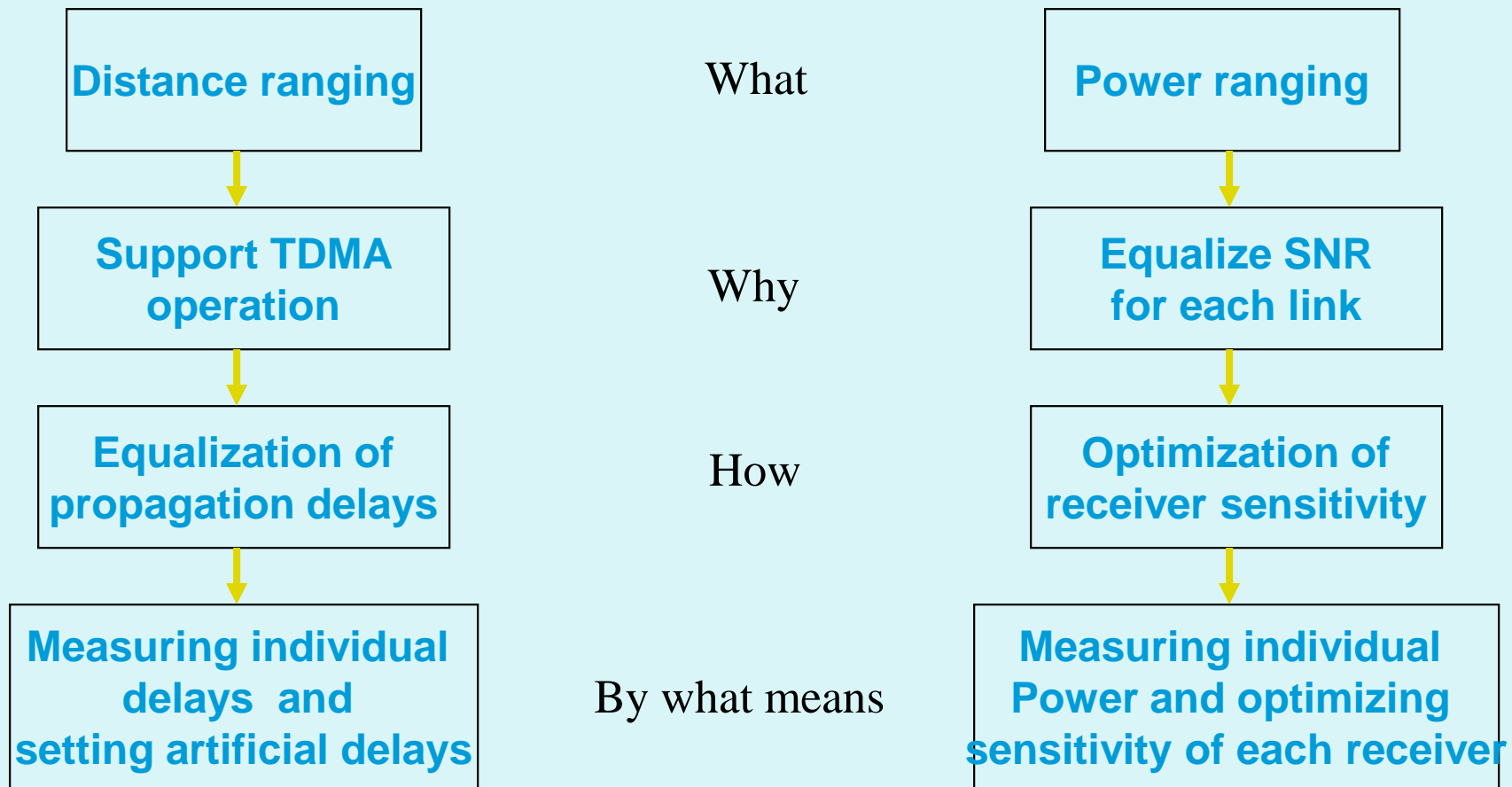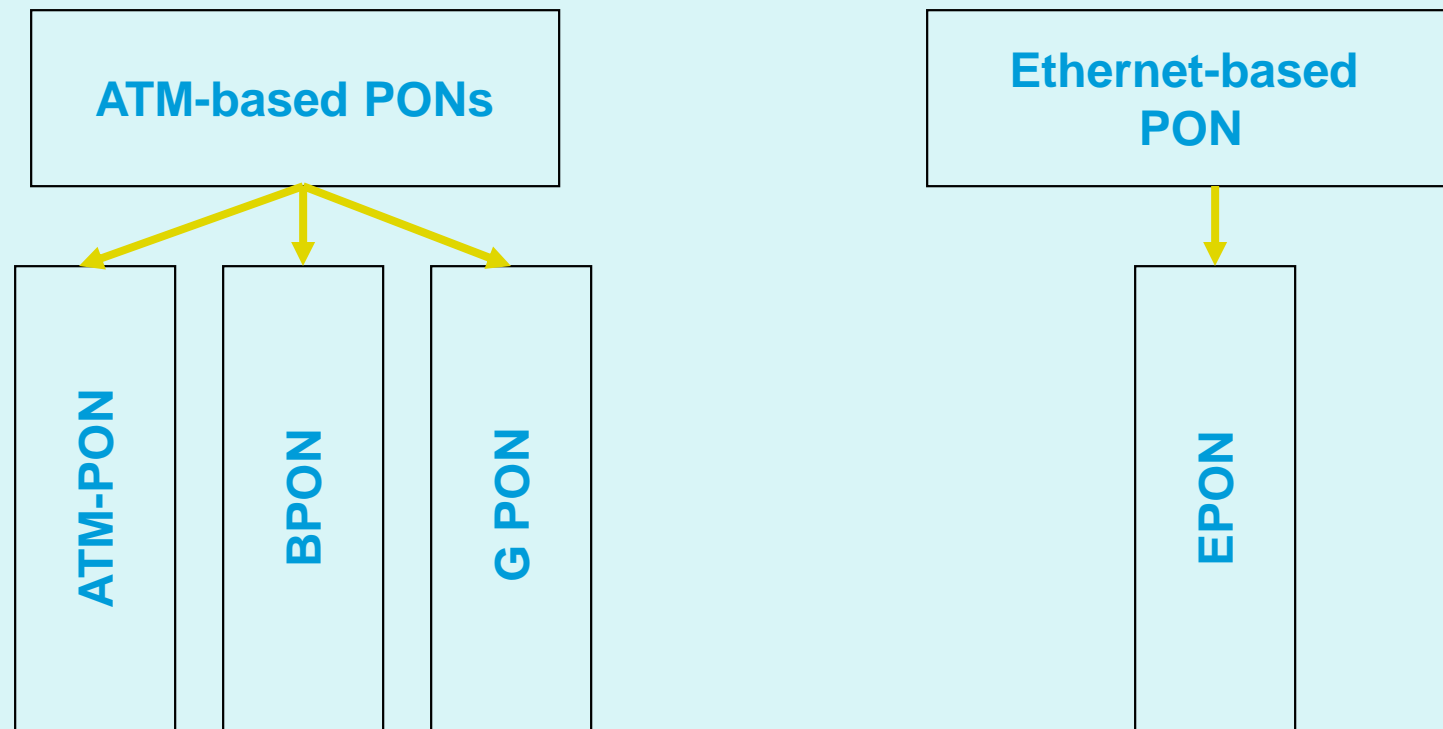
Protocol-based PON classification.
XPON – for general approach.

TDM PONs – Protocols: ATM-PON downstream and upstream frames for symmetrical 155 Mbit/s transmission by G.983 format.

Downstream frame:
56 cells of 53 bytes each: 54 data cells + 2 PLOAM cells

| PLOAM | ATM | ••• | ATM | PLOAM | ATM | ••• | ATM |

OLT → ONT

OLT ← ONT

| ATM | ••• | ATM | MBS | ATM | ••• | ATM |

Upstream frame:
53 slots (A-PON packets) of 56 bytes each (3-byte A-PON overhead followed by 53-byte ATM cell), including MBS
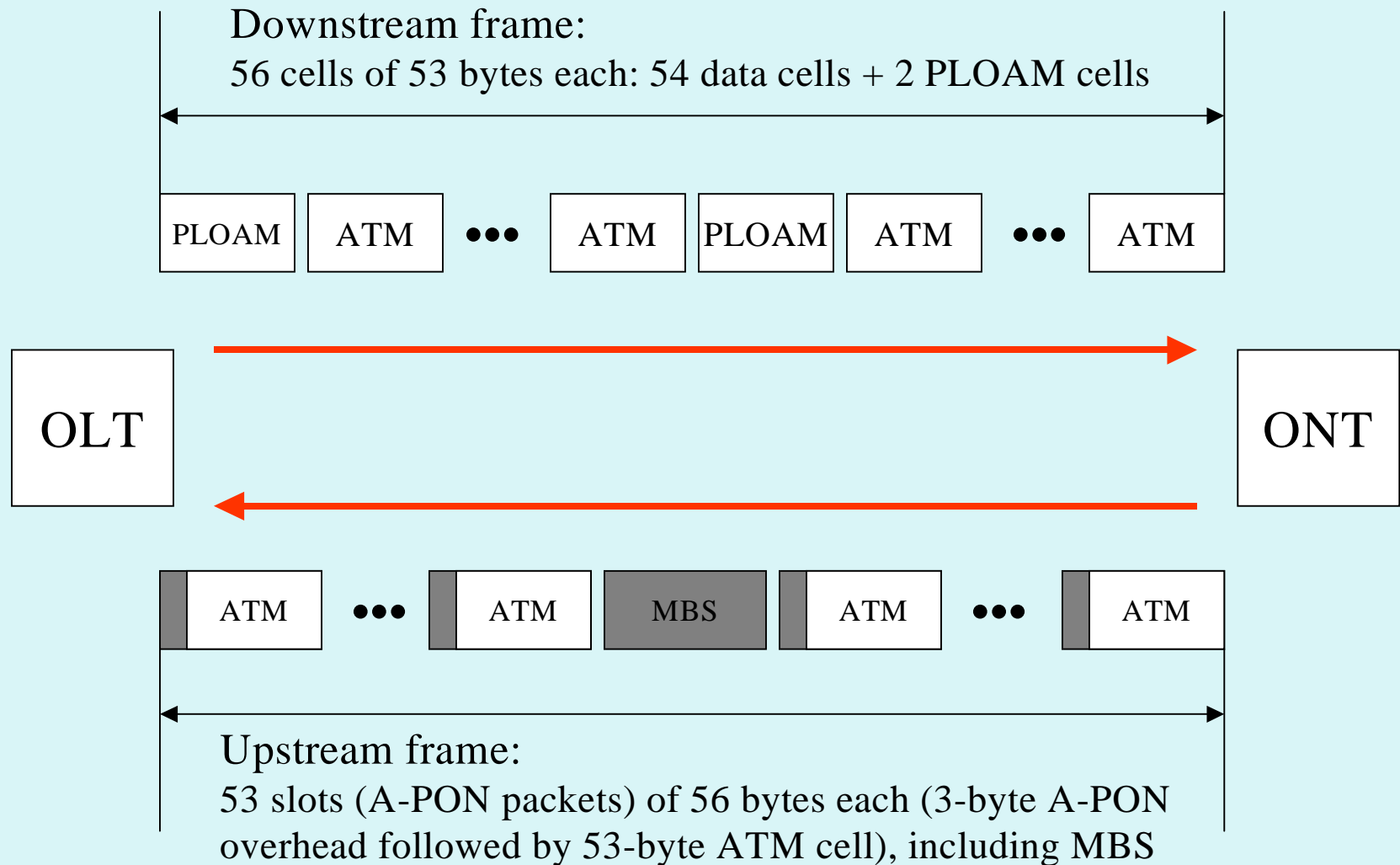
TDM PON – Protocols: MAC (media access control address) for ATM-PON

Requests

Permits

OLT

Splitter

ONU-1

ONU-i

ONU-32
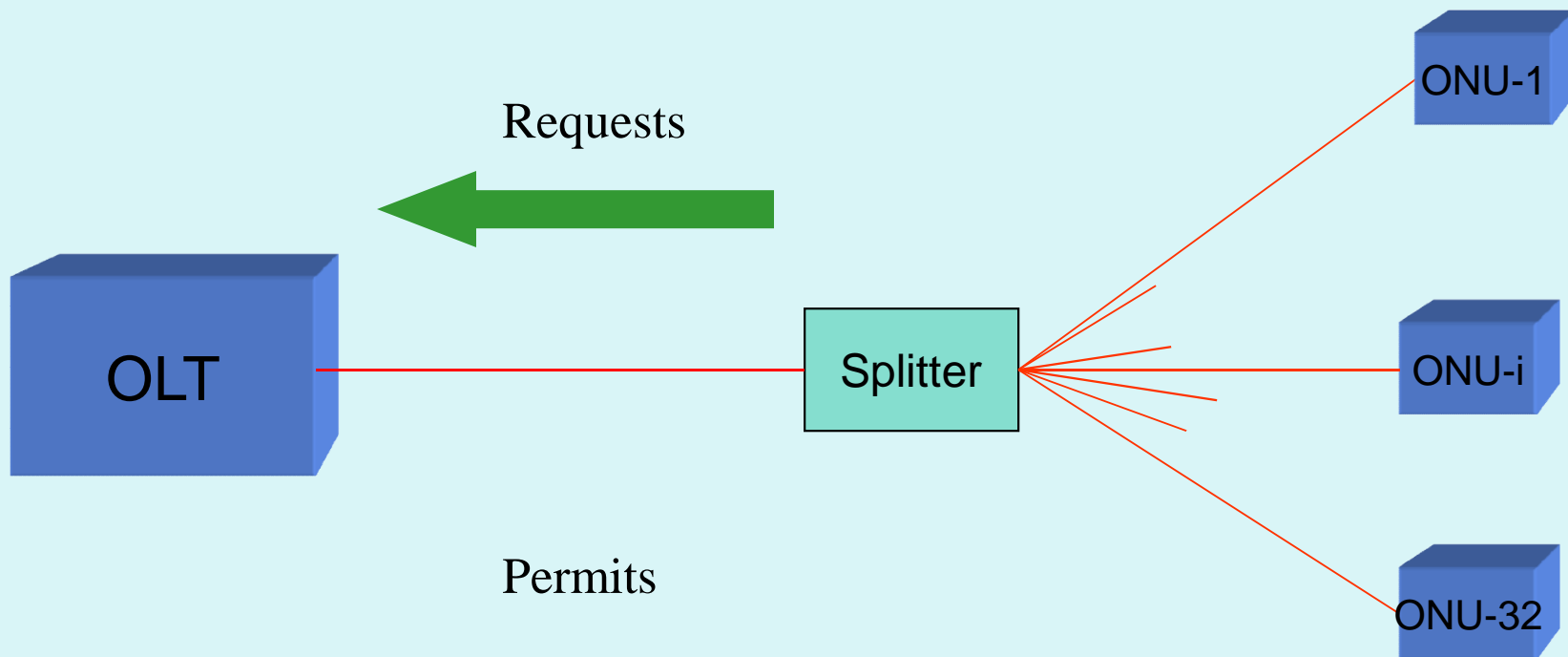
Request/permit operation in the ATM-PON MAC protocol.

TDM PON – protocols: EPON
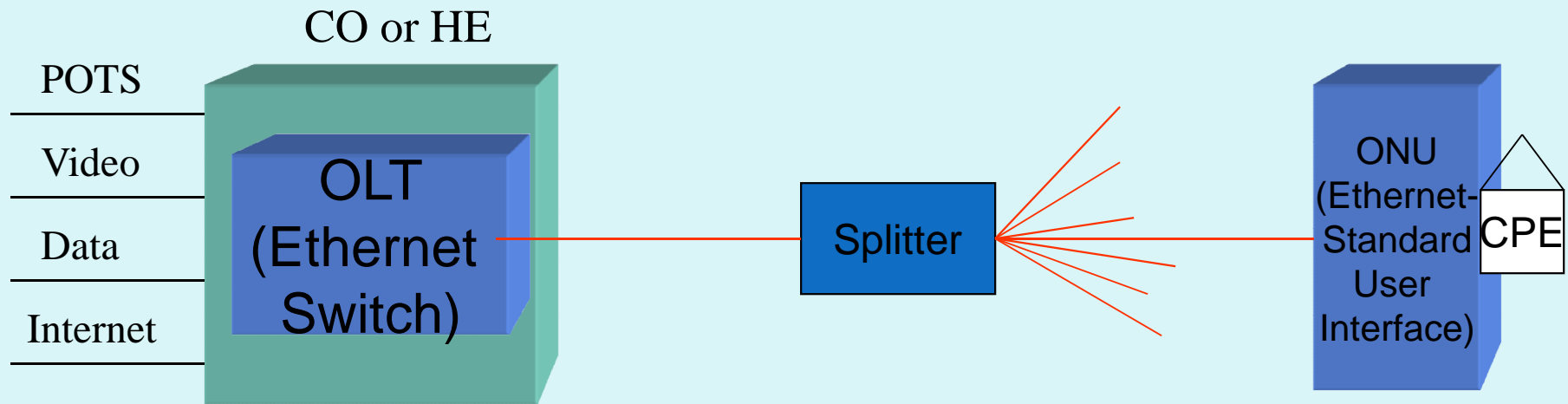
EPON, as well as ATM-PONs, includes OLT, ONUs, and ODN. EPON is defined as point-to-multipoint (P2MP) topology implemented with optical fiber and splitters. Here, the OLT is typically an Ethernet switch or media converter platform, whereas the ONU typically has Ethernet-standard WAN and subscriber interfaces.

TDM PON – EPON transmission

Logical Link ID

header payload ••• FCS

Ethernet frame (variable size)

1   2   3   2   →

OLT

1   2   3   2

ONU 1

1

To user 1

1   2   3   2

ONU 2

2   2

To user 2

1   2   3   2

ONU 3

3

To user 3

EPON downstream transmission.

TDM PON – EPON transmission
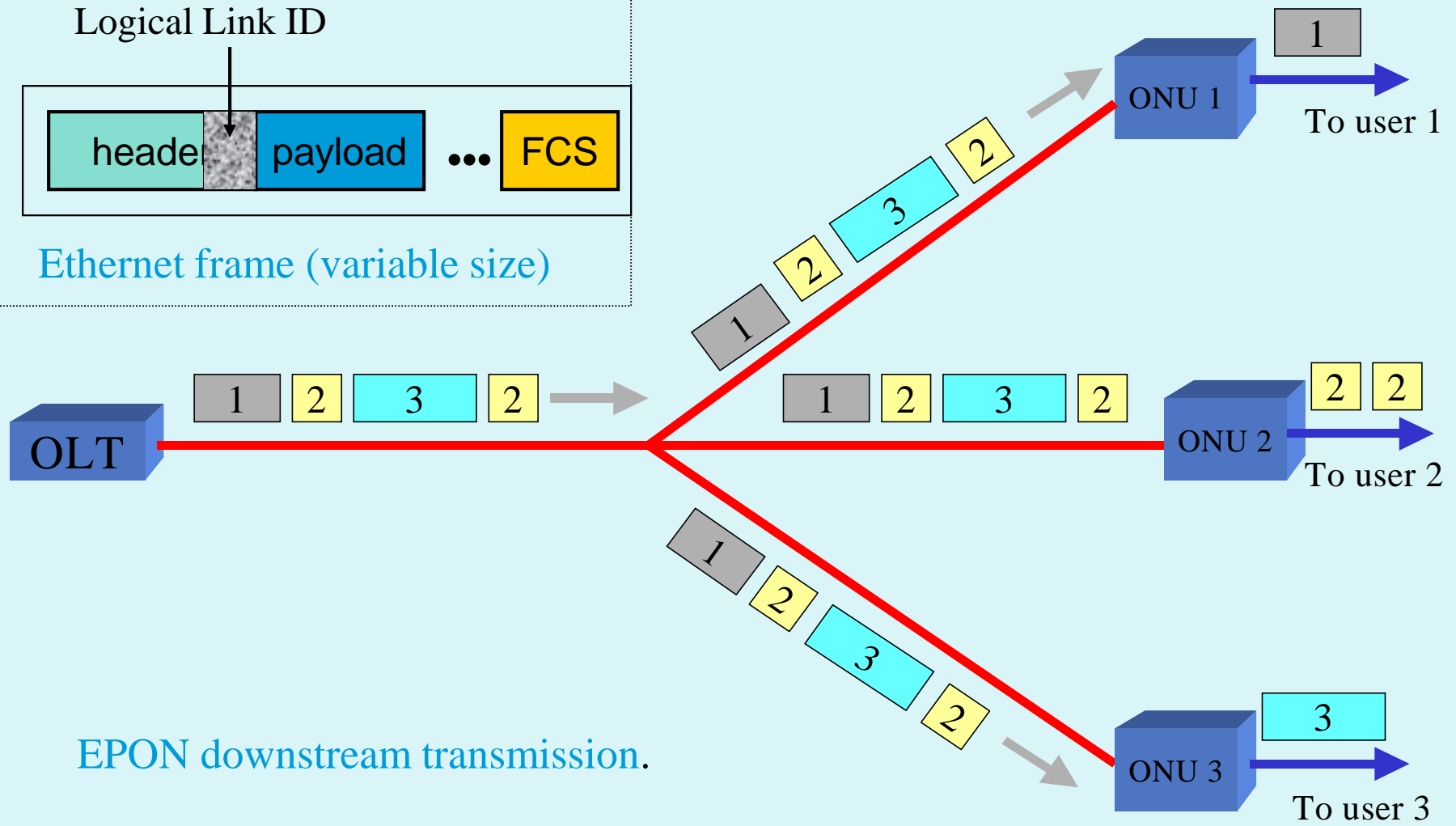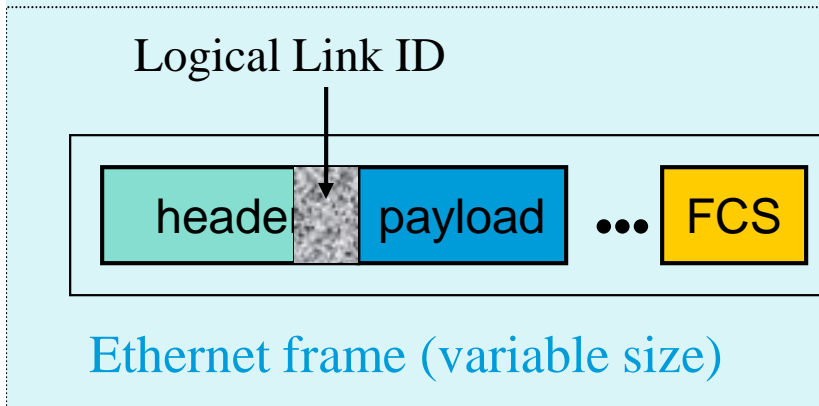
EPON upstream transmission.
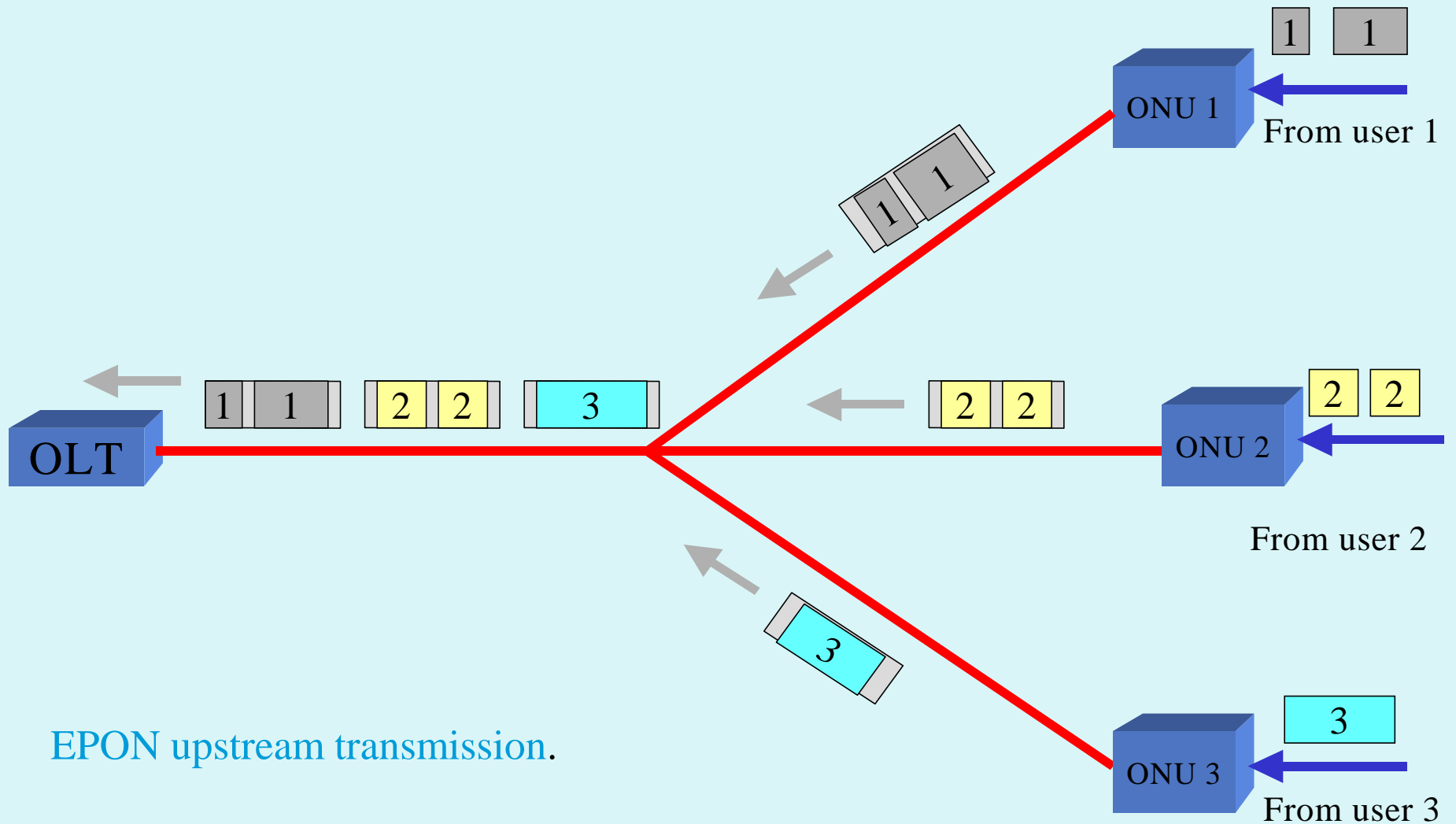
TDM PON – developments

- Development of EPON continues
  - New versions: XG-PON1 and 10G-EPON.

- New generation of TDM APON is considered
  - NG-PON2

- In general, TDM PONs will quickly approach their capacity limits; hence, WDM PONs are considered as the most promising direction .

PON – problems and latest developments: WDM

- Commercially available PONs (e.g., FiOS) are TDM based. TDM technique is inherently restricted in the bit rate; additionally, TDM-based PON has to resolve security and confidentiality issues.

- WDM PON is the natural solutions to these PON problems.

- However, classical WDM approach, as applied to PON, suffers the main drawback: It can't be economically justified.

- Developing colorless ONUs (ONTs) is the main solution to this problem.

Classical WDM PON
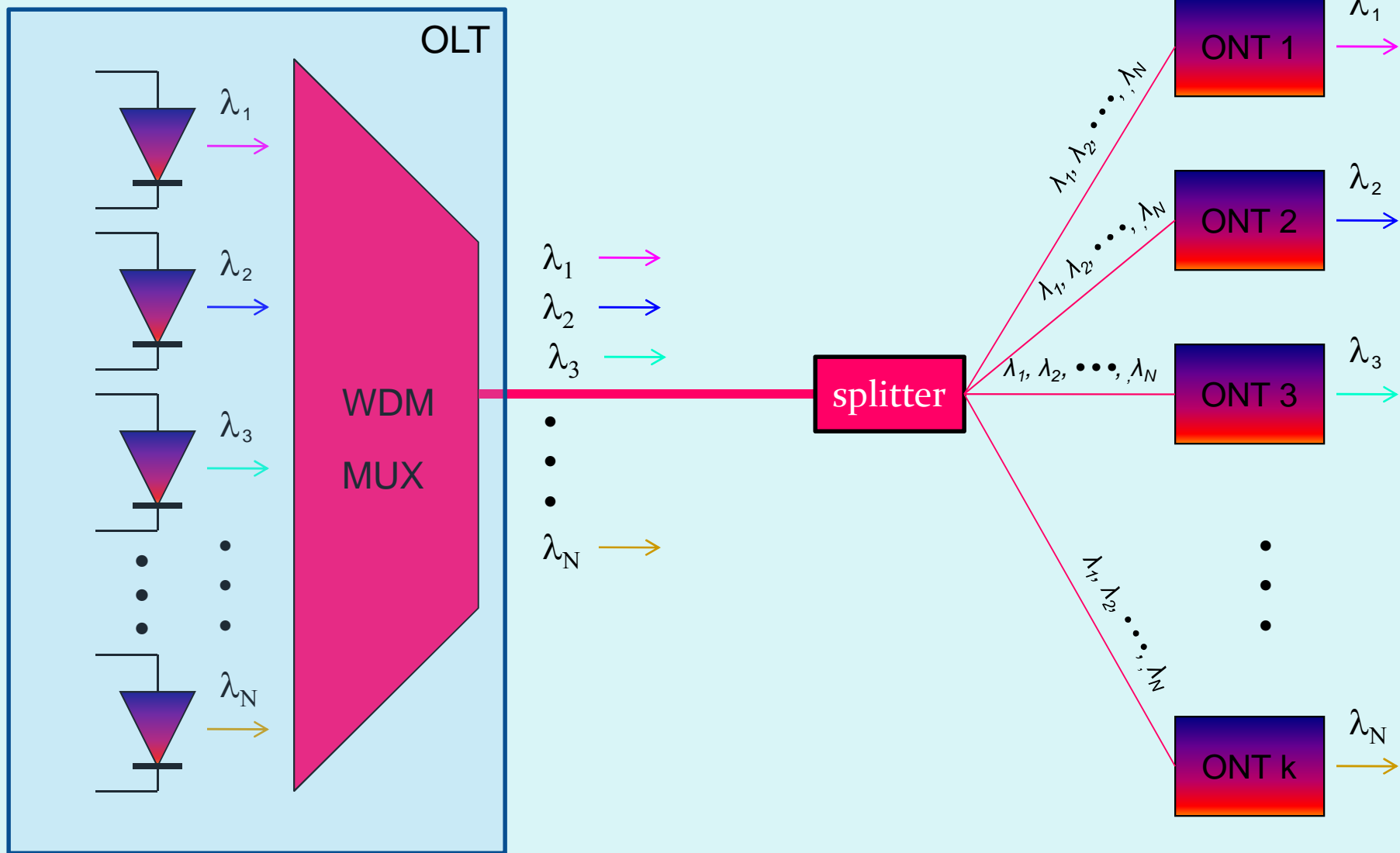
WDM PON - colorless ONU
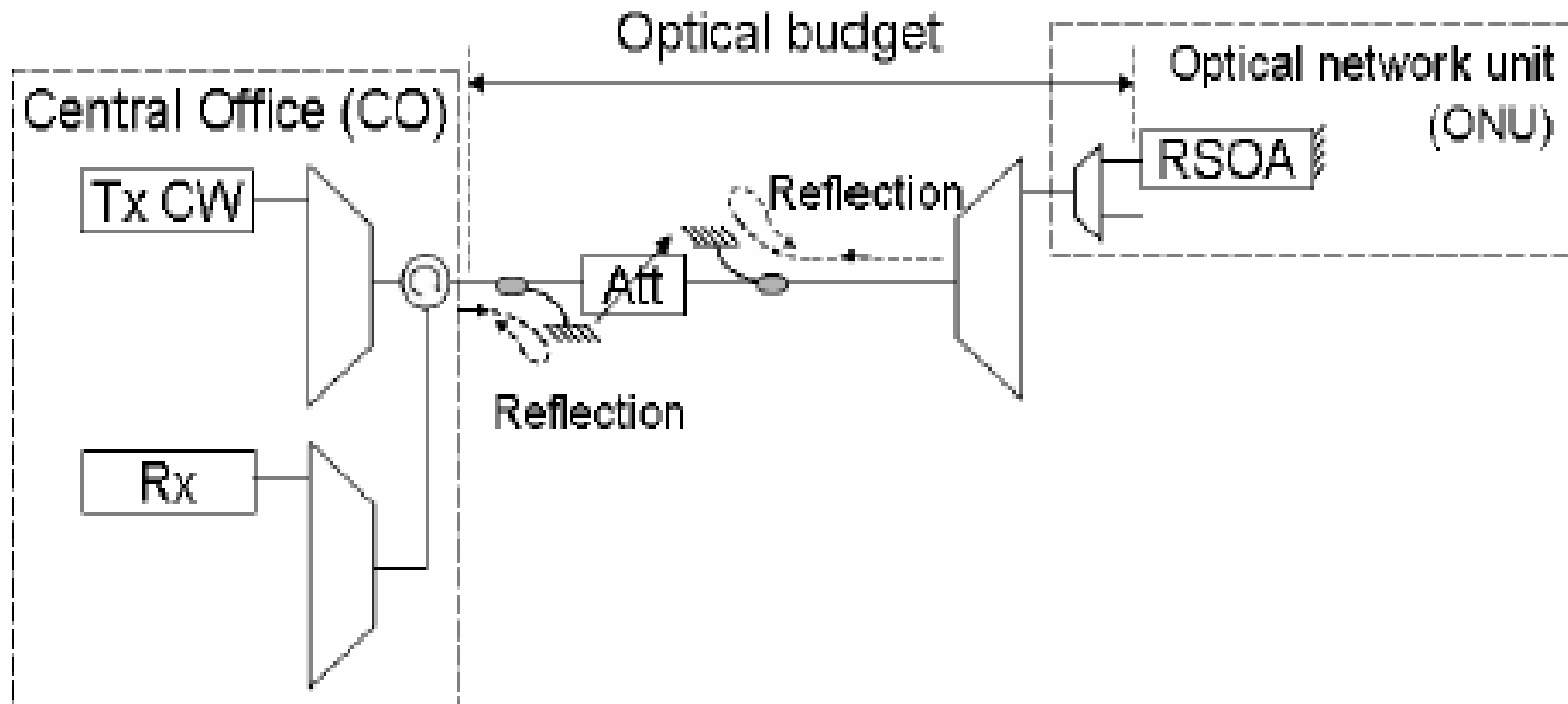
WDM-PON upstream configuration [6]

Various versions of colorless ONU of WDM PON
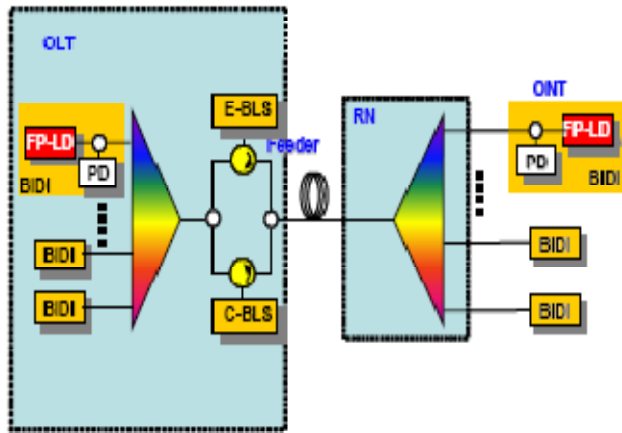
Fig.1. Injection Locked FP-LD WDM-PON
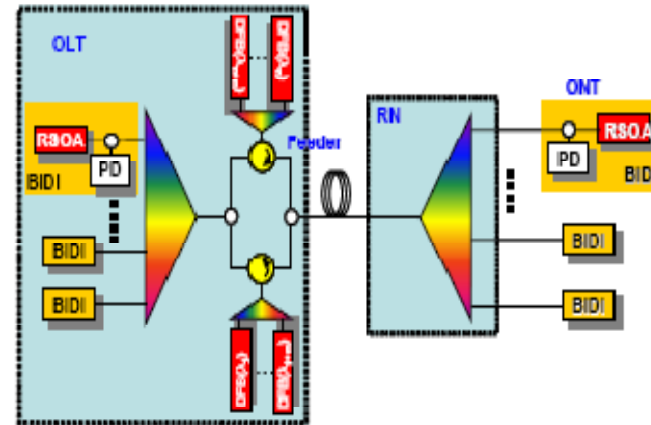
Fig. 2. Laser Injected R-SOA WDM-PON
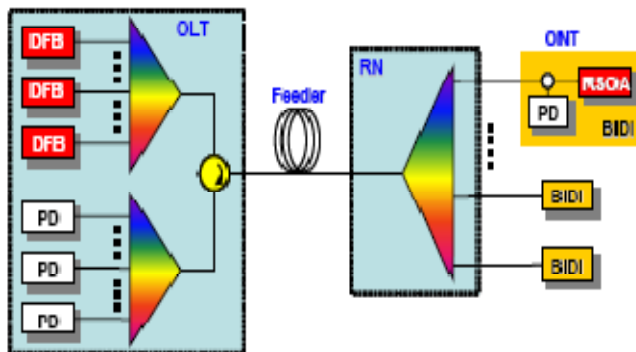
Fig 3. R-SOA based remodulation WDM-PON

[7]

WDM PON trends

- Today, only Korea Telecom has deployed earlier versions of WDM PON.
- All WDM PONs are colorless.
- There are a number of versions of WDM-PONs:
  - Simple WDM
  - Hybrid WDM/TDMA (TDM access)
  - UDWDM (ultra-dense WDM)
  - WDM/OCDM (optical code-division multiplexing)
  - Active-plus-passive hybrid network
- It is shown [37] that a simple WDM is the most efficient for the near future access up to 1 Gb/s.

PON – trends: increase the reach, number and variety of customers
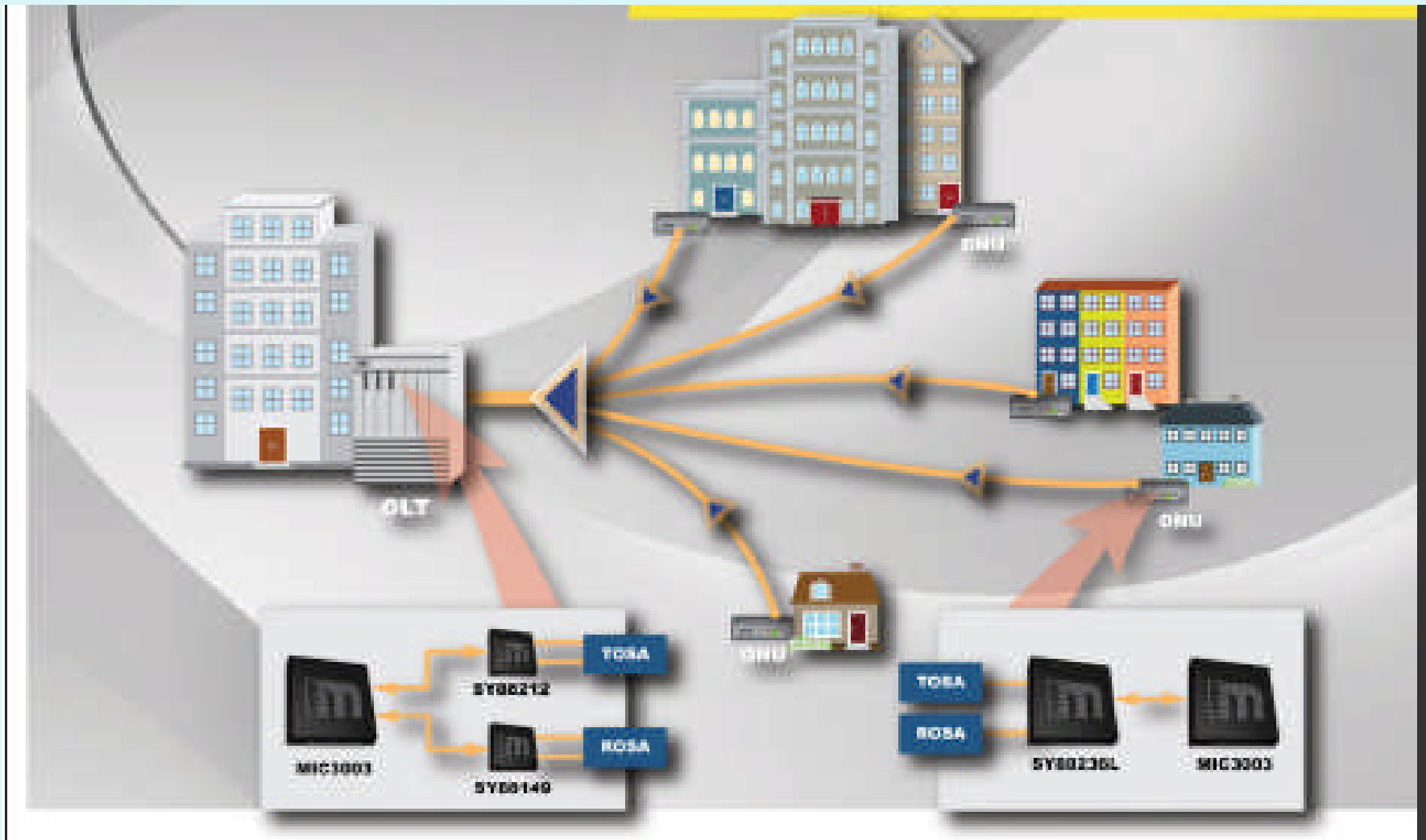
Outline

- Where we are today – current status and problems of optical communications
  - In space, in time and in spectrum
  - Network and its components
  - PON
- Trends
  - Components
  - Networks
- Conclusion

Trends

- We will briefly consider short-term and long-term trends in developing components and networks.

- Some trends have been already considered.

Optical interconnects

- Classifications [2]
- Rack-to-rack (in-room)
  - Card-to card
  - Intra-card
  - Intra-module (on-MCM)
  - Intra-chip (on-chip)
- Main bottlenecks:
  - Pins and pads of processor packages
  - Off-board (card) and dense high-speed copper lines
  - Connectors at the card edges.

- Criteria:
  - Signal integrity (distortion)
  - Bandwidth–distance product
  - Power usage per Gbit/s
  - Bit error ratio (BER) and BER x L
  - Link length
  - Latency
  - Cost per Gbit/s
  - Packaging and density
  - Power consumption and dissipation

Electrical interconnects – problems [8], [9], [11]]

- Technical problems:
  - Bandwidth x Length is low ➔
    - To increase BW, we need to reduce L
    - At this scale, power depends on BW x L and vice versa
  - Delay (~ 20-25 ps/mm) [12].
  - Low noise immunity
    - Crosstalk between channels becomes a problem with the increase of channel density
    - General noise
  - High power consumption (~ 1 mW/mm) and heat dissipation
  - Frequency-dependent loss
- Architectural problems:
  - Performance of CPU and other electronic modules grows much faster than the transmission speed of links among these modules. (By some estimates, wire delay will grow 20 times faster than a gate delay.)

Solution: Optical interconnects
What they are

Point-to-point optical interconnect: Electrically pumped laser diode launches an optical signal into the Si waveguide. Light is collected by the detector structure[13].

InP membrane waveguide layer

micro−disk top contact layer

PD top contact layer

Laser active layer

PD absorption layer

SOI wafer
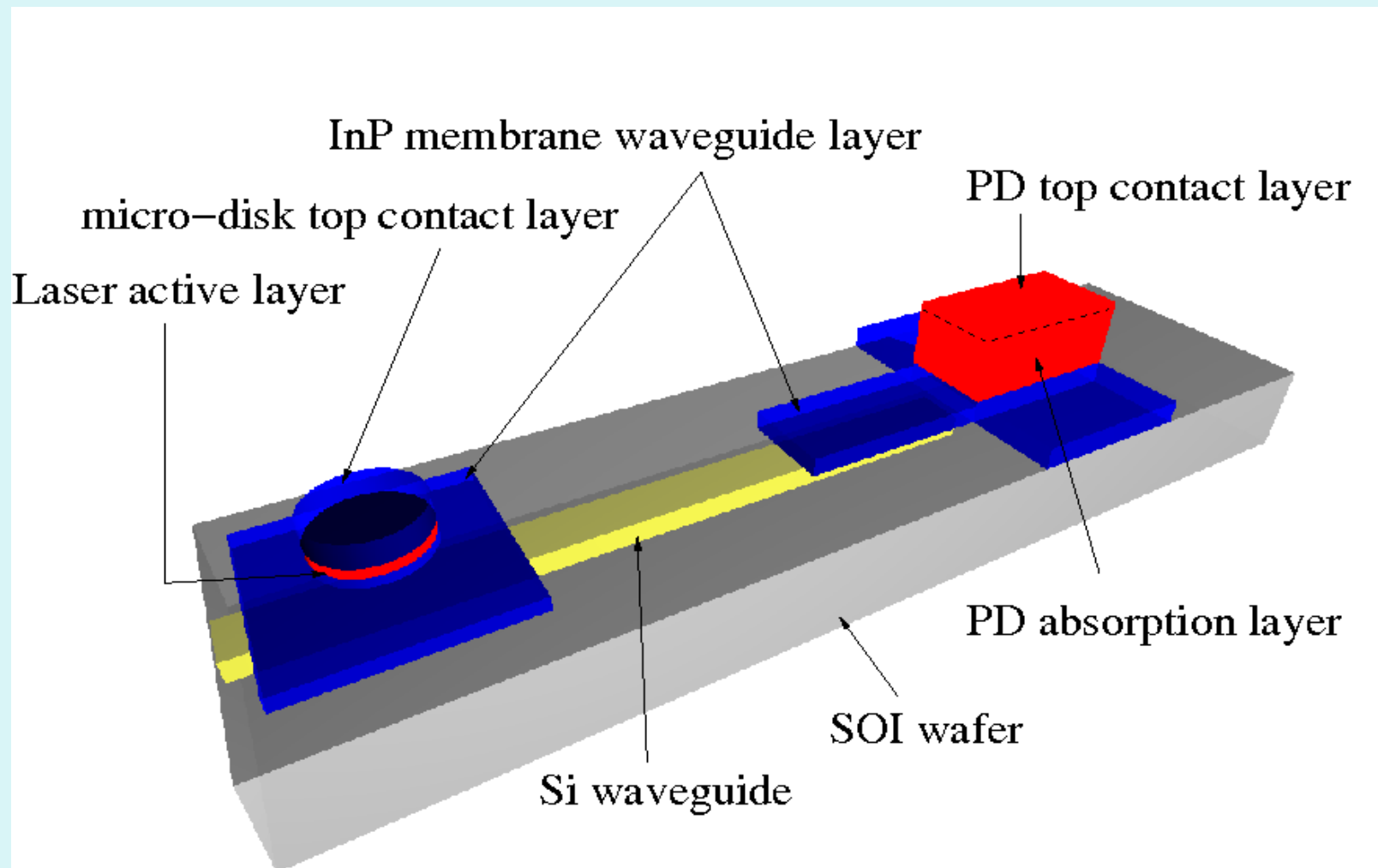
Si waveguide

Optical interconnects

- Main benefits:
  - Theoretically solving almost all problems associated with electrical interconnects. (E.g., delays will reduce to 4-5 ps/mm for polymer and to 10 ps/mm for Si waveguides [12].)
  - In addition optics allows for 3D dense packaging thanks to low crosstalk. (E.g., minimum pitch is 8-9 μm for polymer and 0.5-1 μm for Si [12].)
- Where to expect them first:
  - Supercomputers: They heavily rely on-card (intra-node) transmission among CPUs and memory and on card-to-card (inter-node) transmission
    - "Chip-like " silicon-carrier-based optical module coupled optically and electrically to a circuit card ("Terabus" by IBM) [2], [9].
    - Optical interconnects for "Keisoku" supercomputer [10].
  - Microprocessors: The microprocessor architecture transition from multi-core to many-core will drive increased chip-to-chip I/O bandwidth demands at processor/memory interfaces and in multi-processor systems. Future architectures will require bandwidths of 200GB/s to 1.0TB/s and will bring about the era of tera-scale computing.
    - UNIC, the DARPA's program, funds five-year project (Sun Microsystems) to develop microchip interconnectivity via on-chip optical networks enabled by silicon (Si) photonics and proximity communication [11]

Optical interconnects – example 1
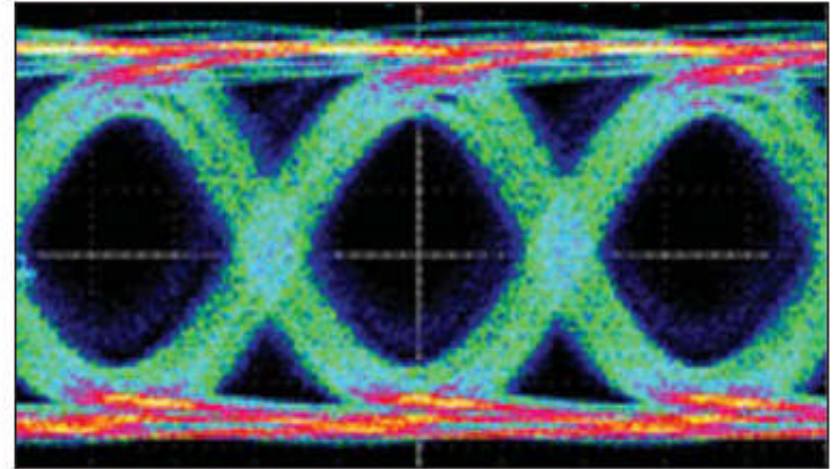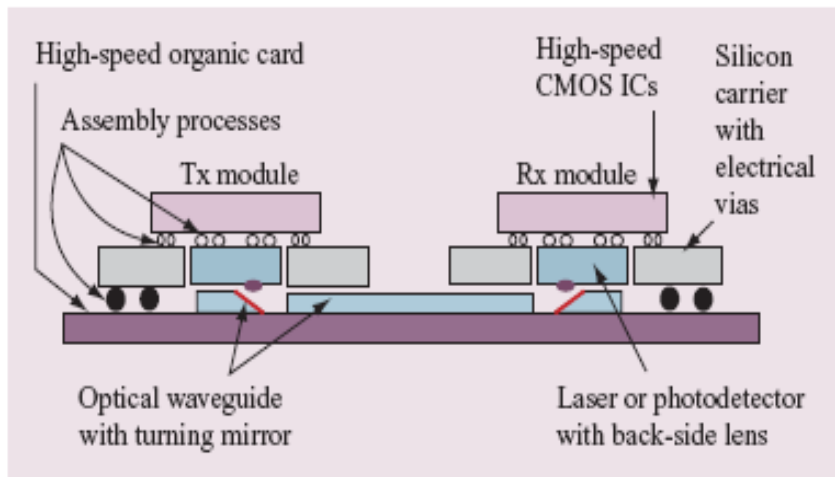
Cross section of Terabus module structure [2a]

Electrical eye diagram at the output of Terabus receiver. The optical input from Terabus transmitter at 14 Gbit/s [2a].
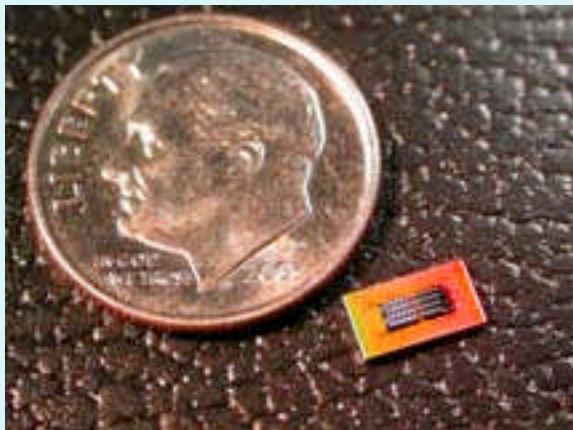
IBM Terabus chip - an optical transceiver with a driver and receiver chips in common CMOS technology, and coupled it with optical components of III-IV materials. The entire integrated package measures 3.25-by-5.25mm [2b].

Optical interconnects – examples 2 & 3
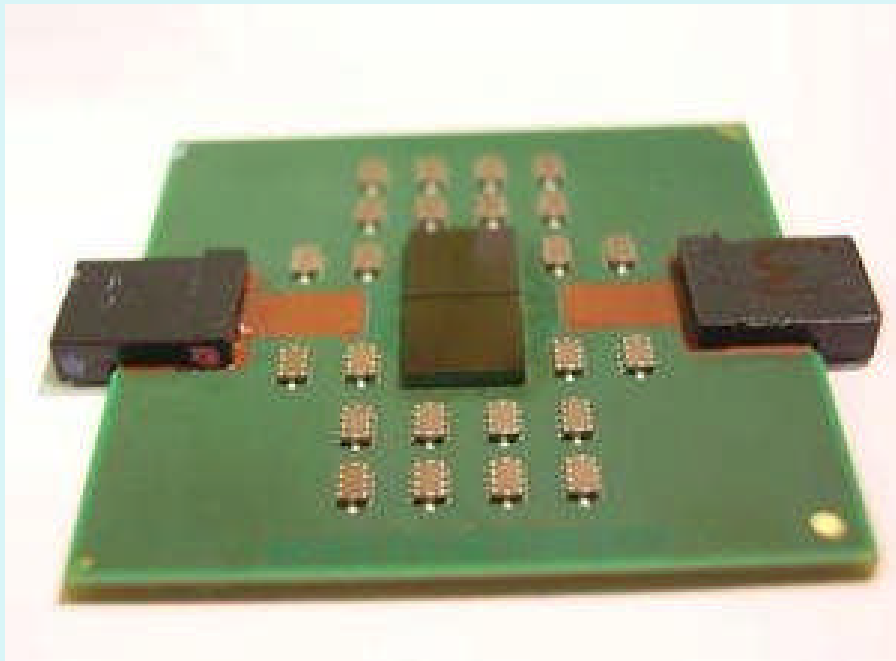
TxRx Optical Links for Flip Chip Components
[Optical InterLinks, LLC – commercially available]
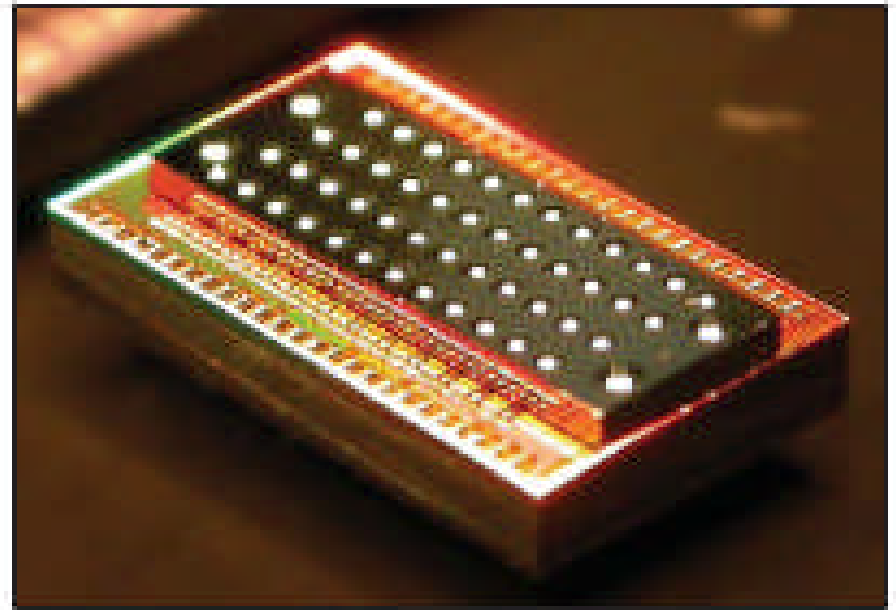
Flip-chip attachment of 48 VCSELs on a
48-channel driver IC [2].

SOI wafer   Source dies   Detector dies

Si waveguide pattern

Si gratings   PD blocks   p–pads

RF–pads   n–pads
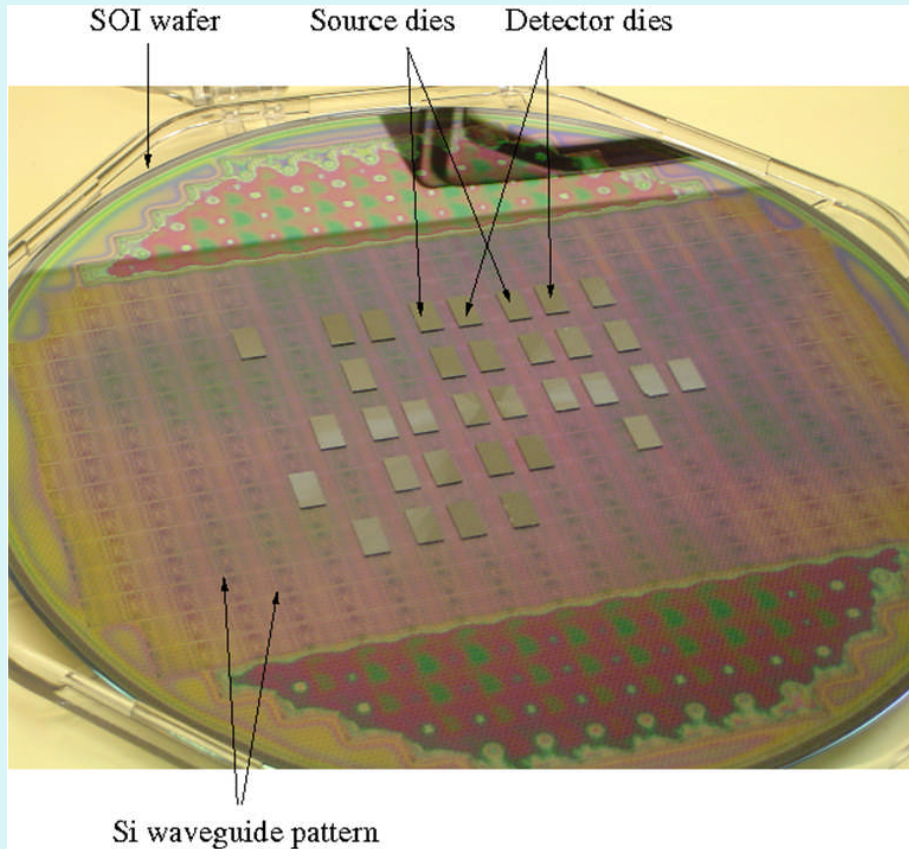
Source and detector dies bonded on SOI wafer [13].
Both pictures are courtesy of Pietro Binetti.
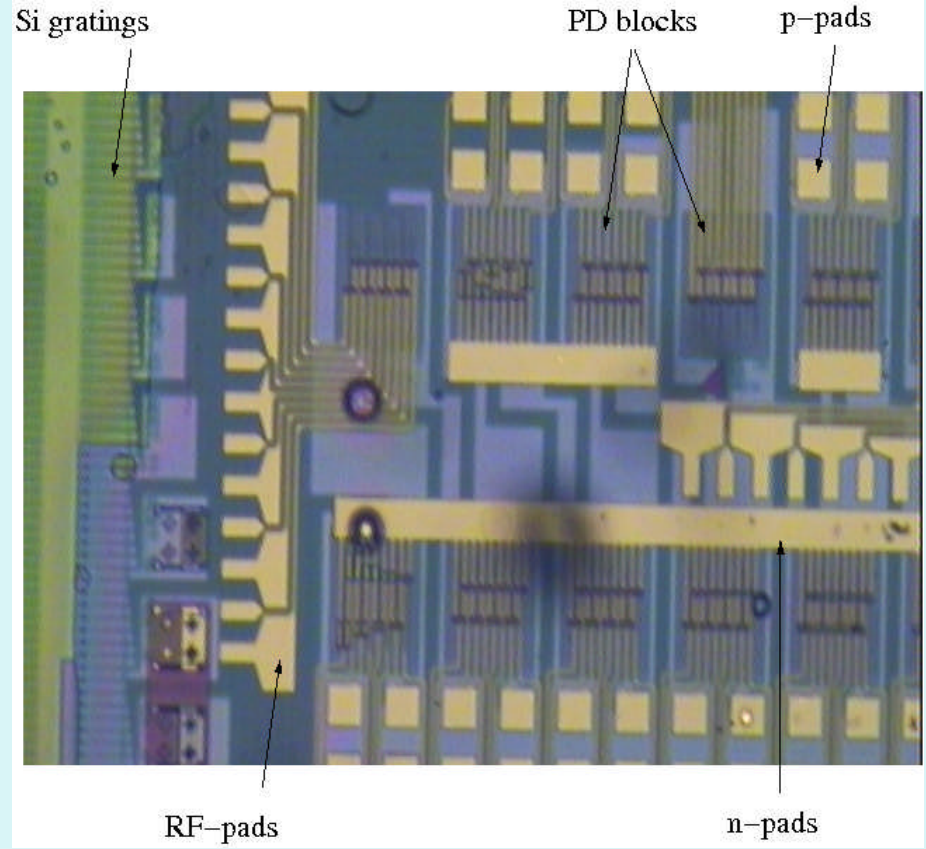
Picture of the fabricated chip. 10 PD blocks with eight devices per block are shown [13].

Optical interconnects - problems

- Today problems:
    - COST: Today optical interconnects cost less and consume less power than the electrical at the length > 10 m (active cables!), but at the shorter length the optical links can't compete with the copper [10].
    - Power consumption of the whole system at the < 1-m scale is still too high because Tx and Rx need higher voltages than plain CMOS chips.
    - Package density: optical waveguides can be placed very densely, but lasers and PDs arrays can't.
    - Temperature is an issue.
    - Reliability and performance are not verified yet.
    - Standards!

Trends - components

- We will consider the trends in development of optical-communication components at the module, component and the link levels.

Main problems and solutions – module level

- Integration
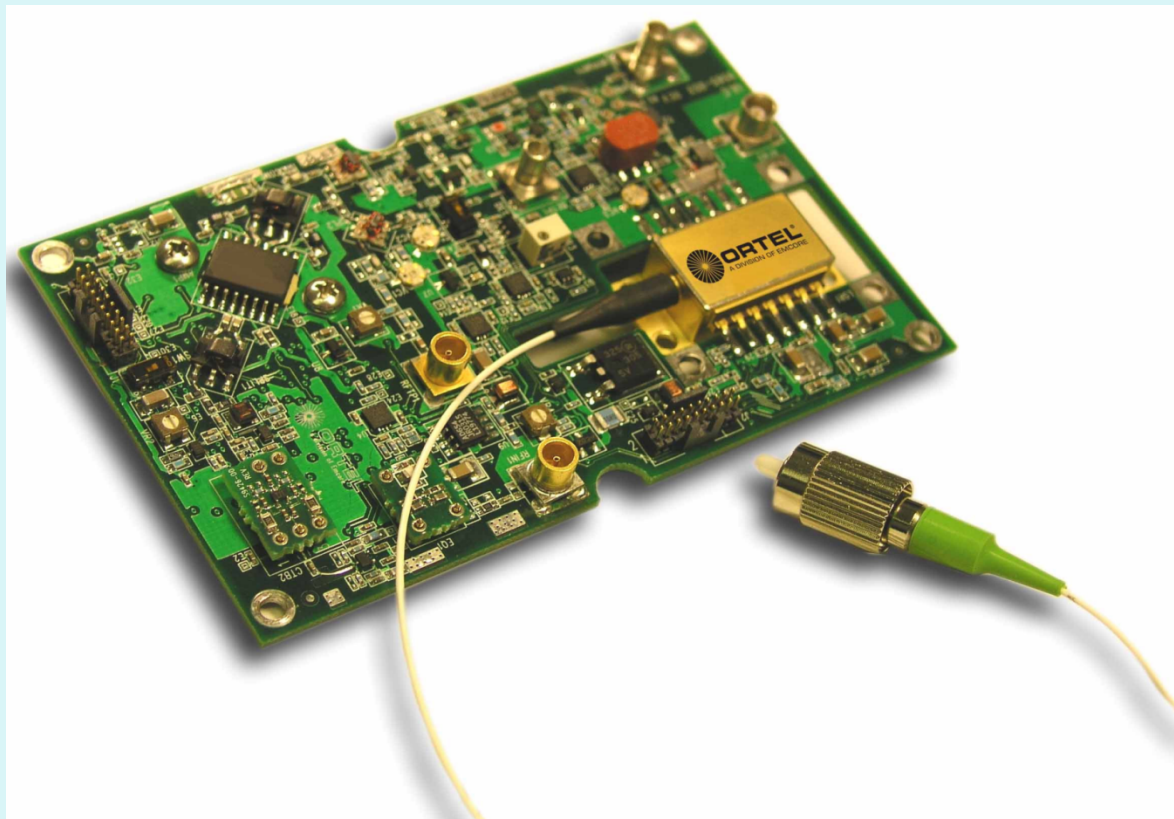
Today: commercially available 1550-nm CATV Tx [Emcore].
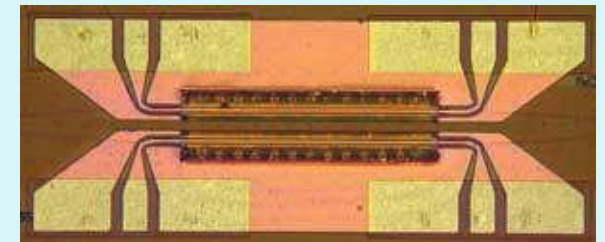
Tomorrow: the array of 16 hybrid silicon tunable lasers with integrated electroabsorption modulators [14].

Main problems and solutions – component level

- Components:
  - Cost of manufacturing ➔ silicon photonics
    - Why silicon photonics: easy manufacturing and easy combining with electronics
    - Problems of silicon photonics:
      - Difficult to make light sources because of bandgap problem
      - Heat dissipation and other compatibility issues [17]
  - Cost of maintenance ➔ have to be miniature, integrated, low-power consumption devices
  - **Electronics did not die:** Potentially it could perform much faster than today [18], but E/O/E conversion can be still a problem.

Monolithically integrated tunable optical transceiver [JDSU]
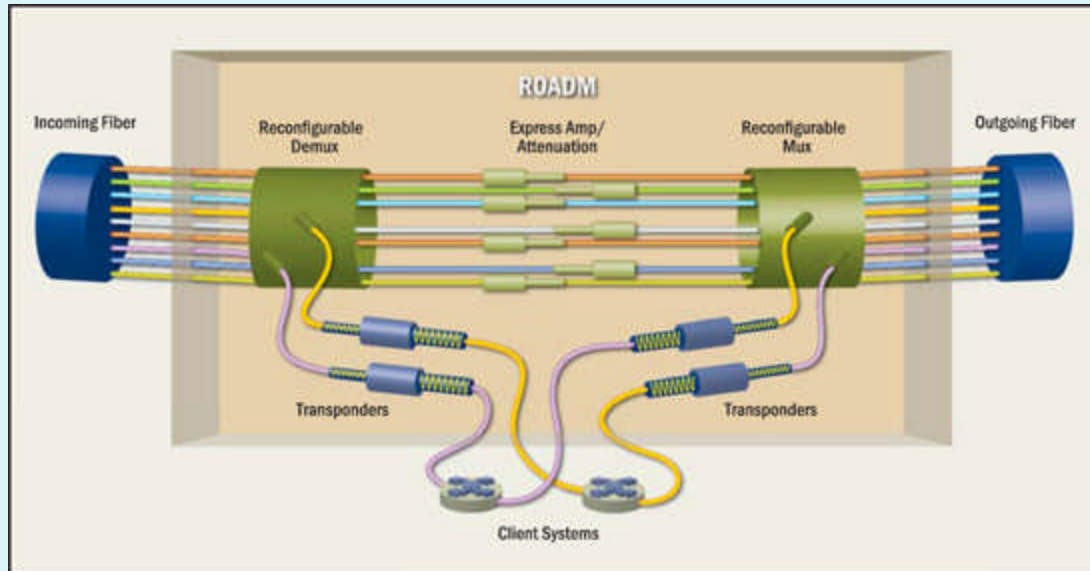
40-Gb/s moduator [Futsitsu]

Trends – components

Today's parameters:
- 50 GHz WSS carrying 100G live traffic
- 50 GHz cascadable to 24+ nodes
- Scalable platforms (1x2 to 1x23)
- High-volume manufacturing (thousands/qtr.)

ROADM

A key component of the Self-Aware Network, ROADMs are fast becoming the core of every optical node, providing the flexibility to remotely reconfigure any or all wavelengths, thereby reducing time-to-service, simplifying the network and streamlining planning and management.

Main problems and solutions – link level

- Optical SiO2 fiber

    - Losses cause decrease in power (attenuation).
    - Dispersion cause decrease in bandwidth by broadening the pulse.
    - Nonlinear effects (mainly self- an cross-phase modulations) cause more dispersion and distort the waveform.

- Waveguides for optical interconnects

    - The tradeoff between the silicon and polymer waveguides density and propagation delay per unit length [12].

➔ Better silica fiber, another type of fiber?

Input pulse   Optical fiber   Output pulse
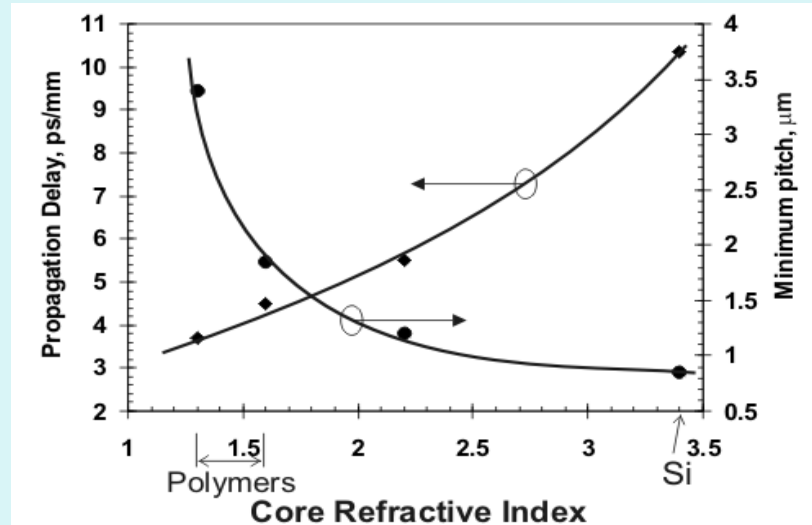
➔ Improvement? another waveguide materials?
➔ plasmonic waveguides?

Modern photonics and optical communications – where do they meet?

- Optical communications could tremendously benefit from research being conducted in photonics today. Areas of particular interest of this research include
  - Plasmonics
  - Nanophotonics
  - Silicon photonics
  - Quantum dots and wires
  - Integration of electronics and photonics
  - Photonic crystals , waveguides and fibers
  - Metamaterials
  - Slow and fast light
  - Single-photon manipulations (generation, modulation, detection, and transmitting)

  (See, for example, the roadmap for European research [18].)

- Let's consider, for example, plasmonics.

Modern photonics and optical communications – where do they meet?

- ## Surface plasmons:

  - Polarization charges are created at the interface between two material.

  - The electrons in metal will respond to this polarization giving rise to surface-plasmon modes. Surface plasmons are the interface modes.

  - They reside at the interface between a metal and a dielectric material.

  - Surface plasmons have combined electromagnetic wave and surface charge properties [19], [20]. In fact, the surface plasmons is a hybrid of electronic and optical wave; i.e., it practically represents a merging of electronics and photonics.

  - When light is coupled with surface plasmons, we have surface plasmon-polaritons.
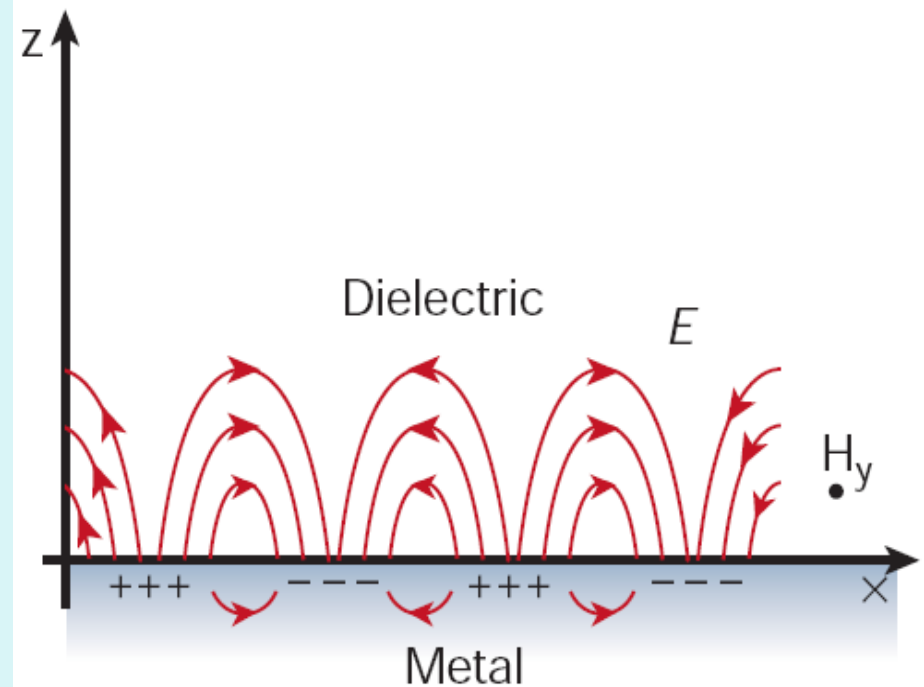
Courtesy of Igor Zozoulenko [20].

Photonics and optical communications –potential applications of surface plasmons (1)

- Surface plasmons applications
- The miniaturization of conventional photonic circuits is limited by the diffraction limit, such that the minimum feature size is of the order of wavelength.
- *Using the surface plasmons we can overcome the diffraction limit,* which can lead to miniaturization of photonics circuits with length scales much smaller than those currently achieved.
- In general, using surface plasmons can open the door for practical applications of nano-optics, where delivery and concentration of the optical radiation energy on the nanoscale is a difficult task because the wavelength of light is on the many orders of magnitude too large [20].
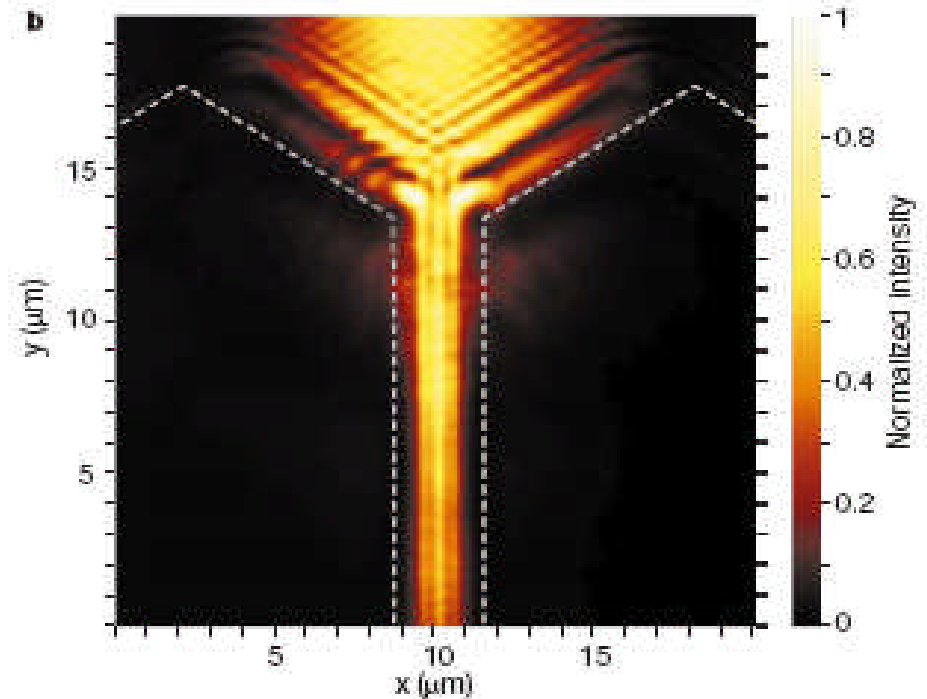
Light propagation in a plasmonic waveguide [20]. The waveguide over centimeter length has been demonstrated; low bending loss has achieved [22].

Photonics and optical communications –potential applications of surface plasmons (2)

- Overcoming the diffraction limit with the help of surface plasmons opens the new way of beam shaping [20]. Researchers can design near-field and far-field almost at will, which would allow for coupling light into nanostrauctures and optical processing [23].
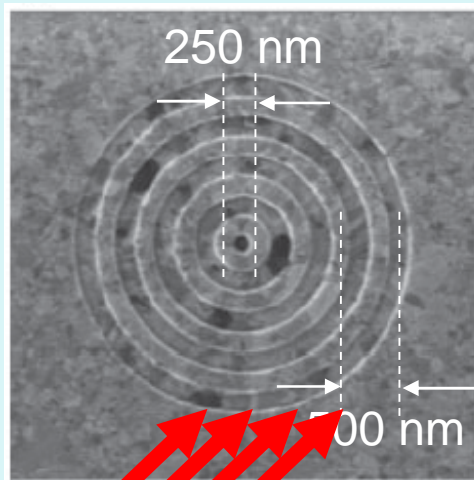
surface plasmon resonance @ 660nm

metallic (Ag) film
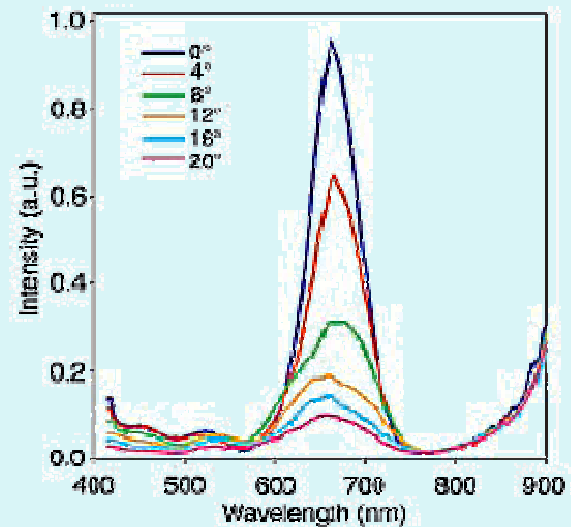
directionality is ± 3°
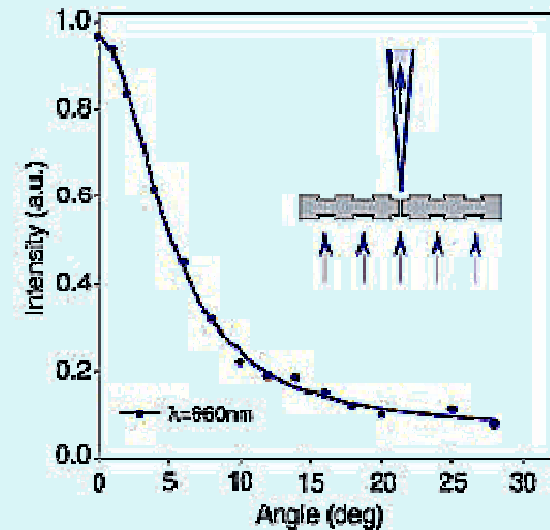
Courtesy of Igor Zozoulenko [20].

light

Photonics and optical communications – potential applications of surface plasmons (3)

- Surface plasmons switched at terahertz rates and consume mJ/sm² power for modulation [24] ➔ new type of modulators? All-optical switches?

- Plasmonic LED approaches 10 GHz modulation bandwidth [25] ➔ using LED for optical interconnects?

- A visible plasmon laser has created [26] ➔ new light sources for nanoscale optics?

- Plasmonic lens increases photodetection capability [27] ➔ new type of photodetector?

- Will integrated devices perform all operations completely optically?

Photonics and optical communications – photonic crystals

- Photonic crystals (semiconductors of light)
  - Key concept – light confinement
  - Applications in optical communications:
    - Photonic-crystal fibers: special properties ➔ fiber lasers and amplifiers, nonlinear devices ➔ dispersion control and compensation, filtering, and switching
    - Photonic-crystal lasers: low threshold and high-speed modulation ➔ optical interconnects
    - Tunable devices
    - Processing devices (could potentially operate at a single-photon level):
      - Switches, photonic memory, and wavelength converters
    - Silicon photonic crystals could lead to integrated optical devices on SOI platform ➔ optical chip? [28])

Photonics and optical communications – photonic crystals

- Photonic-crystal fibers: special properties ➔ fiber lasers and amplifiers, nonlinear devices ➔ dispersion control and compensation, filtering, and switching; single-photon generation.
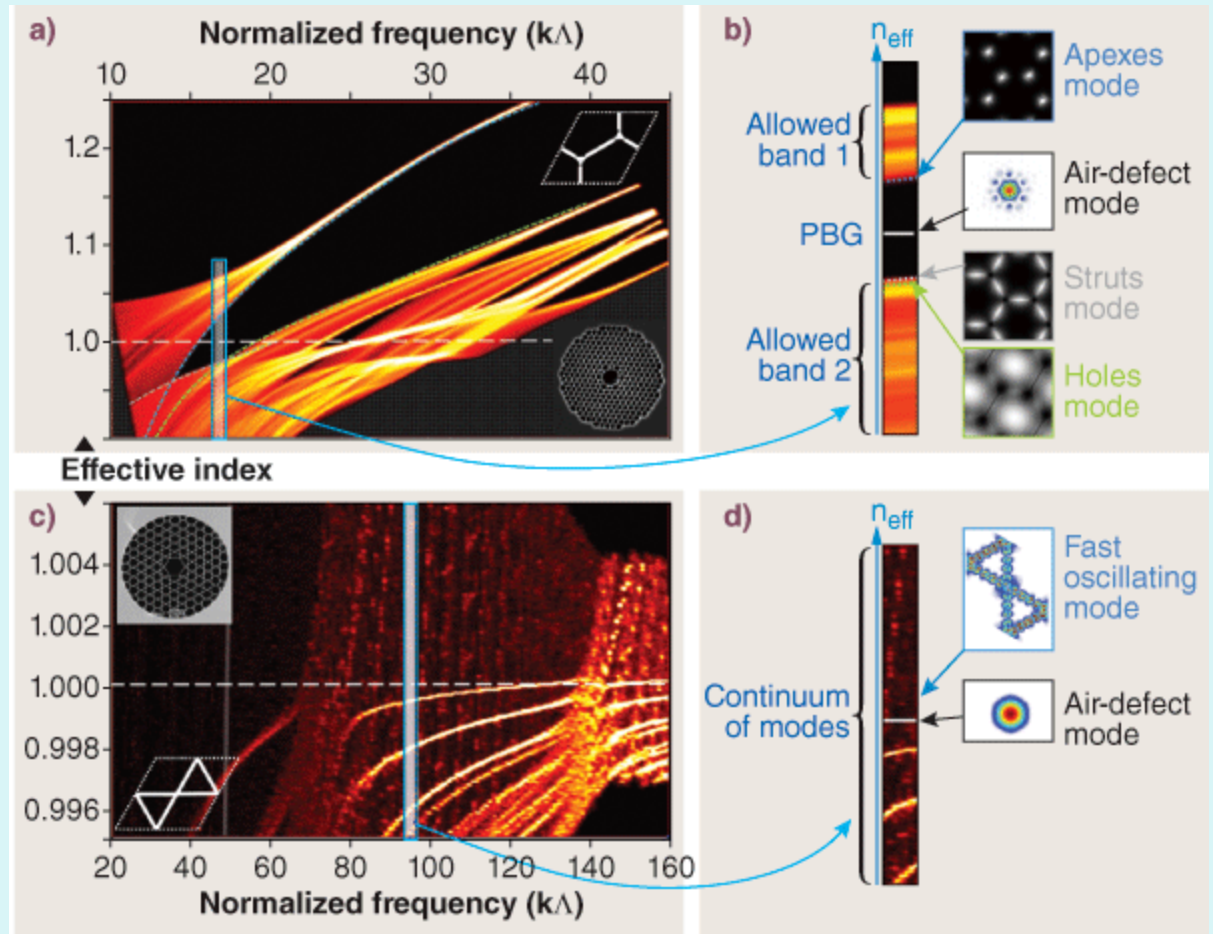
"Two types of hollow-core photonic-crystal fiber guide light in a hollow core with two different mechanisms" [29].

Can we use a single photon in communications?

- Generation and detection of a single photon is a difficult but reachable task [30].

- Modulation

  - "A single photon can be modulated with an arbitrary waveform; for example, three square pulses (top) or two Gaussian pulses (bottom)" [31].

Coincidence counts per 200 s

Unmodulated

Modulated

$t_1 - t_2$ (ns)

Coincidence counts per 200 s

Unmodulated

Modulated

$t_1 - t_2$ (ns)
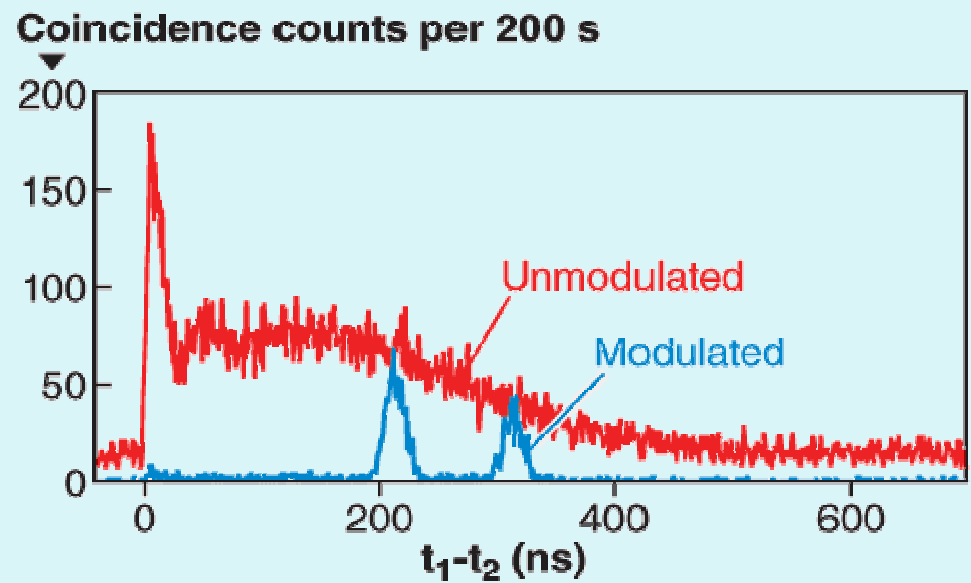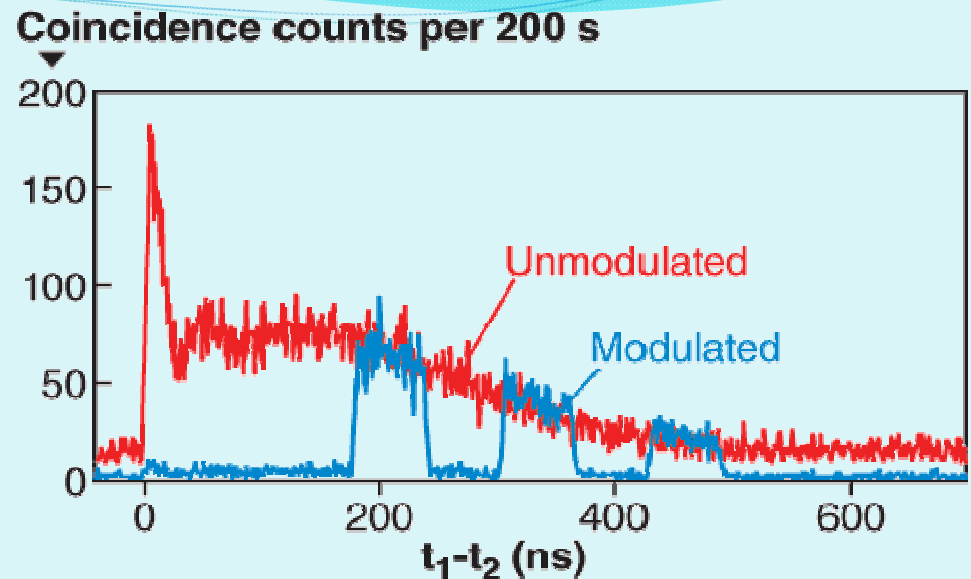
Can we use a single photon in communications?

- ## Single photon can be routed [32].
- ## Single photon can be transmitted over a long distance:

- A single photon was sent and received over 1500 km. Weak laser pulses were directed toward orbiting satellites that mirror optical signals on an exact parallel return path to the source. The team chose parameters that would cause less than one photon per pulse to be returned on average, to simulate a single-photon source. Because the signal travels directly up through only 8 km of the Earth's atmosphere, the link can be established without any deleterious atmospheric or geographic effects (see Figure) [33].

Trajectory, $h = 1000-8000$ km

Satellite with reflectors

Uplink

Downlink

Downlink into FOV of receiver

MLRO

MLRO - Matera Laser Ranging Observatory in Matera, Italy
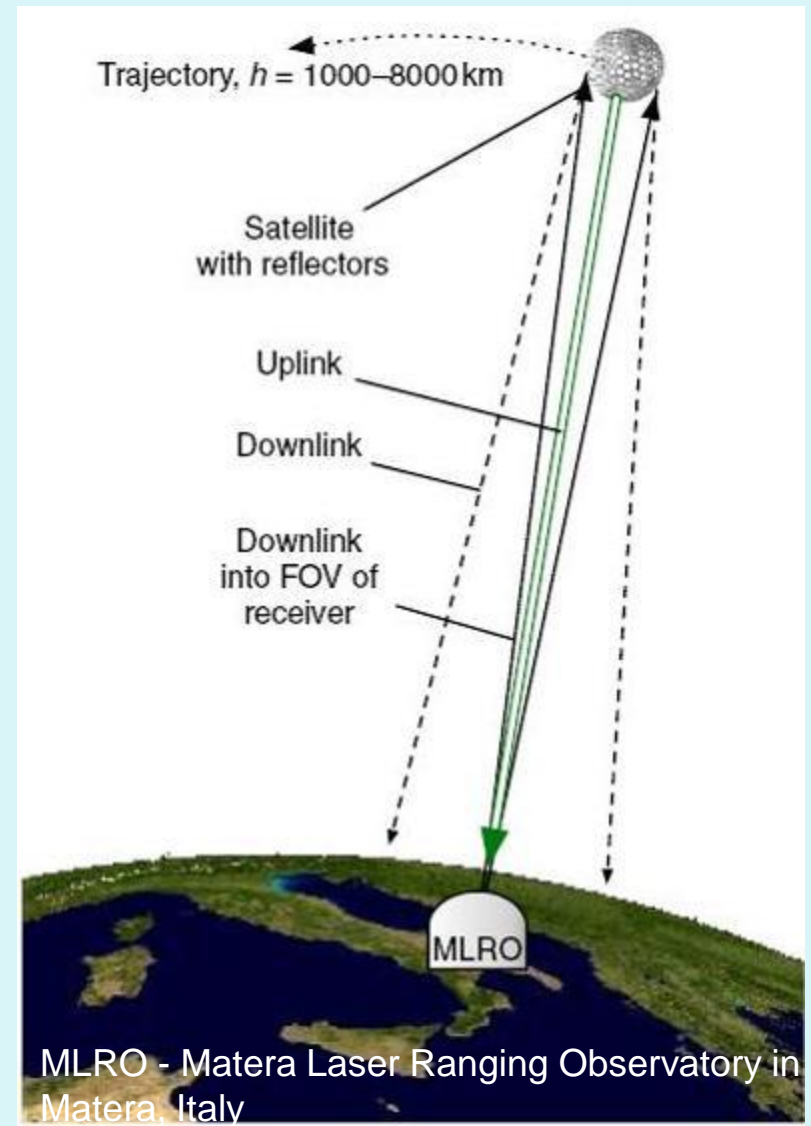
Modern photonics and optical communications – where do they meet?

- Tremendous progress in all areas of optical-communications technology has been achieved, for example:
  - High level of integration of components and modules has been achieved
  - Sophisticated and efficient modulation techniques and devices have been developed
  - Advances in WDM technology has allowed for tens of terabit-per-second transmission with the spectral efficiency approaching its fundamental limit
  - Cost per bit continues decreasing, which makes optical communications competitive at the smaller and smaller scale.

Modern photonics and optical communications – where do they meet?

- On the other side, modern photonics discovers new phenomena and processes, some examples of which we briefly discussed above.

- The meeting point of these two fields is the ideal optical communications systems in any scale, at any time (transmission speed), and at any part of spectrum.

Trends - components

- Optical communications and fundamental research in photonics are not the separate fields: They are closely interconnected and they inspire and motivate each other for further developments.

- Time will show what results of the today's research in photonics become commercial products in tomorrow optical communications.

Outline

- Where we are today – current status and problems of optical communications
  - In space, in time and in spectrum
  - Network and its components
  - PON
- Trends
  - Components
  - Networks
- Conclusion

Trends - network

- We'll consider some trends in network development.

Trends - growth of traffic

- Growth of traffic - sources

- "It is estimated that in 2010 online video consumes 37 percent of total bandwidth during peak viewing hours. And by 2013, Cisco predicts that global Internet traffic will reach 767 exabytes. *It's hard to visualize this amount of data -- the number is 100X larger than all the grains of sand that cover our planet.*

- In the mobile space, Verizon launched its 4G LTE network in December 2010, promising 10X the performance of its 3G network.

- *Mobile space: With the advent of smartphones and tablets connected to the Internet, we should expect the huge groundswell in traffic on optical transport networks.*

- "Therefore the priorities for the optical communications industry in 2011 will be to support the need for faster data rates, more powerful switching, and smarter network architectures that can handle unpredictable and fast-changing traffic patterns and improve cost efficiencies. "

- **Optical communications trends for 2011** by Sinclair Vass, JDSU, Lightwave, March 2011.

Trends - growth of traffic

[35]
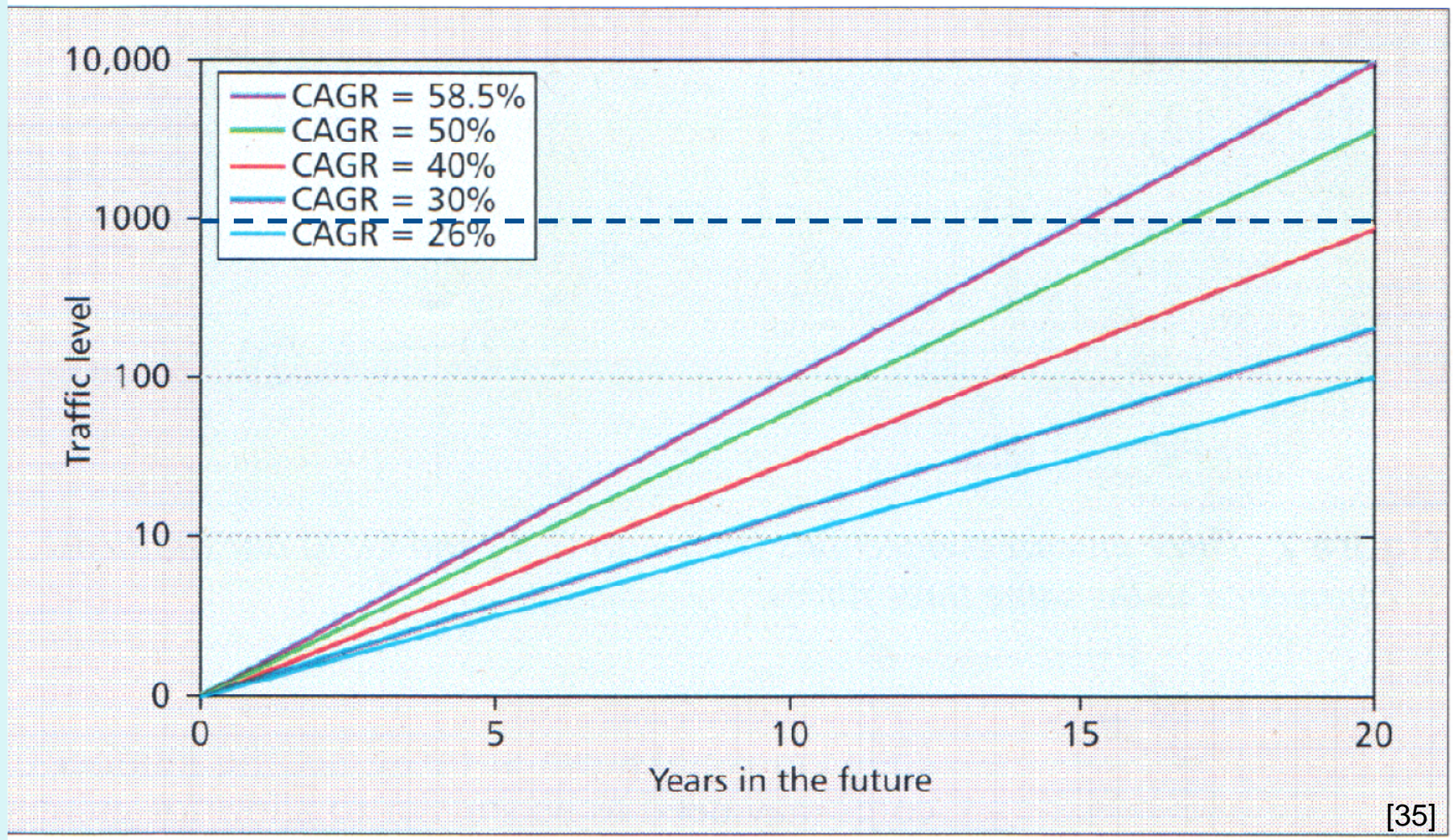
CAGR – compound annual growth rate

Trends - growth of traffic ➜ optical network challenges

- Internet traffic continue to grow at the exponential rate.

- Assuming a compound annual growth rate is on the order of 40%, then Internet traffic will increase by a factor of 1000 in 20 years.

- Thus, *we need to satisfy thousand-fold growth in cost-effective and power-efficient manner.*

- To meet these challenges, we need advances in two directions:
  - Technological advances to increase the network (fiber + routers/switches) capacity
  - Architectural enhancements to reduce the capacity demand. [35]

[35]

Trends – networks: Technological advances

- Transmission – best results of today
  - Capacity of optical transmission systems has increased 100X for past decade, but attaining 1000X increase will be very challenging.
  - Capacity of an optical fiber approaching its theoretical limit (100 Tbit/s).
  - Today's state-of-the-art technology – 80λ x 40Gb/s in the C-band.
  - Total traffic at the largest carrier backbone networks – 4 Tb/s.
  - Optical reach (without regeneration) is on the order of 2,000 to 2,500 km with optical bypass. [35]

Trends – networks: Technological advances

- Transmission – areas for potential growth

  - Spectral efficiency, SE (b/s/Hz) = $\dfrac{Information\ bit\ rate\ (\frac{b}{s})}{Total\ bandwidth\ c\ onsumed\ (Hz)}$

  C-band is about 4,000 GHz ➔

  (16λ x 2.5 Gb/s)/4000 GHz = 0.01 b/s/Hz (1990s)

  (80λ x 40 Gb/s)/4000 GHz = 0.8 b/s/Hz (2010)

  (80λ x 100 Gb/s)/4000 GHz = 2 b/s/Hz (tomorrow)

  (2* x 80λ x 400 Gb/s)/4000 GHz = 8 b/s/Hz (future)

  * Dual polarization.

  - Expanded transmission band

  Expand operation to L-band with one optical amplifier and tunable transponders ➔ 160λ x 400 Gb/s.

  [35]

Trends – networks: Technological advances

- ## Multicore fiber
  - The use of multicore optical fiber (MOF) with one connector would allow for is an excellent alternative to laying new fibers, but it has to be done with connector, one amplifier, etc. per MOF. It could increase the capacity by the factor of 7.

- ## Architectural advances
  - IP Packing: IP flows are bursty ➔ headroom ➔ 25% fill rate of IP links today. Benefit factor = 2.
  - Multicasting: *(A payload is delivered to many recipients via one connection with branches rather than via individual connections)* ➔ less demand for capacity.
  - Asymmetric traffic: Many applications don't require symmetric connections ➔ asymmetric connections result in less capacity demand.
  - Improved caching: *(Caching is a technique of persisting the data in memory for immediate access to requesting program calls.)* Data is stored in nearby location ➔ less capacity demand .
  - Dynamic optical networks: *(Connections are rapidly established and torn down automatically by request/)* Reduce the required capacity by a factor of 5.

[35]

Trends – networks: Technological advances

	Benefit factor	Percentage of traffic subject to benefit	Effective capacity multiplier
Available excess capacity in today's networks	3	100%	3
Increased spectral efficiency	10	100%	10
Expanded transmission band	2	100%	2
Multicore single-amp fiber	7	100%	7
More efficient IP packing	2	80%	1.7
Multicast/asymmetric/caching	4	20%	1.2
Dynamic networking	5	25%	1.3
Total effective capacity multiplier			~1100

Table 1. *Summary of the factors affecting transmission.*

[35]

Trends – networks: Technological advances

IP Routers

- Building today's electronic routers and switches operating at 3Tbit/s speed is already a challenge; it becomes more of an impediment in the future.

- Development of routers of size 160 Tb/s has been announced.

- Restrictions for further growth:

  - Today power consumption is about 10 Watts per 10 Gb/s. At this rate, the potential future 3,000-Tb/s router would consume 30 Megawatts. With expecting technology improvements, it's assumed to be reduced to 350 kilowatts.

Trends – networks: Technological advances

	Benefit factor	Percentage of router capacity affected by factor	Effective capacity multiplier
Larger IP routers	250	100%	250
More efficient IP packing	2	100%	2
Optical edge aggregation	2	100%	2
		Total effective capacity multiplier	1000

Building large IP routers will provide 250-times increase in network capacity.

Trends - networks

- "Components and systems that add intelligence to the transport layer of networks will be developed in 2011. The goal of these new optics will be to create *self-aware networks* that have a flexible photonic layer and can adapt to changing traffic patterns, new applications, and unexpected bandwidth fluctuations in a very seamless way.

  Three big industry buzzwords -- *colorless, directionless, and contentionless* -- describe important elements of self-aware networks. These features provide functionality that enables any type of wavelength to travel across the network in any direction and to any desired destination.

  New, sophisticated optical switching components are being developed to construct network and node architectures that provide automated end-to-end wavelength, transponder, and route flexibility. These new components and architectures will build upon and complement the *wavelength-selective switch* (WSS), which will continue to be the central building block for flexible optical networks. "

- **Optical communications trends for 2011** by Sinclair Vass, JDSU, Lightwave, March 2011.

Trends – network transmission

- **Transmission gets faster and more flexible**

  "This year will finally see 40G networks go mainstream, as price points shrink and bandwidth skyrockets. Coherent modulation schemes will increase the length of 40G network links and act as a precursor for volume deployment of 100G coherent modulation schemes.

  The 100G market will follow closely behind 40G. More major NEMs will demonstrate platforms designed in-house and start to deploy the first networks, while also looking to outsource second-generation designs to optical component vendors. In fact, many in the industry believe that 100G will take off very strongly in 2011, capturing a large percentage of the high-speed market and curtailing growth of 40G significantly."

- **Optical communications trends for 2011** by Sinclair Vass, JDSU, Lightwave, March 2011.

Trends – network transmission

- **Modulation**

- In the line-side 100G space, *dual polarization quadrature phase-shift keying (DP-QPSK) with coherent detection* has become both widely supported and adopted for new bandwidth deployments, with the first such networks currently going live. This is driving demand for a new range of *high-speed optical components including modulators, narrow line width lasers, and passive multiplexing devices.*

Trends – network: optical transport network

THE EVOLUTION from circuit-switched TDM to packet-based transport requires the interplay of a variety of technologies and protocols. Therefore, packet-based networking needs an agent to hold the pieces together and ensure smooth operation, just as SONET/SDH does in legacy TDM transport.

For many networks, particularly at the core, Optical Transport Network (OTN) fills that role. OTN provides DWDM-enabled packet transport with similar management functions as SONET/SDH, while adding forward error correction (FEC) and more efficient accommodation of such traffic types as Ethernet, Fibre Channel, and even SONET/SDH itself.

Lightwave, January 2011

Trends – network: optical transport network

- Optical network peer model

- IP and OTN are treated as a single integrated network. Here, an OXC is treated like another router as far as the control plane is concerned. From routing and signaling points of view there is no difference between a router-to-OXC interface and OXC-to-OXC interface. Once a lightpath is established across the OTN, it can be considered as a virtual link between edge routers. Therefore, edge IP routers are involved in optical transmission ➔ **OTN is transparent to IP.**

Optical communications – where are we going?

Ideal optical communications network
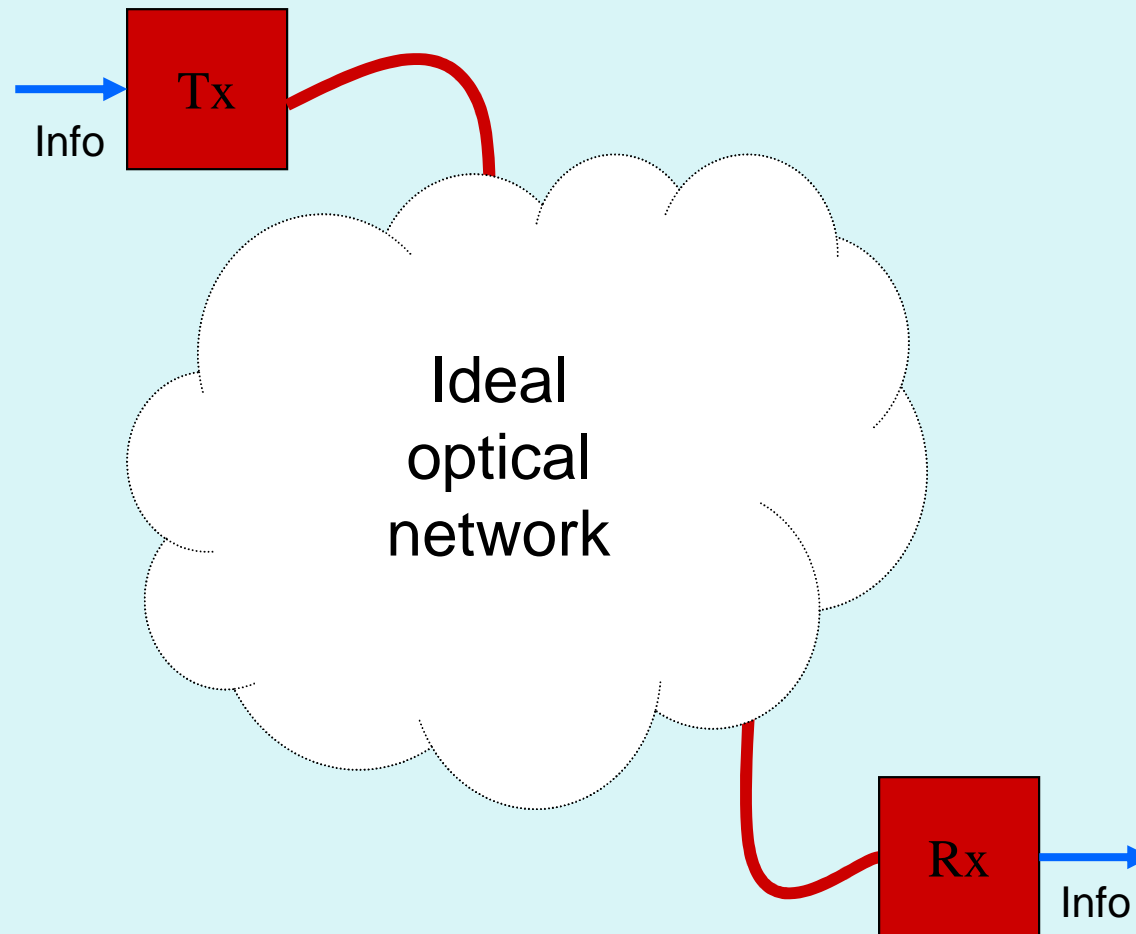
Conclusion

- Research in optical communications shows that the staggering growth of Internet traffic (1000-fold increase in 20 years) can be supported by the optical communications if its capacity will properly increase by advances in transmission, switching/routing and architectural aspects of network. These advances will be based on both technological improvements and architectural enhancements.

- Time will show what results of the today's research become commercial products in tomorrow optical communications.

Conclusion

- Thank you very much for listening to me so long time.

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