SAPIENZA
UNIVERSITÀ DI ROMA

Network Infrastructures

A.A. 2023-2024

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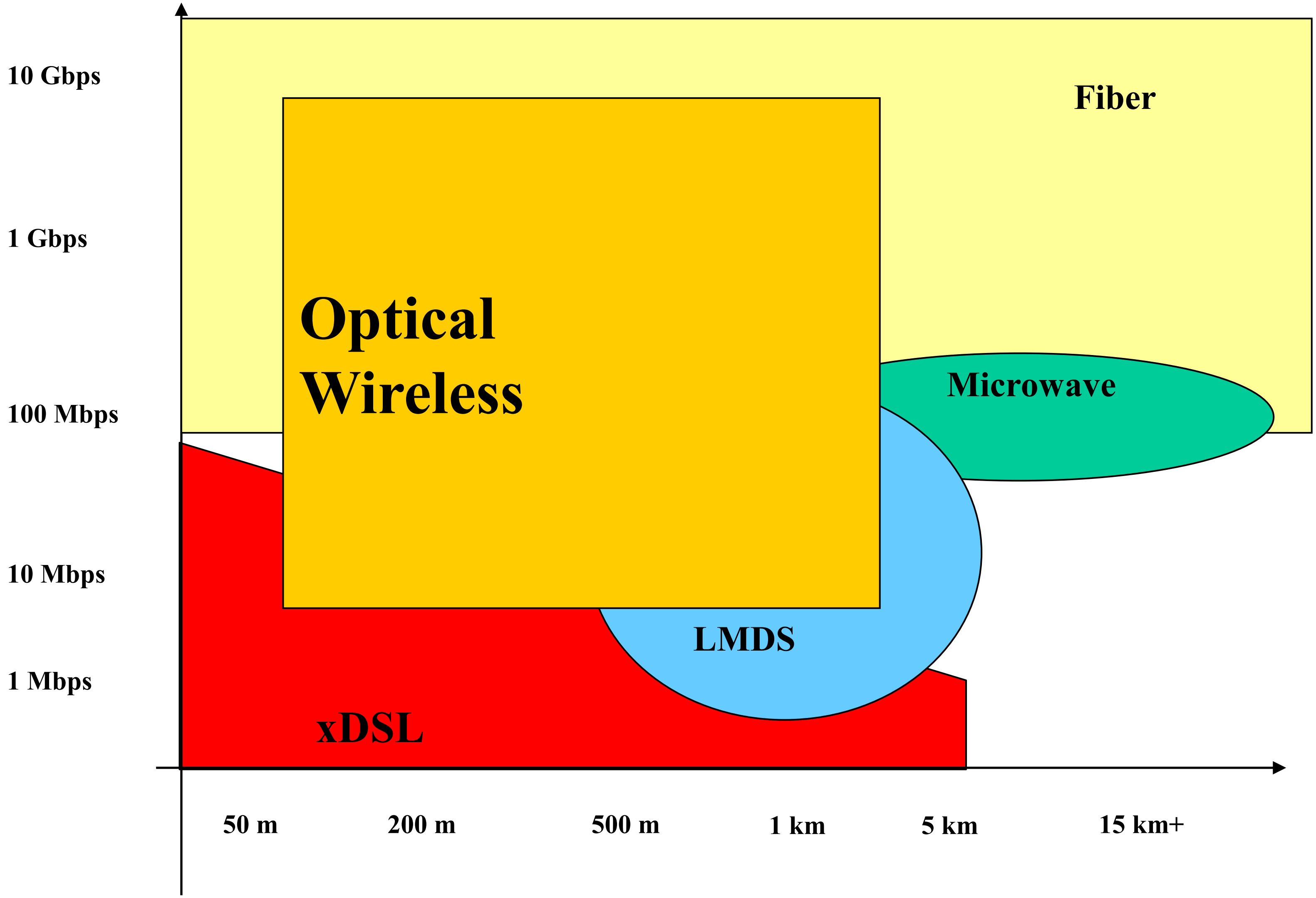
Outline

- Why FTTx
- How FTTx: PON
- Principles of Optical Fibre Systems
- PON characteristics (APON, BPON, EPON, GPON)
- Future: WDM PON
- Application
- Market (cost, unbundling)

Part of these slides are taken from:
Towards Fiber to the X (FTTX): Passive Optical Networks,
Francesco Matera Responsabile Area Tecnologie Reti di Nuova Generazione
mat@fub.it ; +39 06 5480 2215

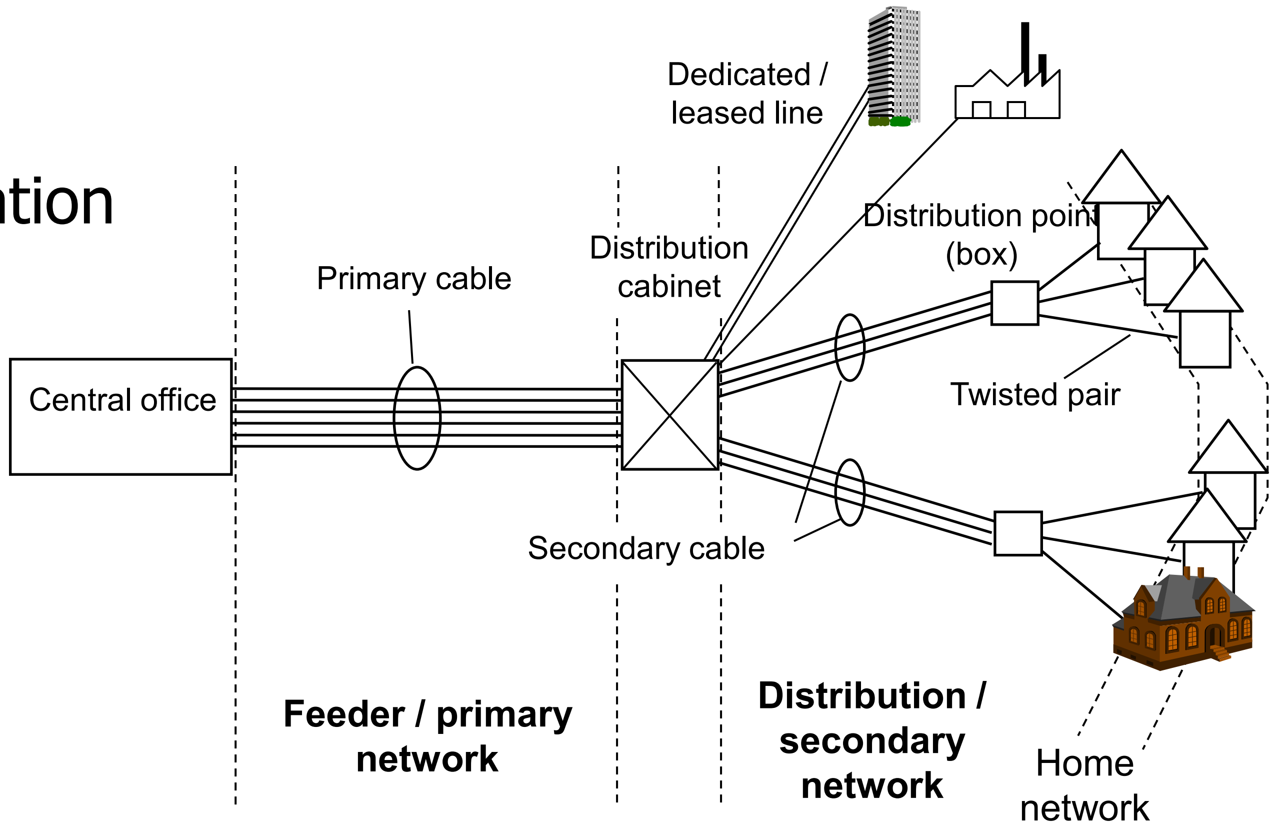
Main source: Project EU E-Photon/One+, Lessons from Prof. A. Pattavina, G. Maier, Politecnico di Milano

Access/backhoul



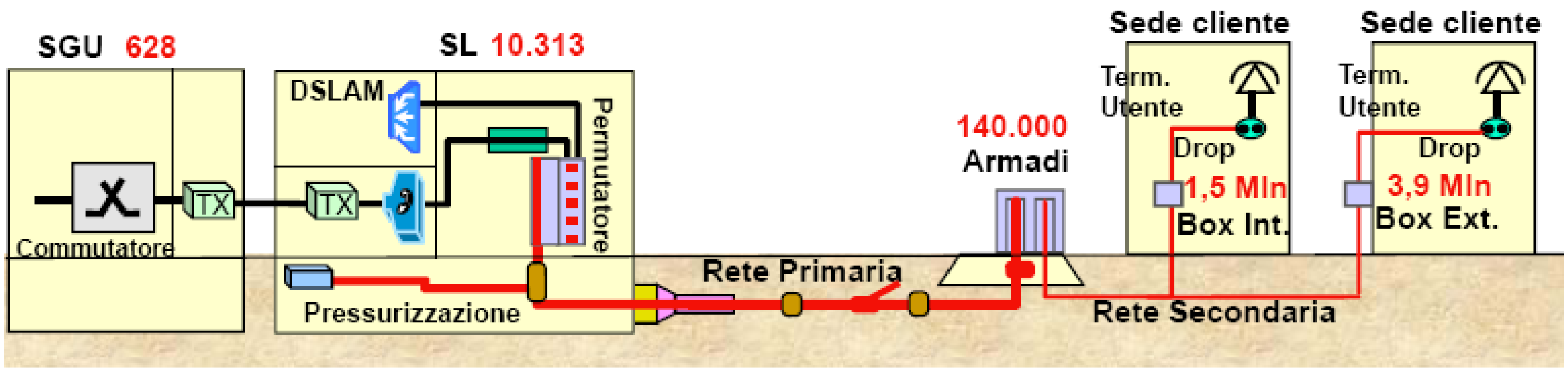
PSTN access-network Physical architecture

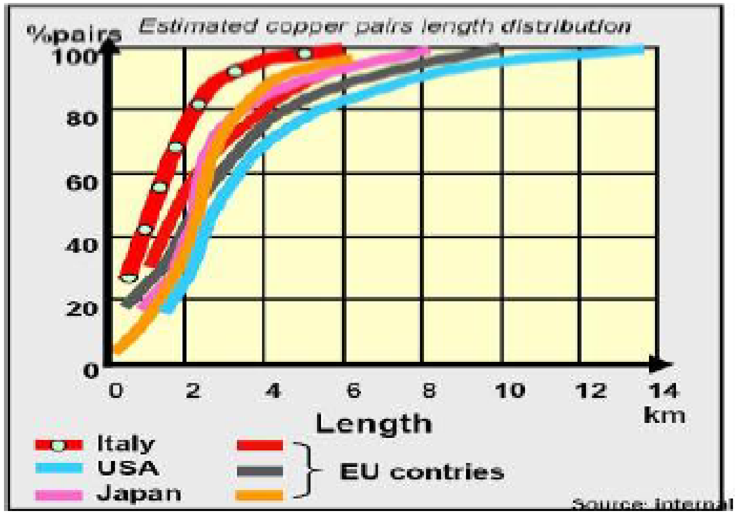
- Primary network
  - High sharing
  - Cost minimization
- Secondary network
  - Flexibility
  - Branching
- Cables
  - Primary
    - 2400-2000 pairs
    - In duct or pipe
  - Secondary
    - 100-10 pairs
    - Trenched or aerial
- Cascading more stages of cabinets is possible but rare



Telecom access networks

La rete accesso in rame oggi

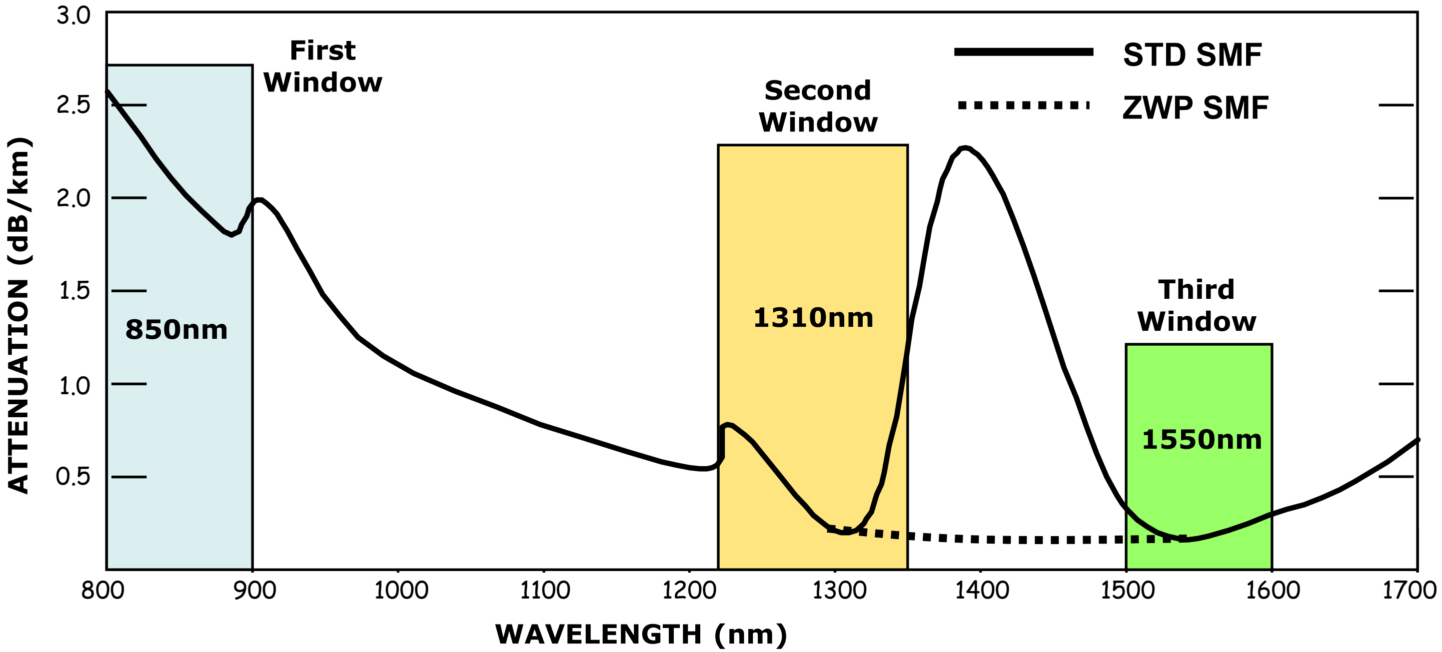




- ~ 530.000 km cavo
- ~ 110.000.000 km coppia
- ~ 140.000 armadi
- ~ 5.500.000 distributori/terminazioni

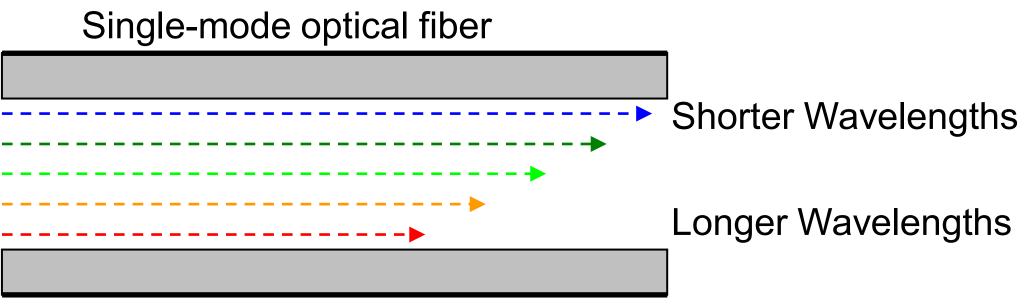
Optical Fiber: Attenuation

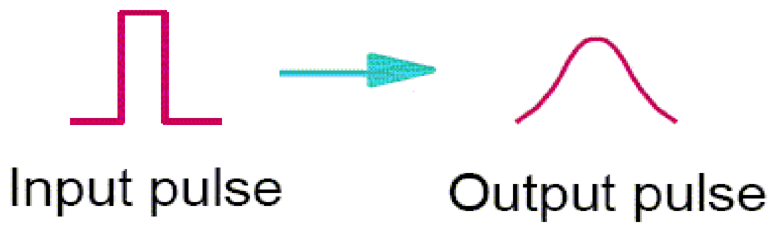
- Single Mode Fiber (SMF) to achieve large distances
  - **<u>ITU G.652 SMF (STD)</u>**
    - "water peak" attenuation renders the 1360nm–1480nm spectrum unusable for data transmission
  - ITU G652c/d SMF (ZWP)
    - "zero-water peak"

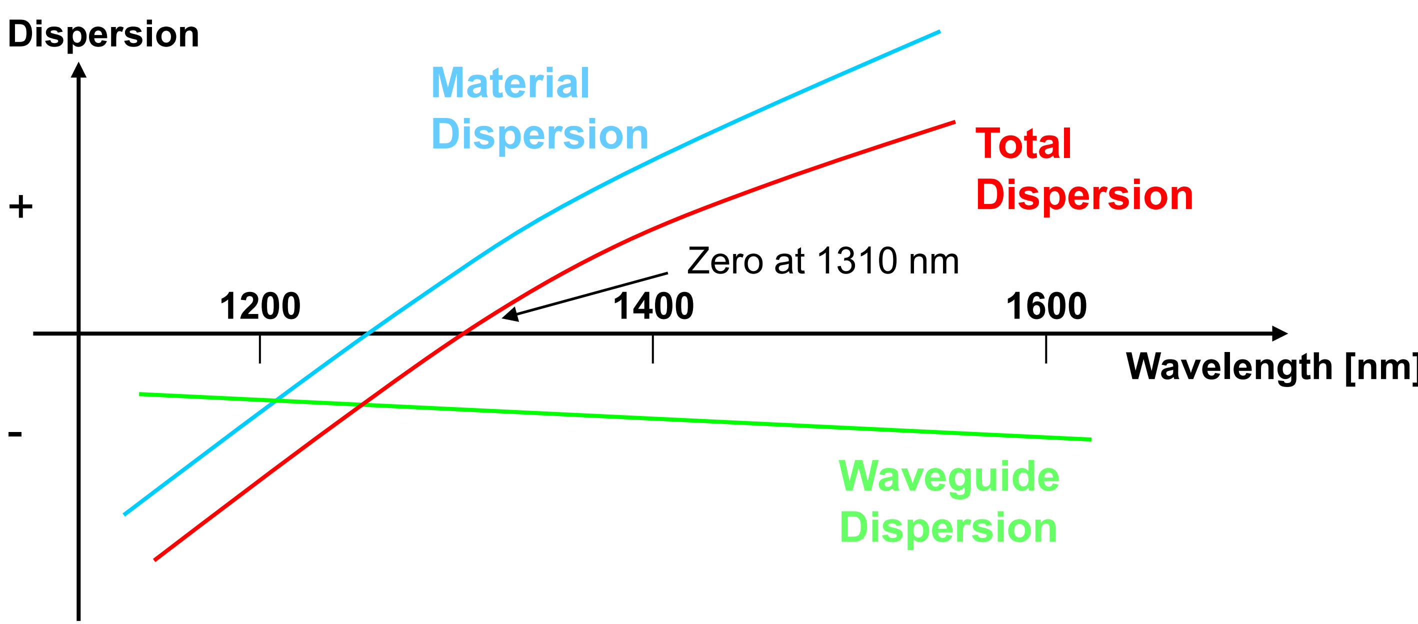


Optical Fiber: Chromatic Dispersion

- Causes signal pulse broadening



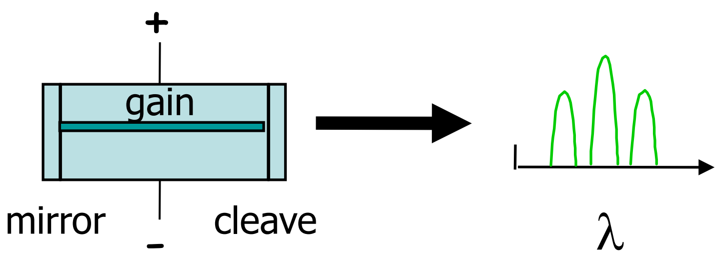




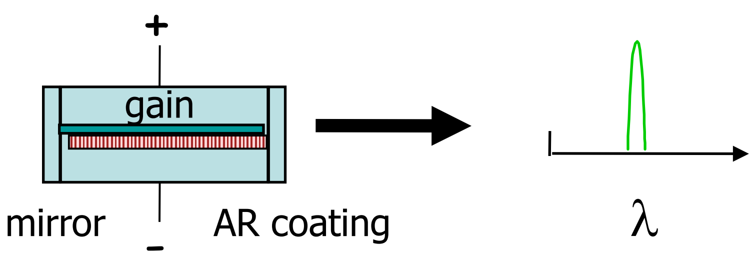
Lasers Diodes (LD)

- Fabry-Perot (FP)
  - Cheap
  - Noisy
    - Sensitive to chromatic dispersion
  - Used on 1310 nm

Simple FP



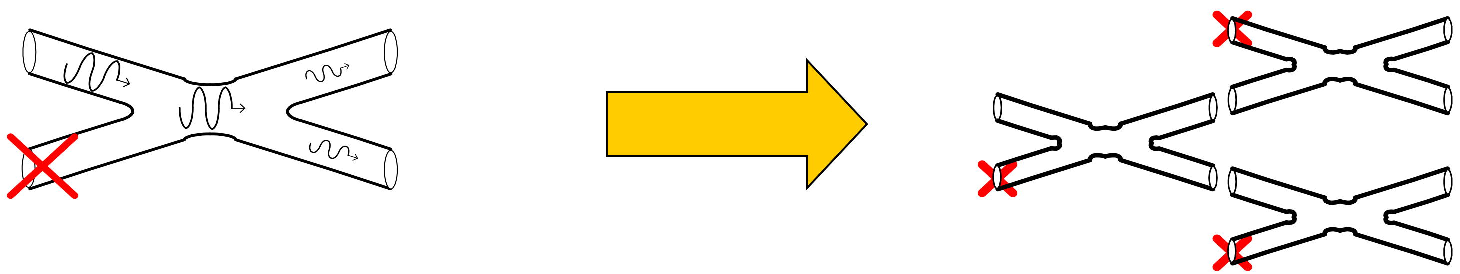
DFB



- Distributed Feedback (DFB)
  - More expensive
  - Narrow spectral width
    - Less sensitive to chromatic dispersion
  - Used on 1550 nm (or 1310 nm)

Passive Splitters

- 1x2 Splitter
- 1xN Splitter



- The basic element consists of two fibers fused together
- Every time the signal is split two ways, the signal is reduced by *10log(0.5)=3dB*
  - Loss ~*3dB* x log_2*(#ONUs)*

	Conventional	Low-loss
Splitter 1x2	3.7dB	3.4dB

Photodiodes (PD)

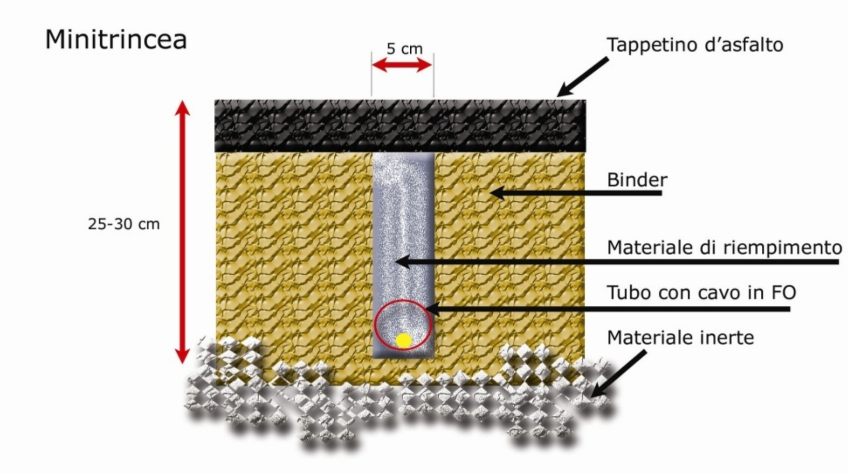
- PIN Photodiodes
  - Good optical sensitivity (~-22 dBm)
  - Silicon for shorter λ's (eg 850nm)
  - InGaAs for longer λ's (eg 1310/1550nm)
- Avalanche Photodiodes (APDs)
  - Higher sensitivity (~-30 dBm)
  - Primarily for extended distances in Gb/s rates
  - Much higher cost than PIN diodes

Transceiver Assumptions

	TX Power	RX Sensitivity
ONU (FP+PIN)	0 dBm	-22 dBm
OLT (DFB+APD)	1 dBm	-30 dBm

- **Upstream (@1310nm) Power Budget = 30 dB**
- **Downstream (@1490nm) Power Budget = 22 dB**

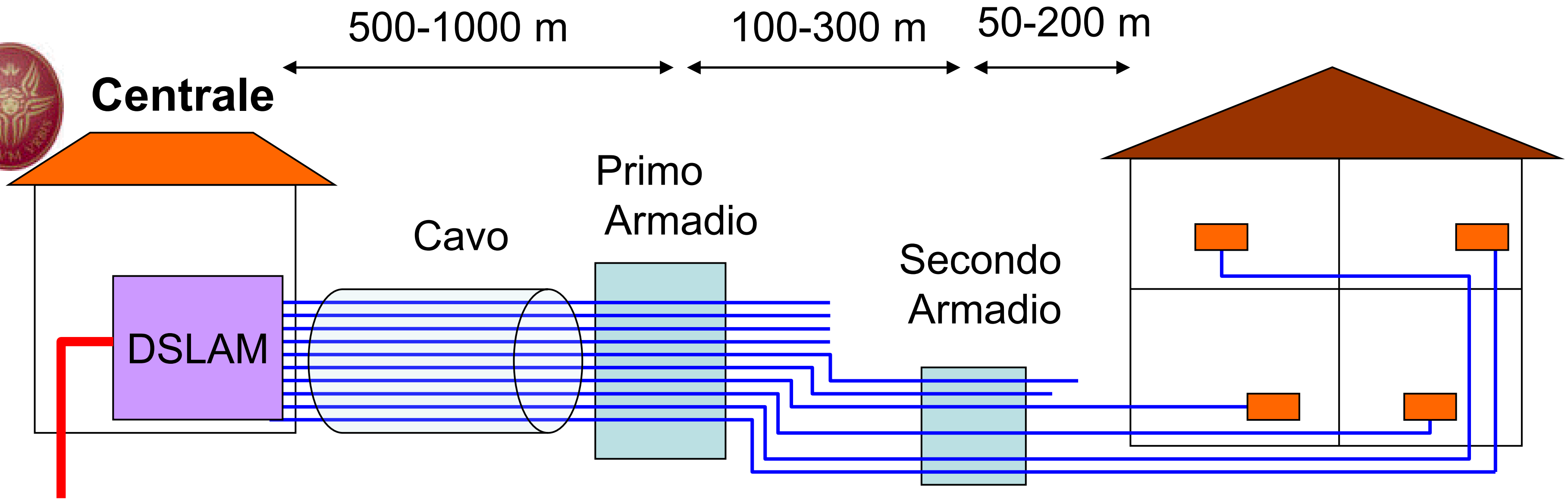
Fiber installation



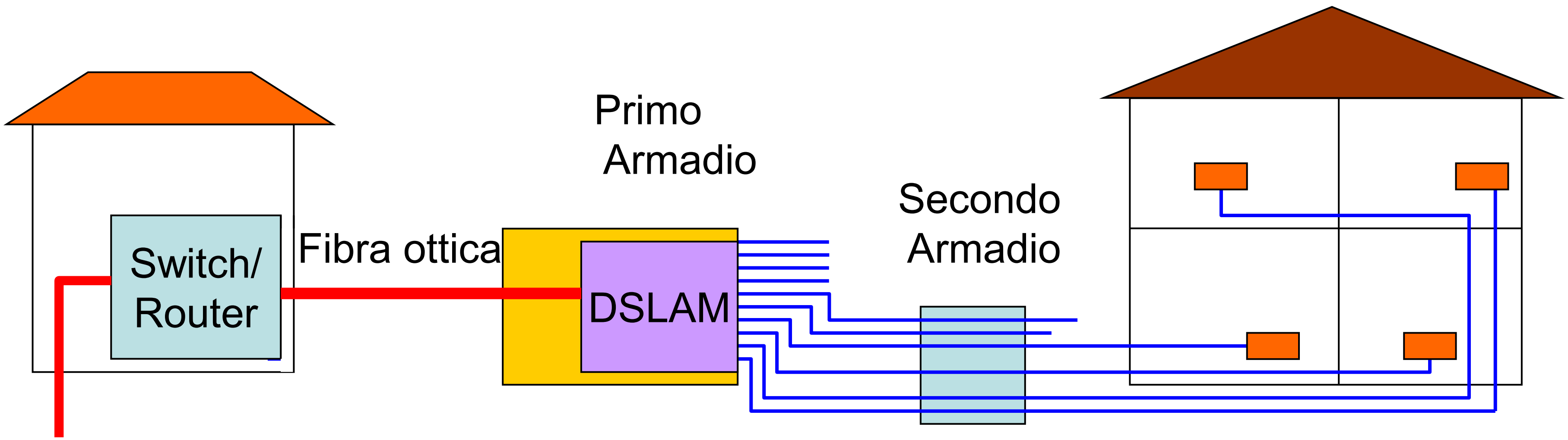
La microtrincea come semplice ed economica soluzione per la diffusione della fibra ottica nella rete di accesso (from HighBand)

Soffiaggio della fibra (ERICSSON)

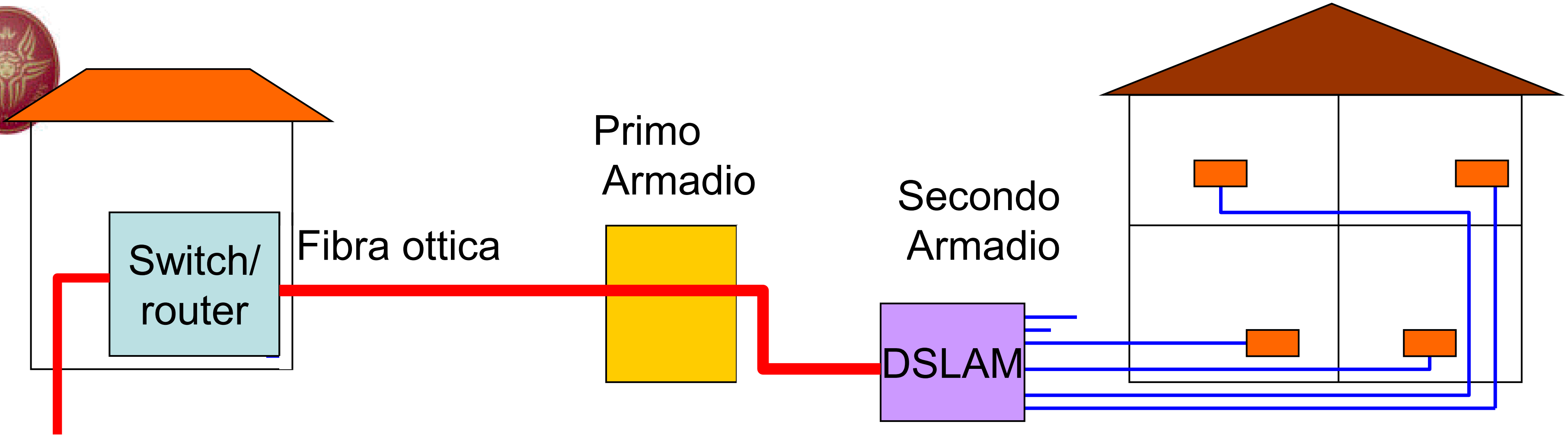
30-40 K €/km per microtrincea



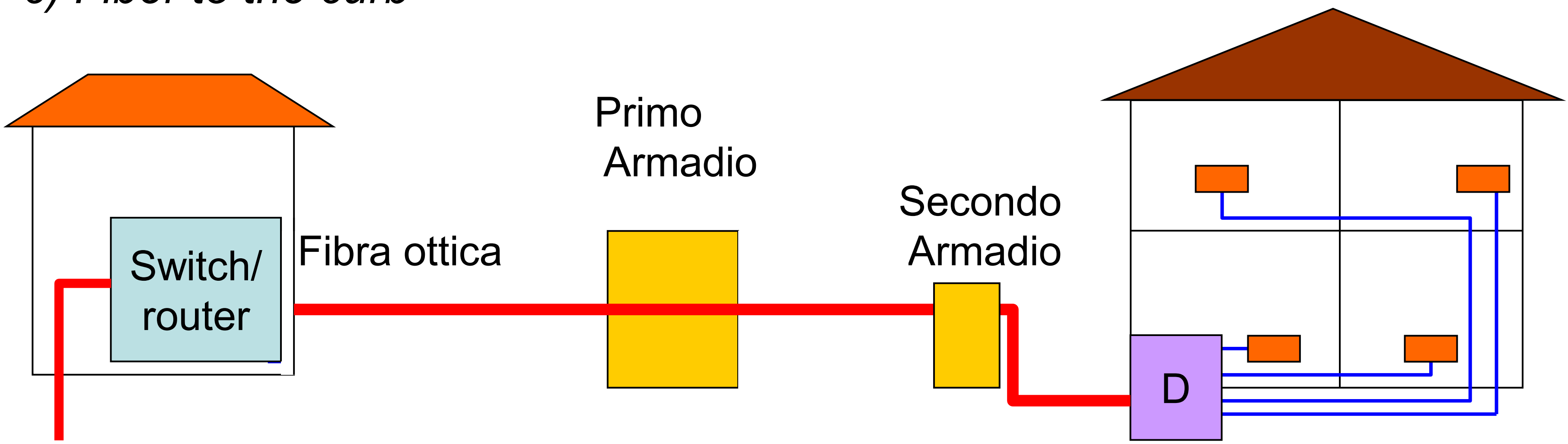
a) Best current architecture



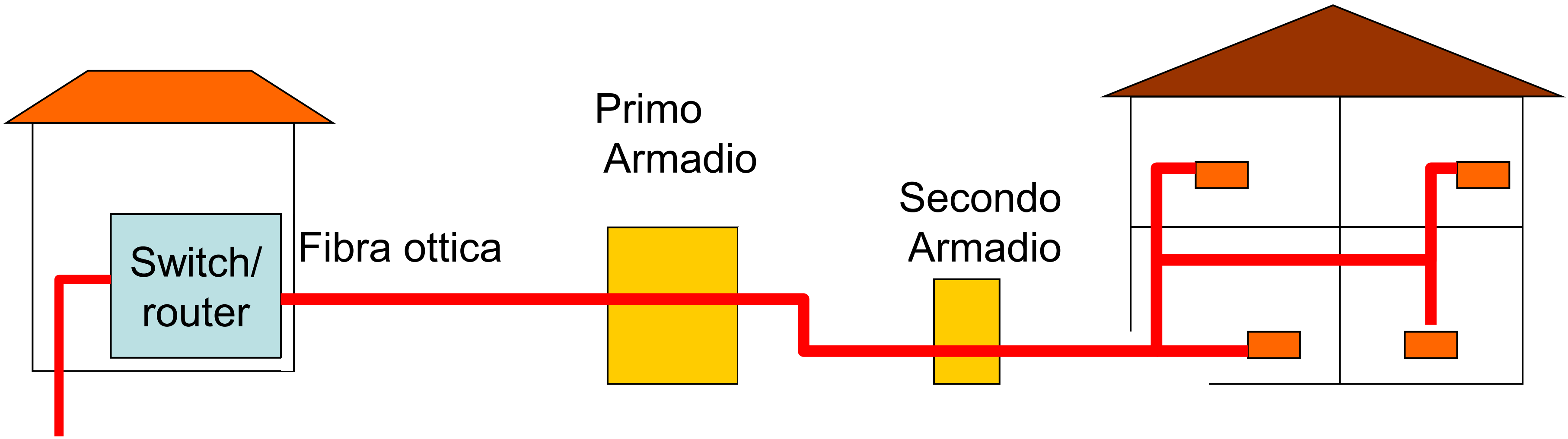
b) Fiber to the cabinet



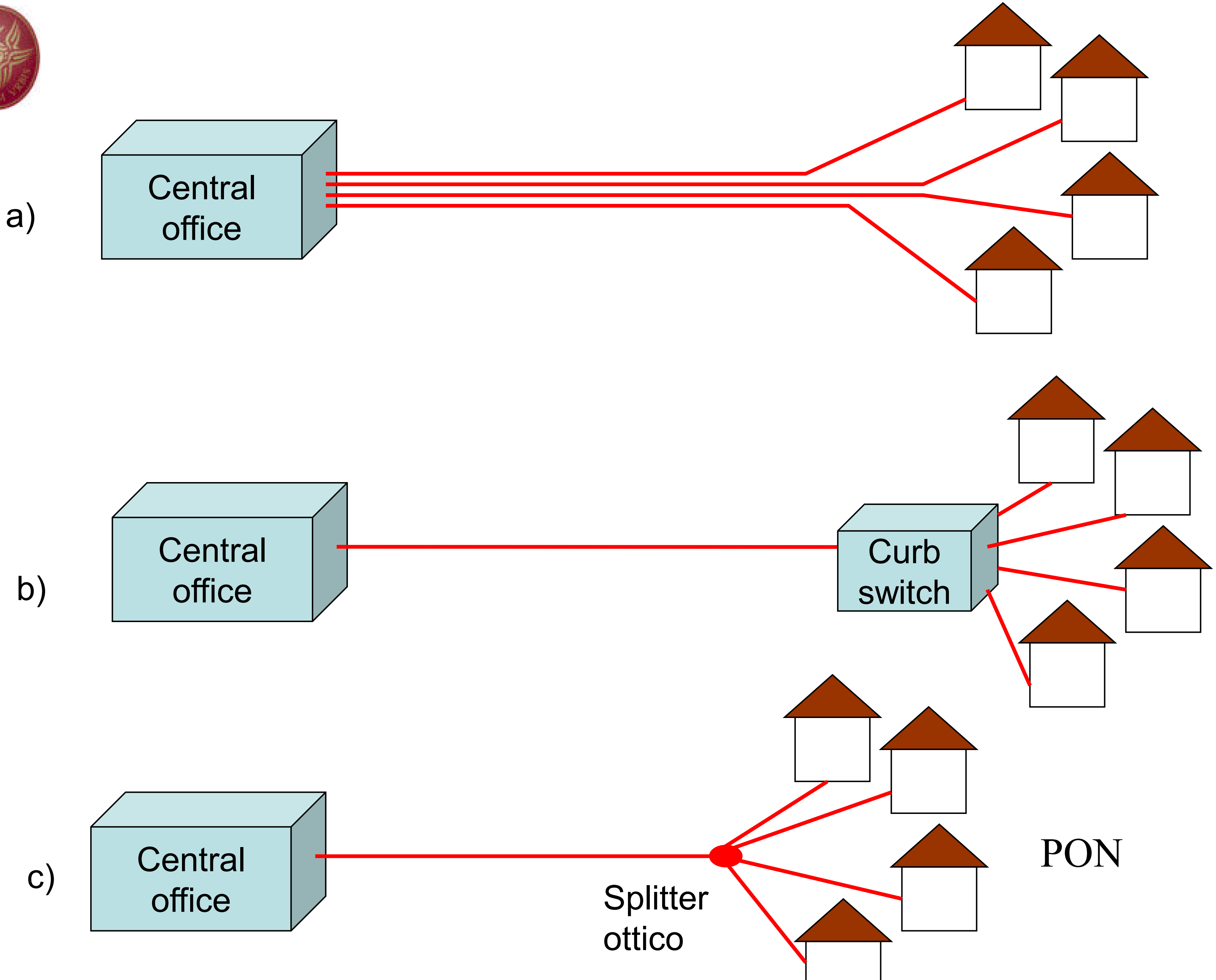
c) Fiber to the curb



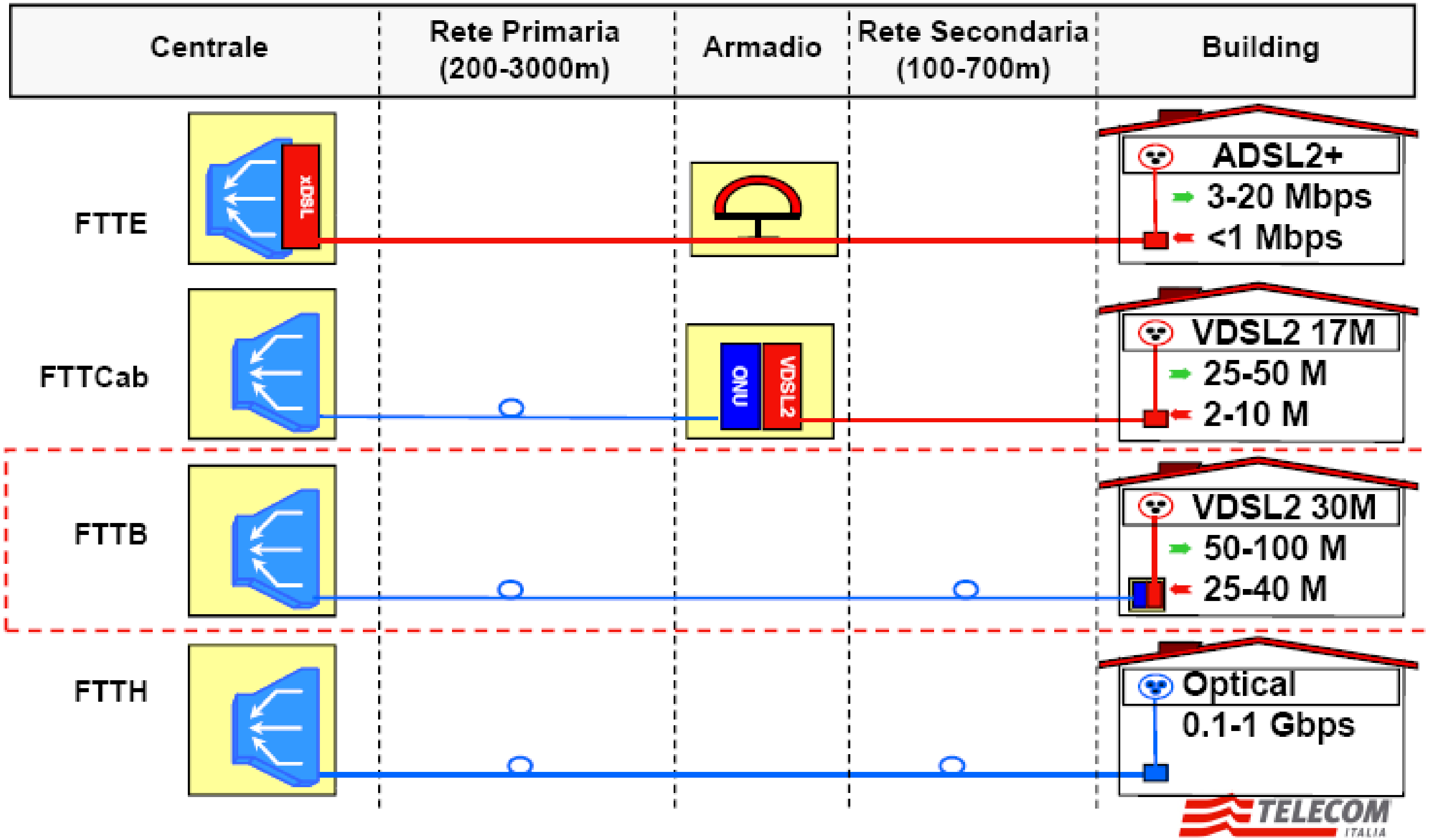
d) Fiber to the building



e) Fiber to the home

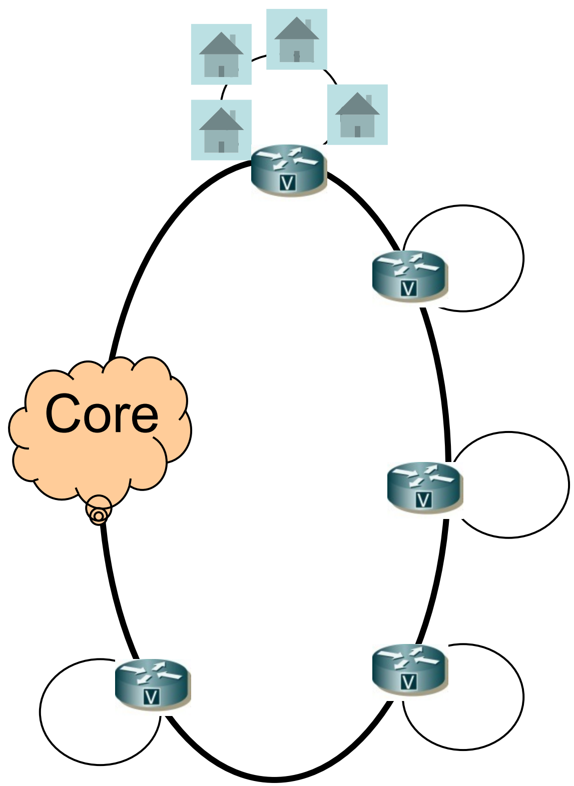

a)
Central office
b)
Central office
Curb switch
c)
Central office
Splitter ottico
PON

Access capacities

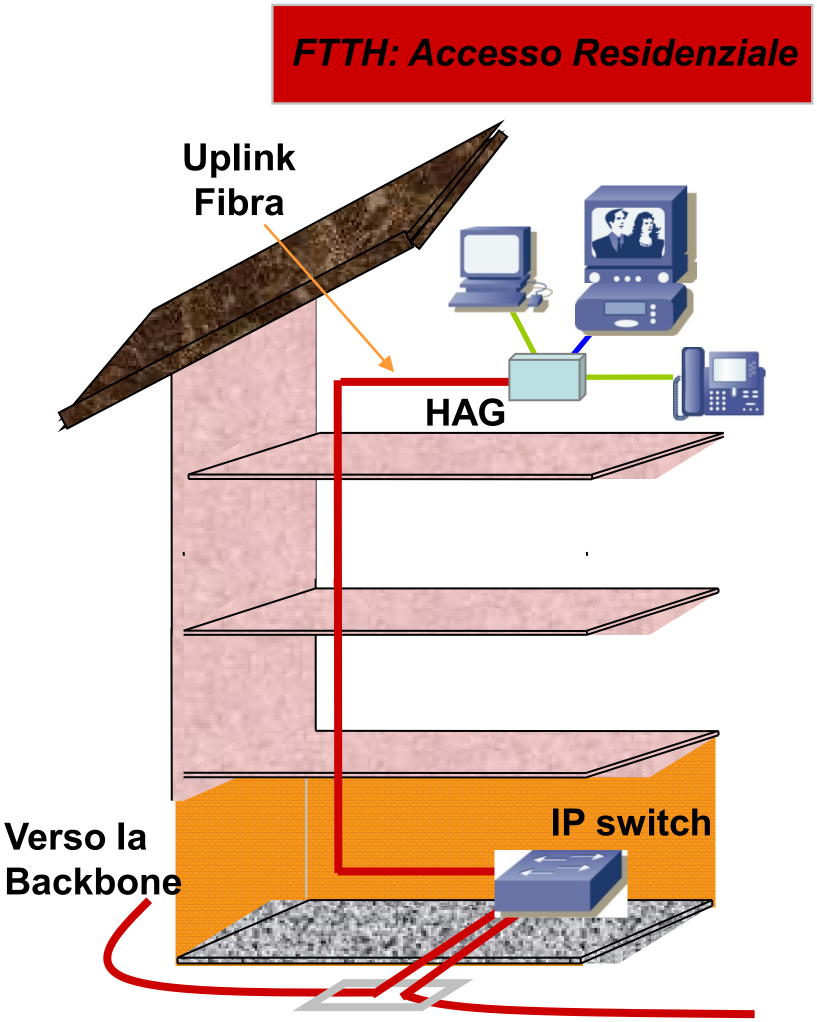


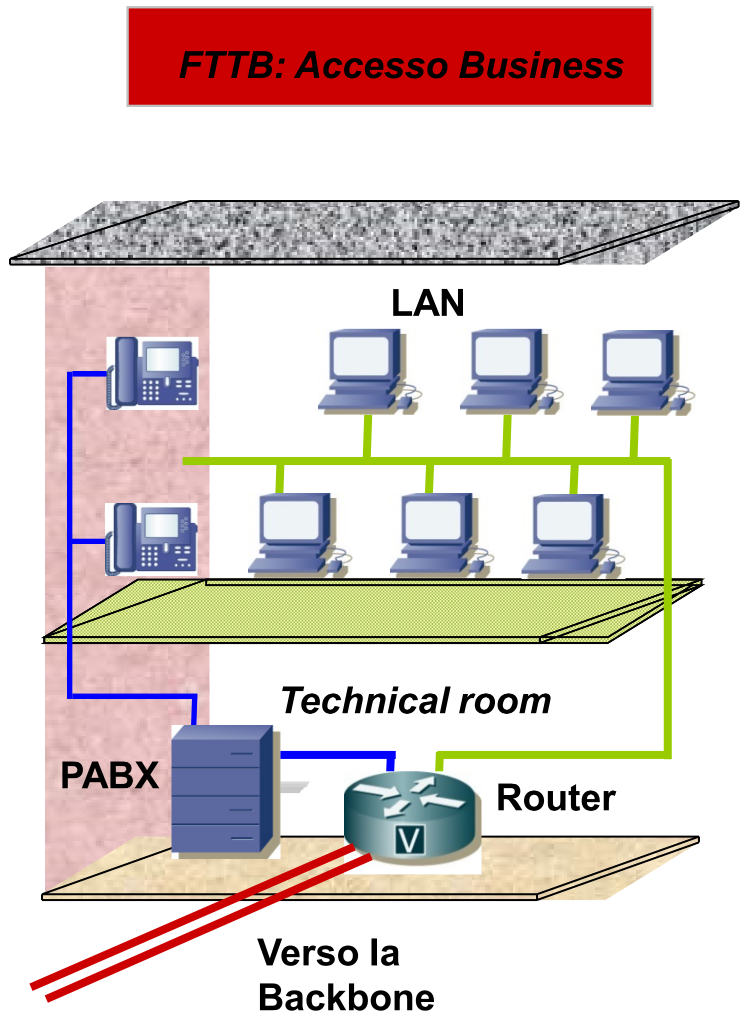
GbE based: FASTWEB

Daisy chain architecture



First case in Europe:Fastweb 2000





FTTx = Fiber-to-the-x

- FTTH - Home
- FTTC - Curb
- FTTN - Node or Neighborhood
- FTTP - Premise
- FTTB - Building or Business
- FTTU - User
- FTTZ - Zone
- FTTO - Office
- FTTD - Desk

Basic PON operations

- The optical line terminal (OLT) broadcasts data downstream on 1,510 nm and the ONTs burst data back upstream on 1,310 nm in their assigned time slots.

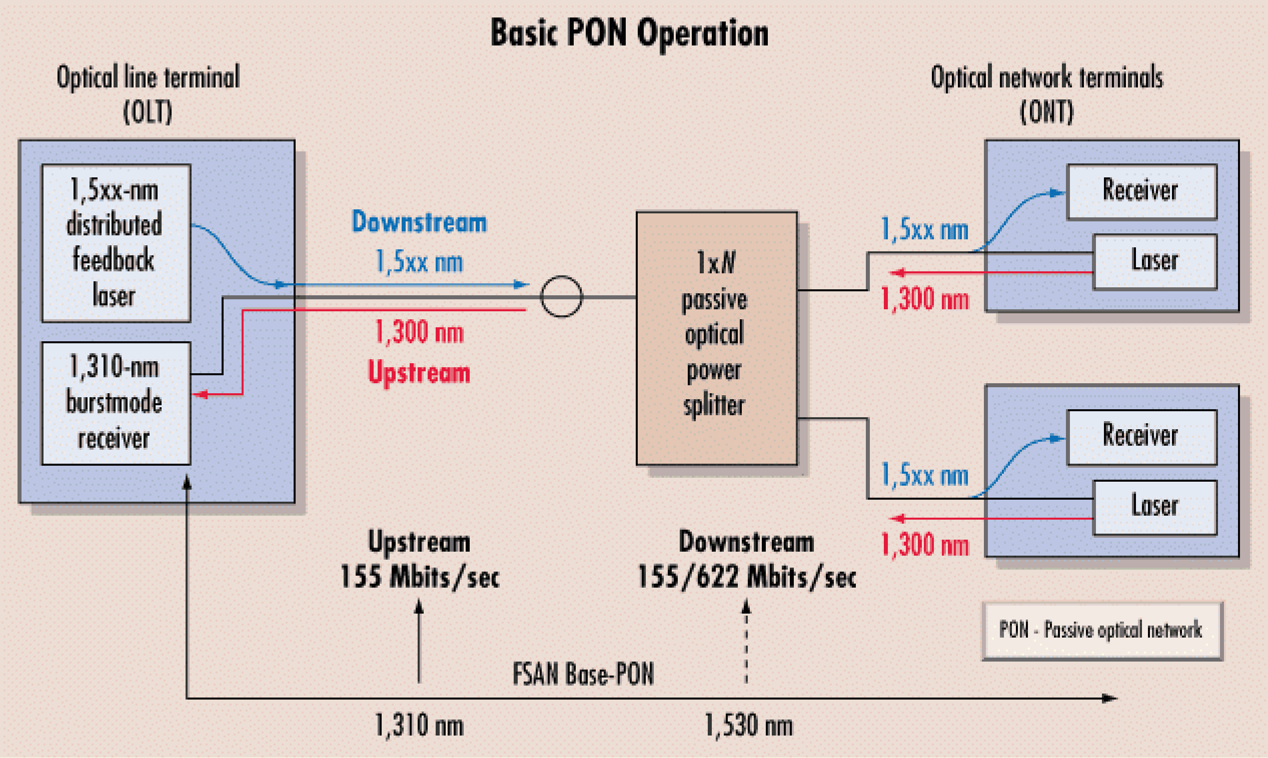
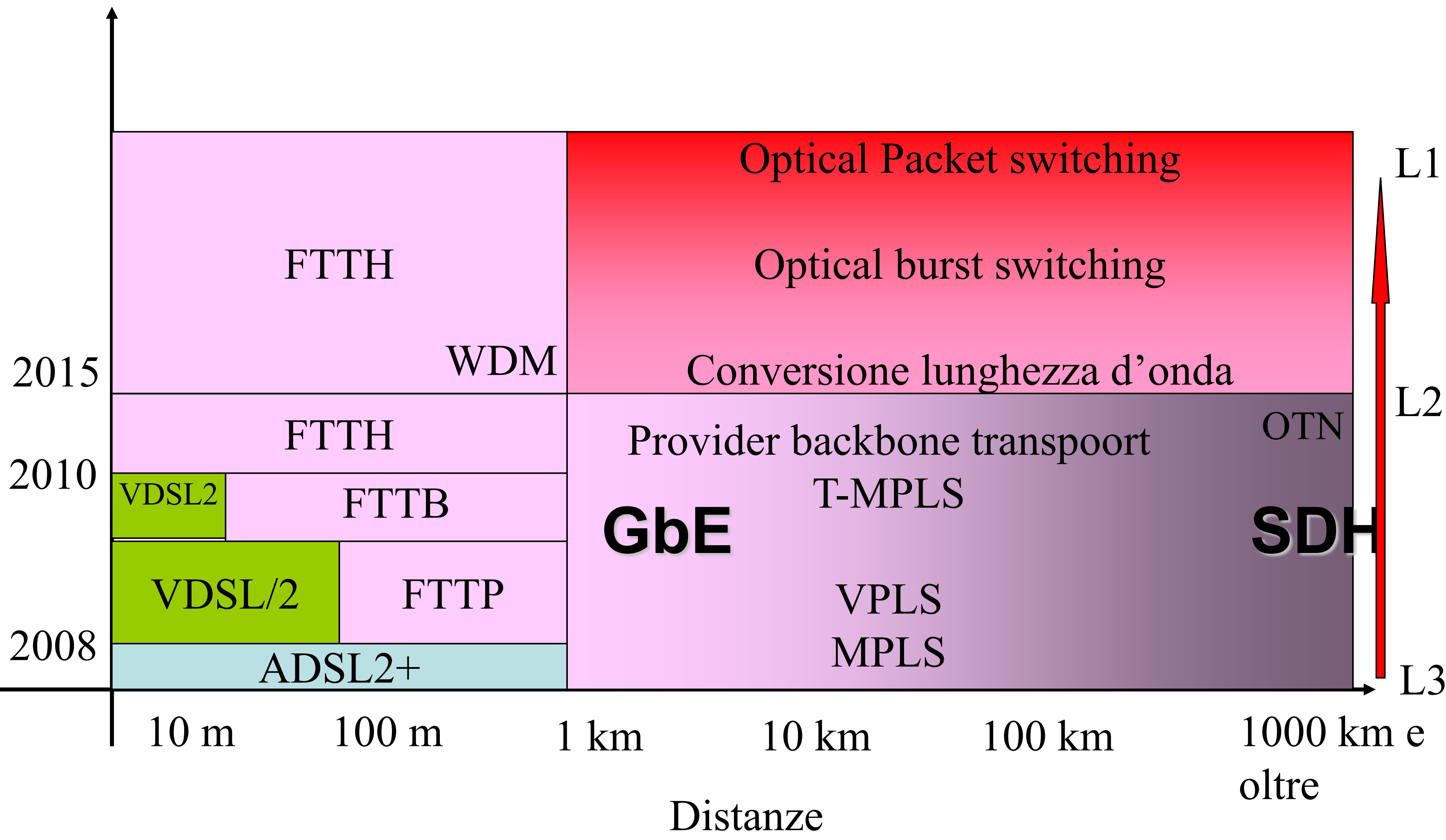


Figure 1. A basic passive-optical-network operation enables service to as many as 32 optical-network terminals (ONTs). Each ONT, in turn, can be connected to multiple subscribers, making fiber more affordable for access networks.

Photonics Evolution



Time vs. Spectrum Sharing

- Downstream → *point-to-multipoint* network
  - The OLT manages the whole bandwidth
- Upstream → *multipoint-to-point* network
  - ONUs transmit only towards the OLT
  - ONUs cannot detect other ONUs transmissions
  - Data transmitted by ONUs may collide

Need of a channel separation mechanism to fairly share bandwidth resources

TDMA

Time Division Multiple Access

↔

WDMA

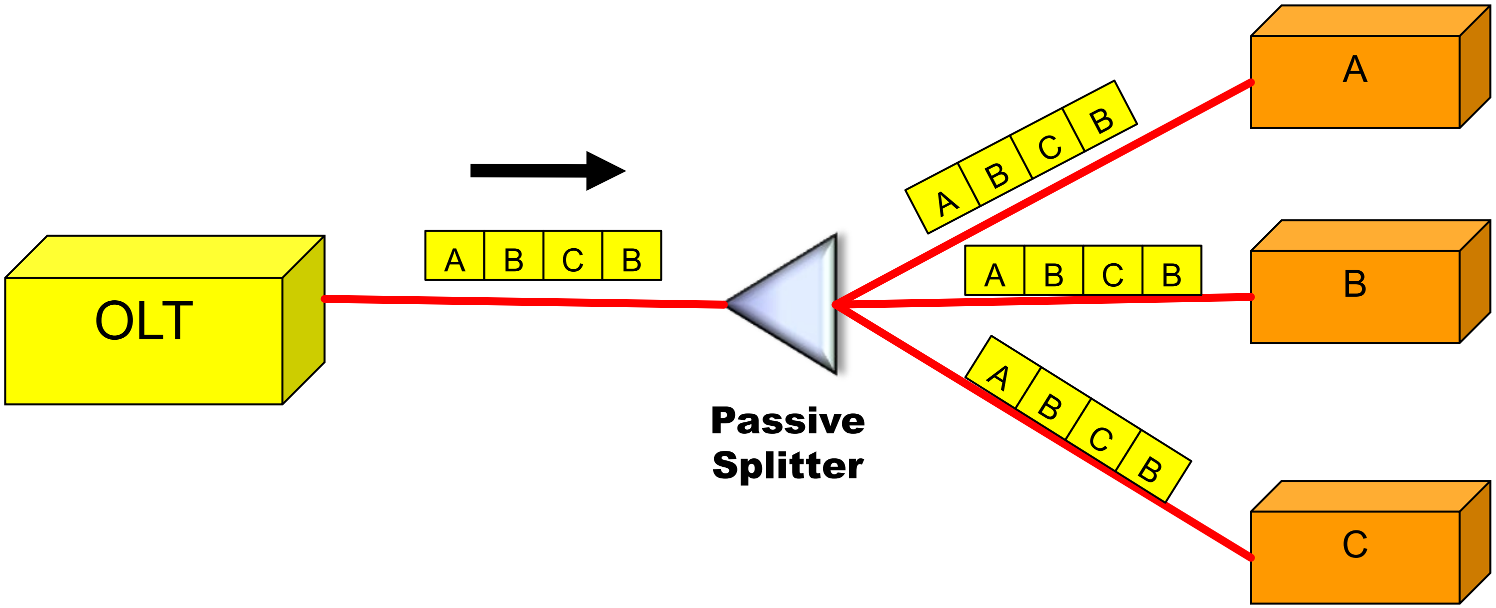
Wavelength Division Multiple Access

PON Overview

- **TDM-PONs**
  - Standardized
  - Use few wavelengths (typically 2 or 3)
  - Low cost and mature devices (splitters, lasers, etc.)
  - Limited power budget
    - Maximum distances ≤ 20km, Split ratios ≤ 64
  - Traffic distribution
    - Broadcast scheme in downstream
    - TDMA techniques in upstream
  - Examples: APON/BPON, EPON & GPON
- **WDM-PONs**
  - Proposed in literature and/or demonstrated
  - Introduce WDM techniques and devices (AWG)
  - Long-reach and bandwidth
  - Examples: CPON, LARNET, RITENET, Success-DWA…

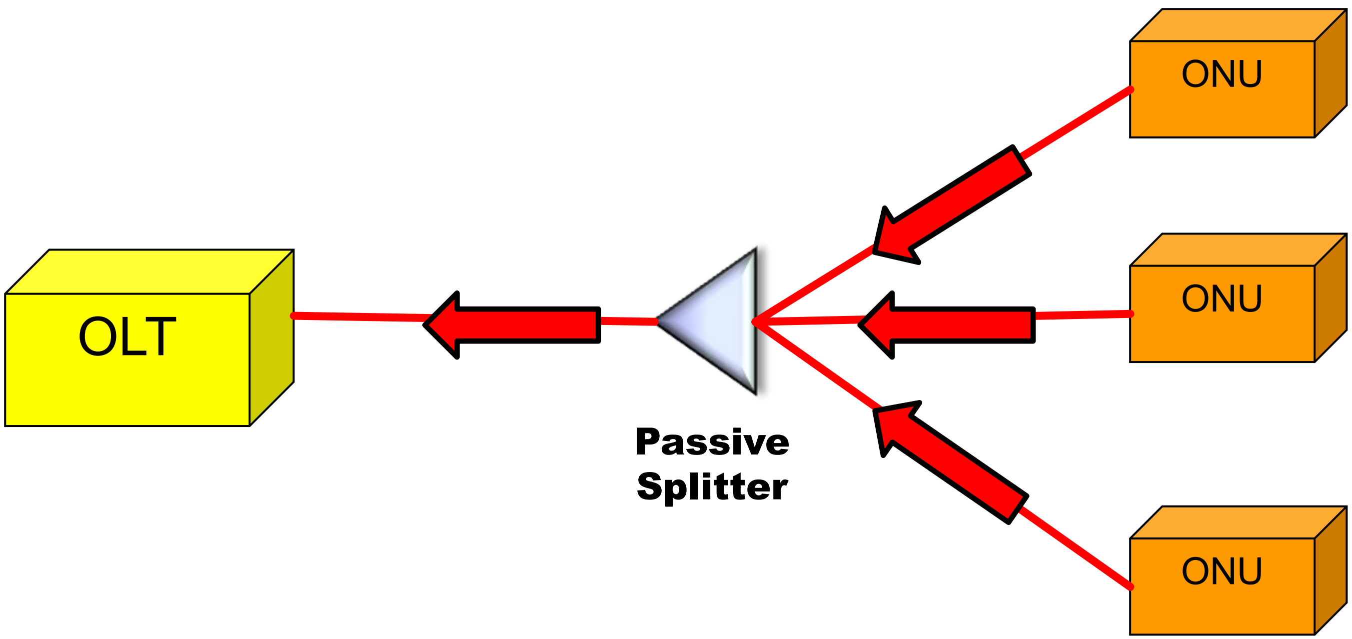
Downstream Traffic Scheduling

- OLT schedules traffic inside timeslots
  - -Time Division Multiplexing (TDM) scheme
- Time slots can vary from ~μs to ~ms



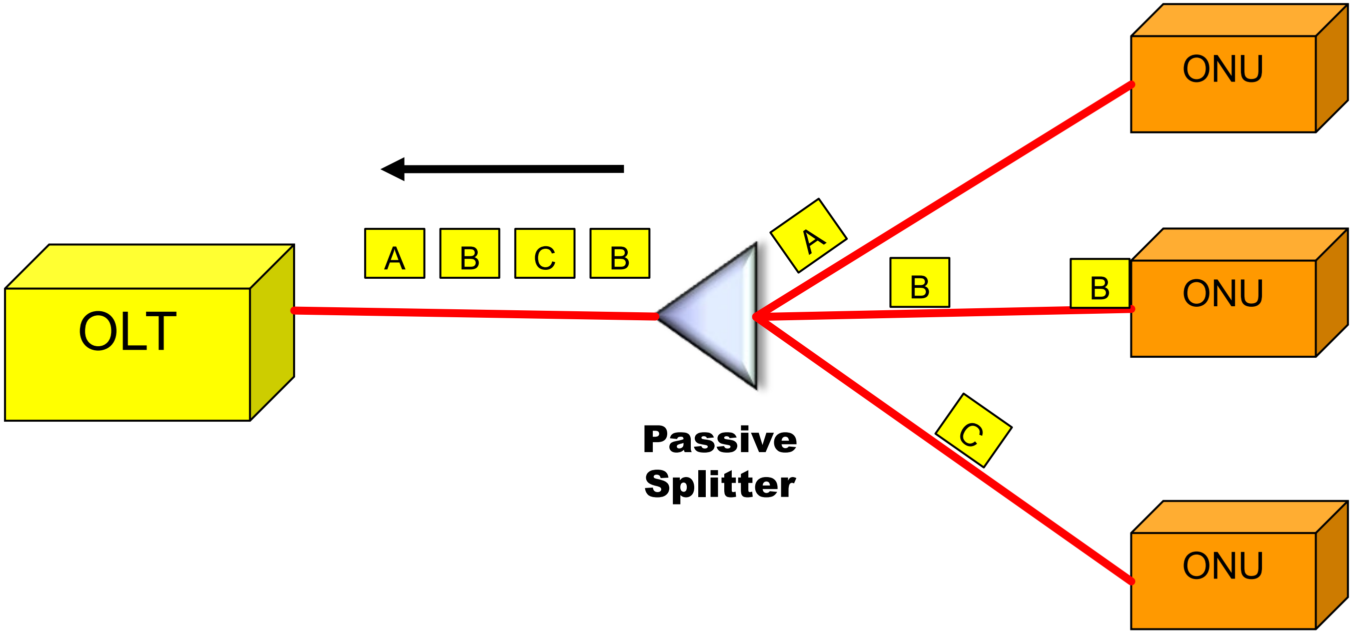
Upstream Traffic

- All ONUs share the same upstream channel
  - ONUs cannot exchange data directly
  - Collisions may occur at the splitter/combiner



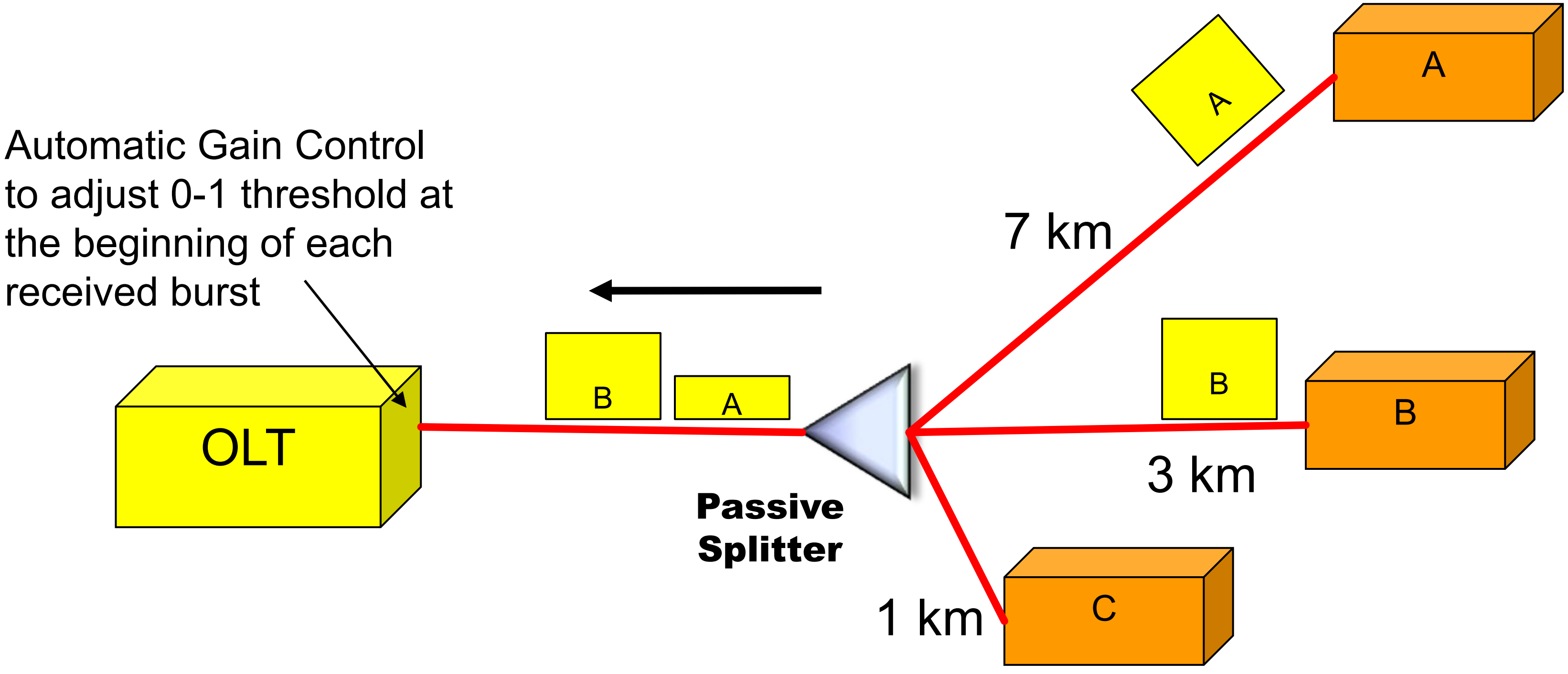
Upstream Traffic Scheduling 2/4

- In general, PON standards propose Time Division Multiplexing Access (TDMA) schemes
  - Upstream time slicing and assignment



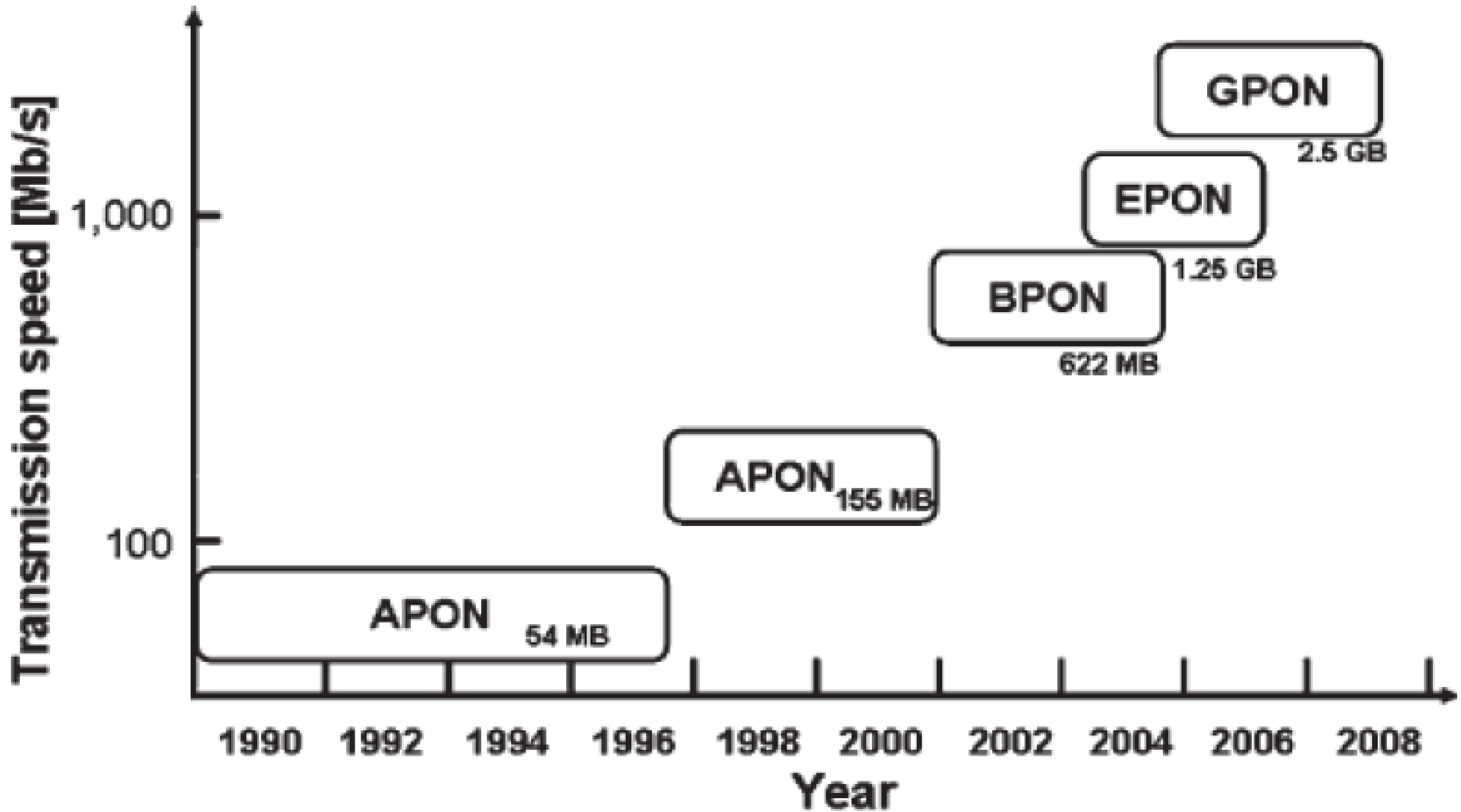
Upstream Frame Reception

- The OLT receives frames with different powers
  - Much difficult to recover synchronism (clock and data recovery)
  - Burst Mode Receiver (complex) @ OLT
    - Sets 0-1 threshold on a burst basis



Evolution of the standards

10 GB EPON



Fiber in the loop
PON standardization: a brief history

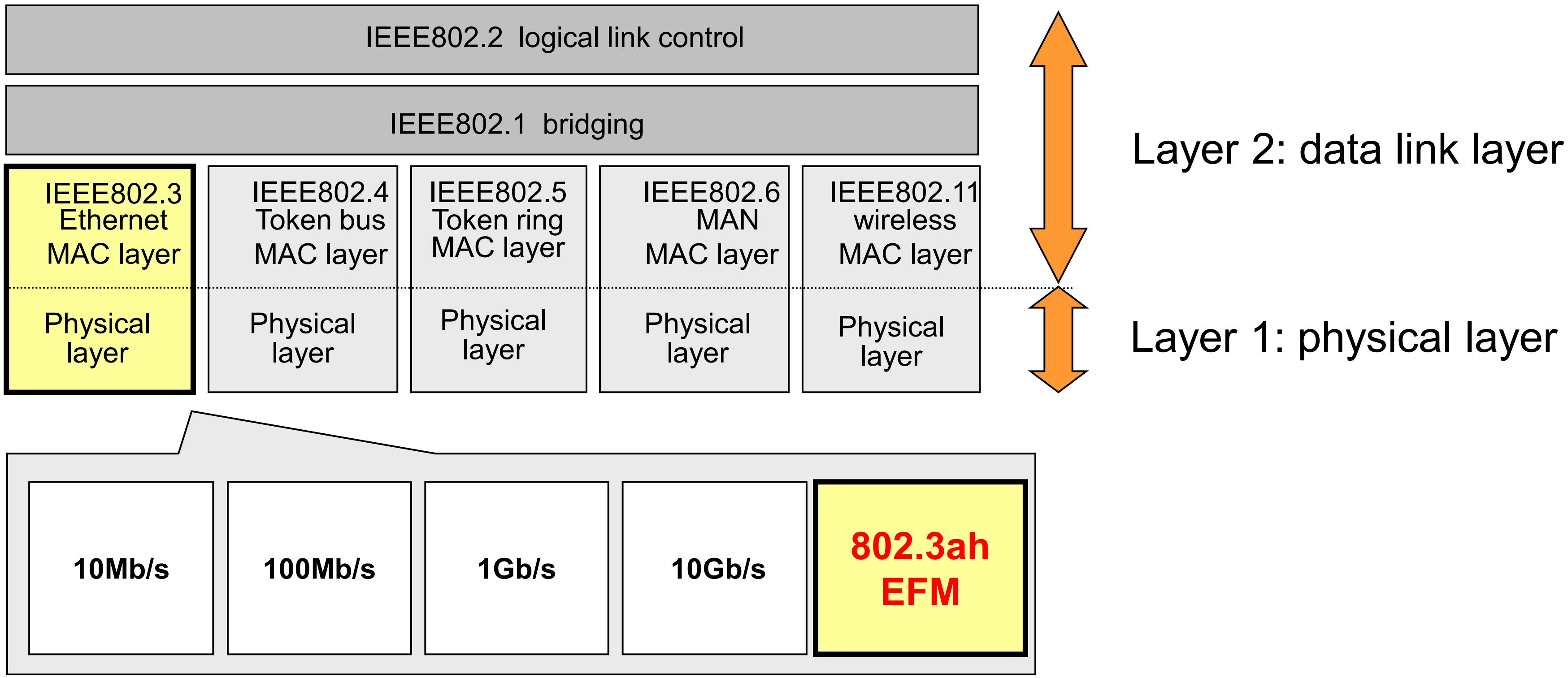
- ATM PON (A-PON)
  - Traffic is carried using ATM raw-cell format and framing
  - 1982: idea of PON (British Telecom)
  - 1987 – 1999: PON testbeds by BT, Deutsche Telekom (Eastern Germany), NTT (Japan), BellSouth (Atlanta, USA)
  - 1995: 622 Mbit/s APON testbed (RACE BAF project)
  - 1996: beginning of Full Service Access Network (FSAN) works
  - 1997-’98: ACTS BONAPARTE and EXPERT/VIKING projects
- Broadband PON (B-PON)
  - APON system is standardized by ITU-T with a new name to indicate that the PON can offer full broadband service and not just ATM
  - Line rates: 155 Mbit/s symmetrical or 622/155 Mbit/s down/upstream; ONU/OLT max distance: 20 km; max. # ONUs: 64
  - 1998-’00: ITU-T G.983.1 (physical aspects) and G.983.2 (ONT management and control)
  - 2001-’02: other ITU-T G.983.x and Q.834.x, e.g.
    - G.983.4/.7: Dynamic Bandwidth Assignment (DBA), providing statistical multiplexing (⇒ more users per ONU) and Quality of Service (QoS) enforcement
    - G.983.3: adoption of WDM to increase capacity or to carry video signals

Fiber in the loop
PON standardization: a brief history

- Ethernet PON (EPON)
  - Traffic is carried using Ethernet framing
    - Cheaper user equipment then BPON
    - Ethernet much more widespread than ATM
  - Higher subscriber rates (up to 1.25 GbE symmetrical), 16 ONU (power budget)
  - 2001: IEEE 802.3ah Study Group "Ethernet in the First Mile (EFM)"
  - First documents in Sept. 2003)
  - 2004: final approval of Standard IEEE 802.3ah
- Gigabit-capable PON (G-PON)
  - Traffic is carried by using different possible framings: ATM (G.983 base) or via G-PON Encapsulation Method (GEM), which can interface SDH (G.707 base) or Ethernet (IEEE802.3 base).
  - Various line rates, up to 2.4 Gbit/s symmetrical, ONU/OLT max distance: 20 km; max. # ONUs: 64-128
  - 2001: activity initiated by the FSAN group
  - 2003: ITU-T G.984.x

Ethernet Standards in EPONs

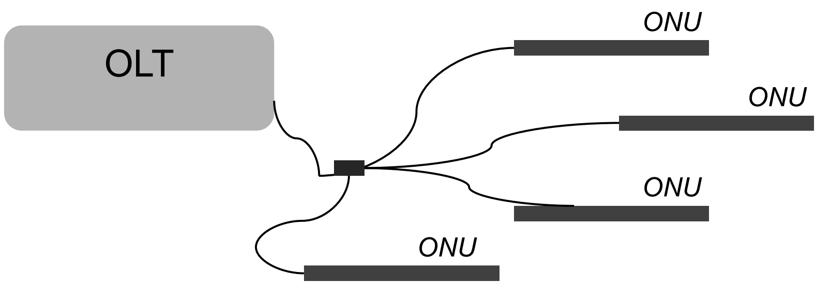
- EPON started to be standardized by IEEE 802.3ah EFM since 2001, it was ratified in 2004



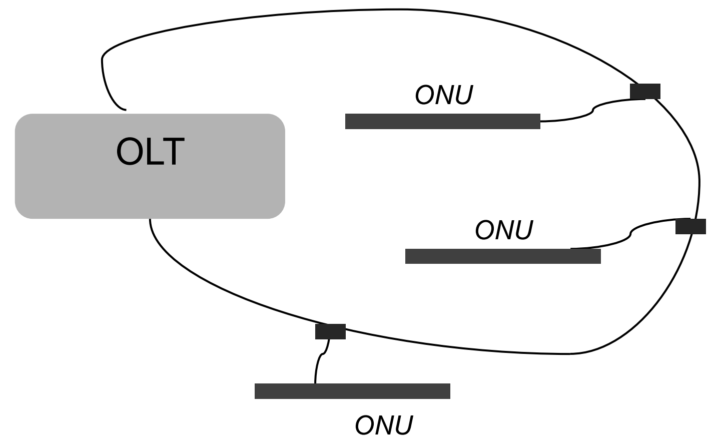
Ethernet PONs (EPONs)

- All packets carried in EPON are encapsulated in Ethernet frames
  - Support for variable size packets
- Similar wavelength plan to BPON
- Maximum bit rate is 1Gbps MAC-MAC (1.25 Gbps at the physical layer with 8b/10b line coding)
- Minimum number of splits is 16
- Maximum reach is
  - 10 km (FP-LD @ ONUs, limited by dispersion in downstrea for G.652)
  - 20 km (DFB-LD @ ONUs)
- Different configurations are allowed

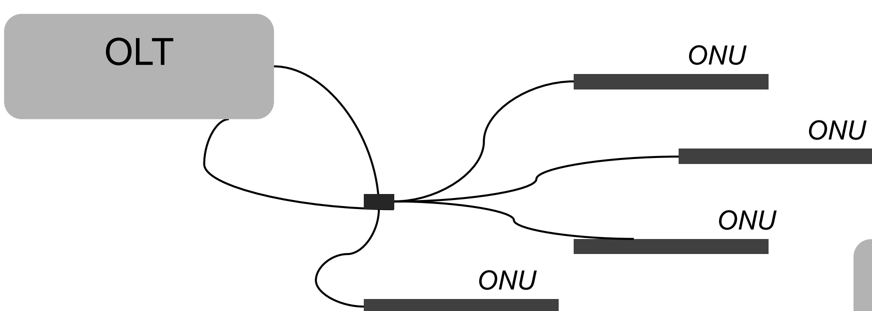
EPON Configurations



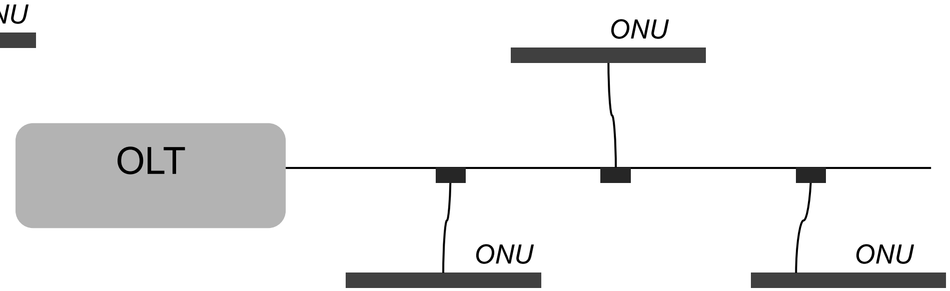
1) Tree Topology



(2) Ring Topology



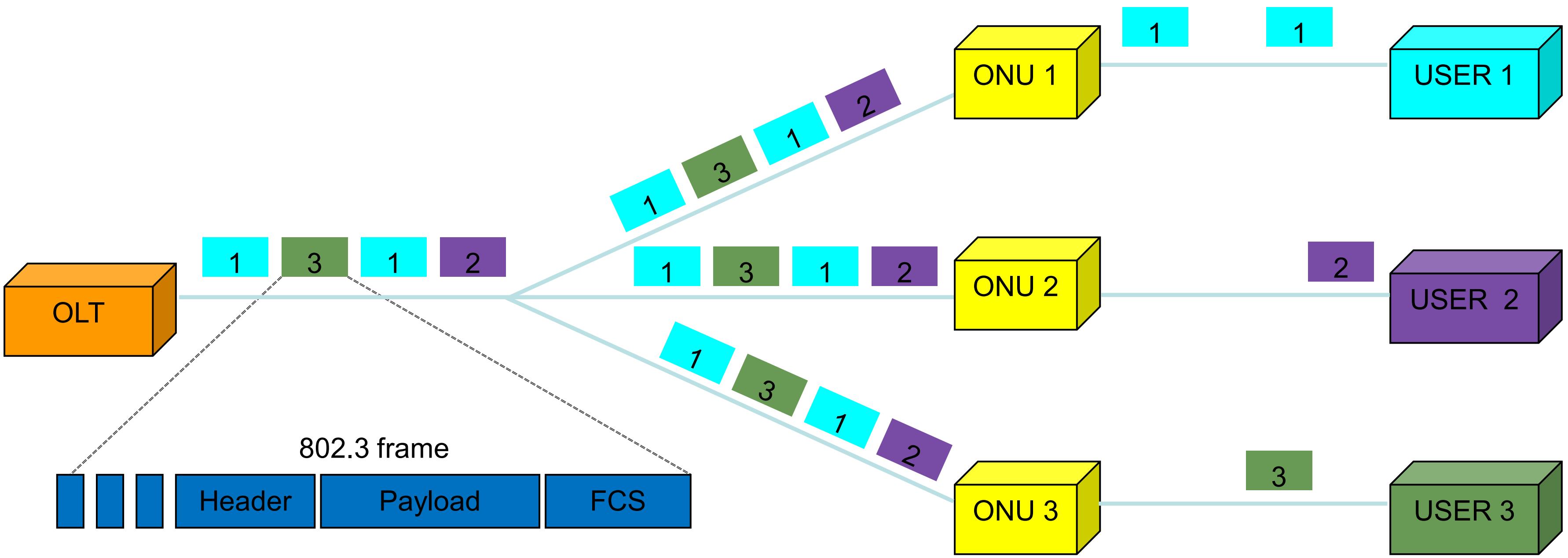
(3) Tree with Redundant Trunk



(4) Bus Topology

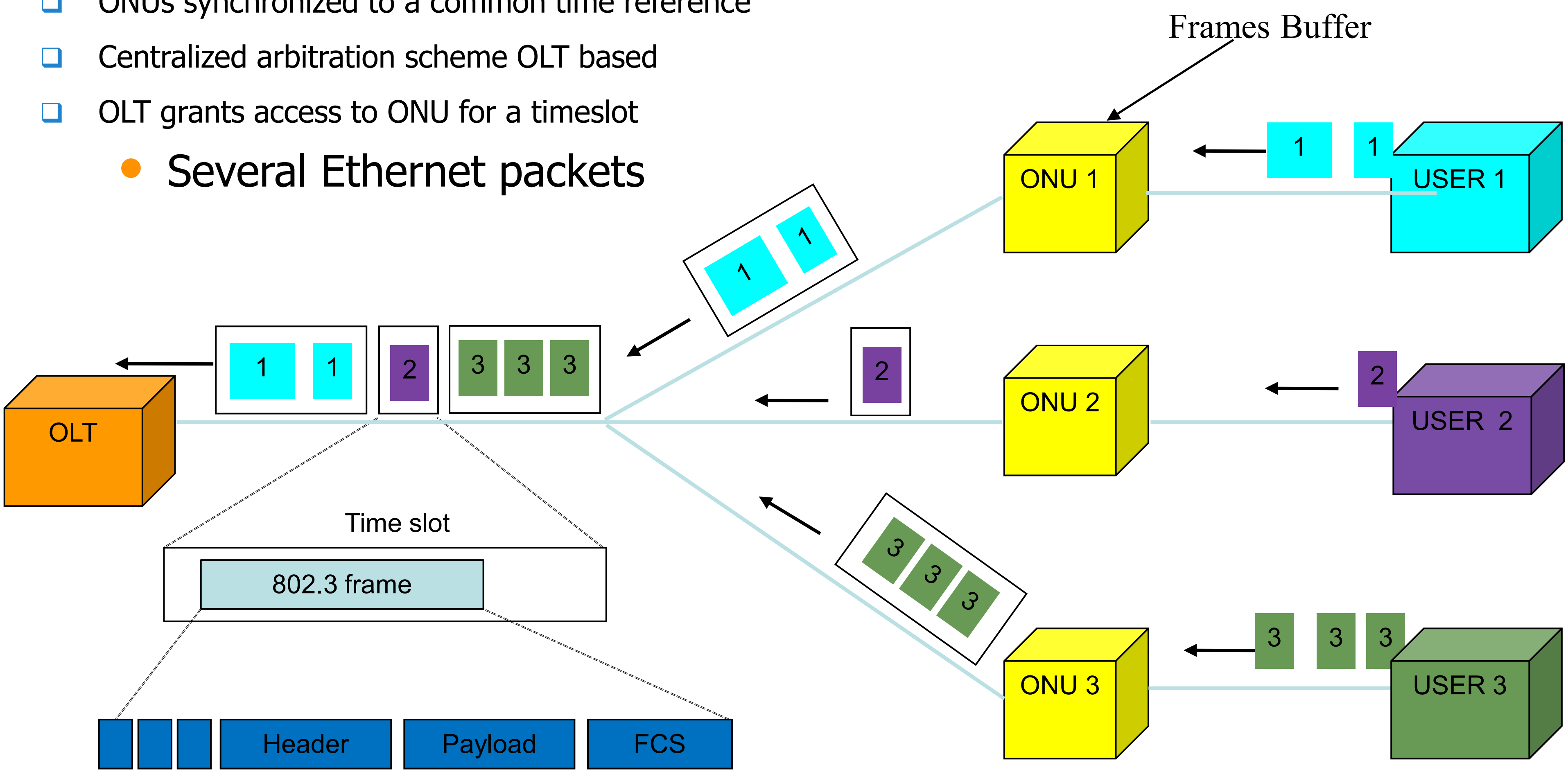
EPON Downstream Traffic

- Similar to a shared medium network
- Packets are broadcasted by the OLT and selected by their destination ONU



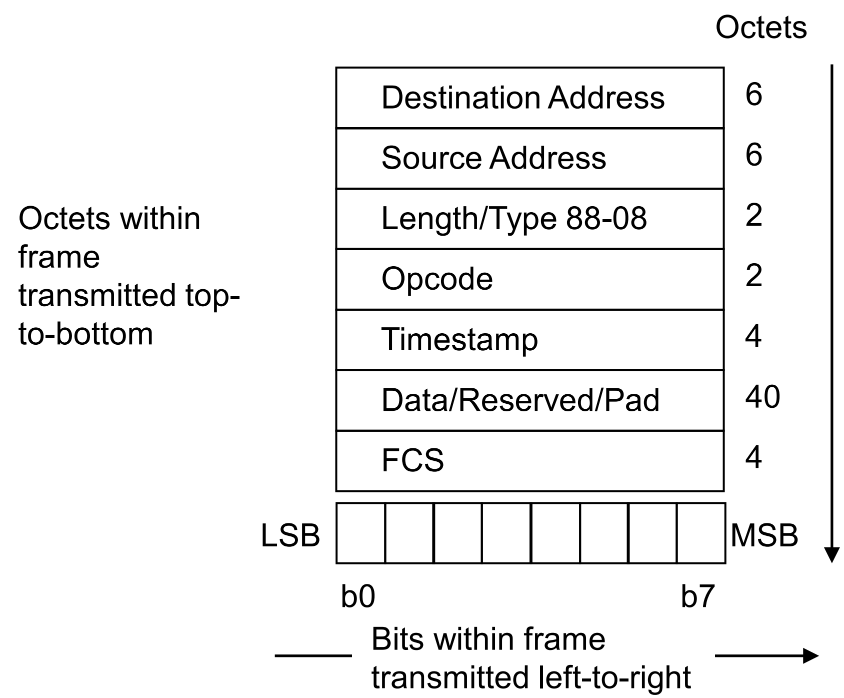
EPON Upstream Traffic

- ONUs synchronized to a common time reference
- Centralized arbitration scheme OLT based
- OLT grants access to ONU for a timeslot
  - Several Ethernet packets



The Multi-Point Control Protocol (MPCP)

- Original Ethernet MAC protocol cannot operate properly in the upstream channel (no collision detection) since each ONU cannot hear other ONUs
- MPCP (Multi-Point Control Protocol) is a new function of the MAC control sublayer. It is developed to support dynamic capacity allocation but the algorithms are an equipment vendors choice (Dynamic Bandwidth Allocation - DBA)
  - In-band signalling
  - Messages (64 bytes)
    - GATE
    - REGISTER
    - REGISTER_REQUEST
    - REGISTER_ACK
    - REPORT



Autodiscovery mode

- 3 control messages:
  - **Register, start message sent by OLT;**
  - **Register_Request, answer message from ONU not registered yet;**
  - **Register_Ack, message by OLT that allows ONU registration.**

GPON Standardization

ITU-T	Outline	Adoption
G.984.1	G-PON service requirements (General characteristics)	Mar. 2003
G.984.2	G-PON Physical Layer spec. (Physical Media Dependent (PMD) layer specification)	Mar. 2003
G.984.3	G-PON TC layer spec. (Transmission convergence layer specification)	Feb. 2004

G.984.1 Service Requirements

Item	Target	
Bit rates	1.25Gbit/s symmetric or higher (2.4 Gbit/s). Asymmetric with 155/622Mb/s upstream	
Physical reach	Max. 20 km or max. 10 km	
Logical reach	Max. 60 km	
Branches	Max. 64 in physical layer	
Wavelength allocation	Downstream: 1480 – 1500nm Upstream: 1260 – 1360nm	Downstream video wavelength (1550 – 1560nm) may be overlaid

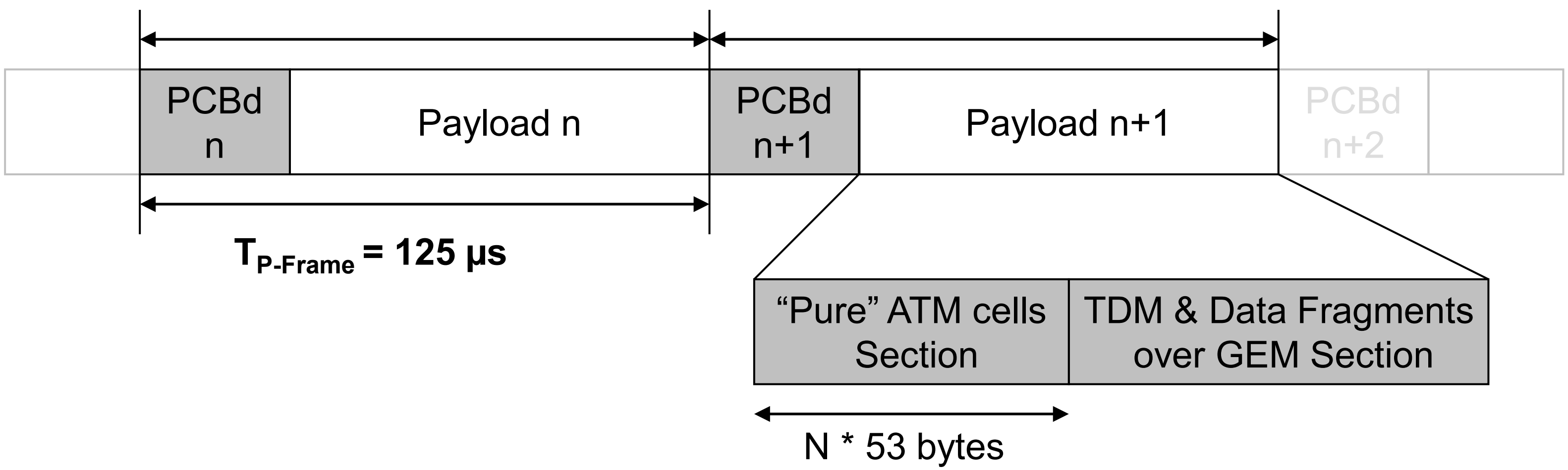
GPON Encapsulation Mode (GEM)

- GEM provides a *Generic Frame* where to carry both TDM and packet traffic over fixed data-rate channels
  - Similar Generic Framing Procedure (GFP) used in SDH/SONET

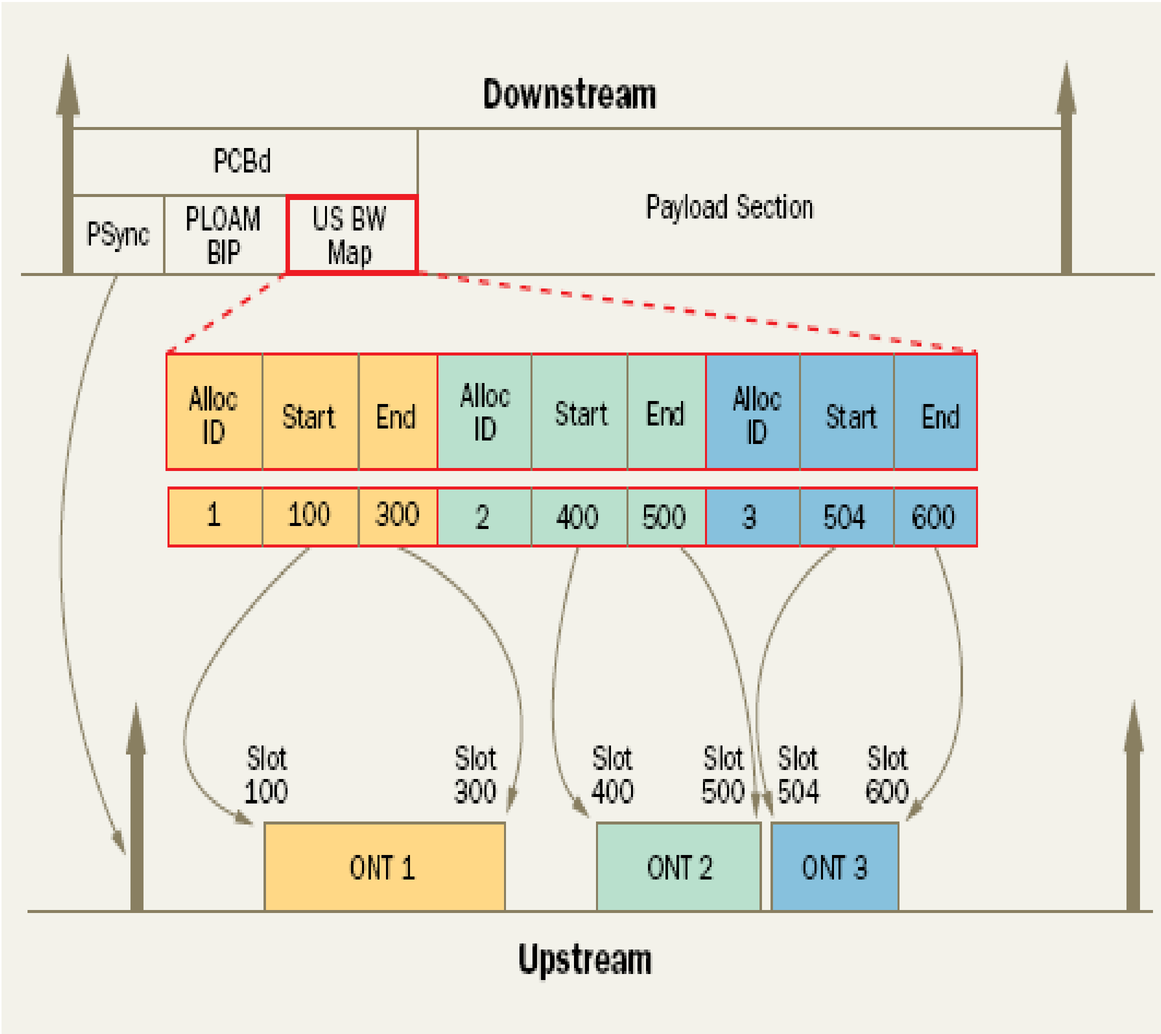
- A *Generic Frame* consists of:
  - a core header
  - a payload header
  - an optional extension header
  - a payload
  - an optional frame check sequence (FCS).

Downstream Frame Structure 1/3

- It consists of
  - a Physical Control Block Downstream (PCBD)
  - the ATM partition (N×53 bytes)
  - the GEM partition



GPON Header

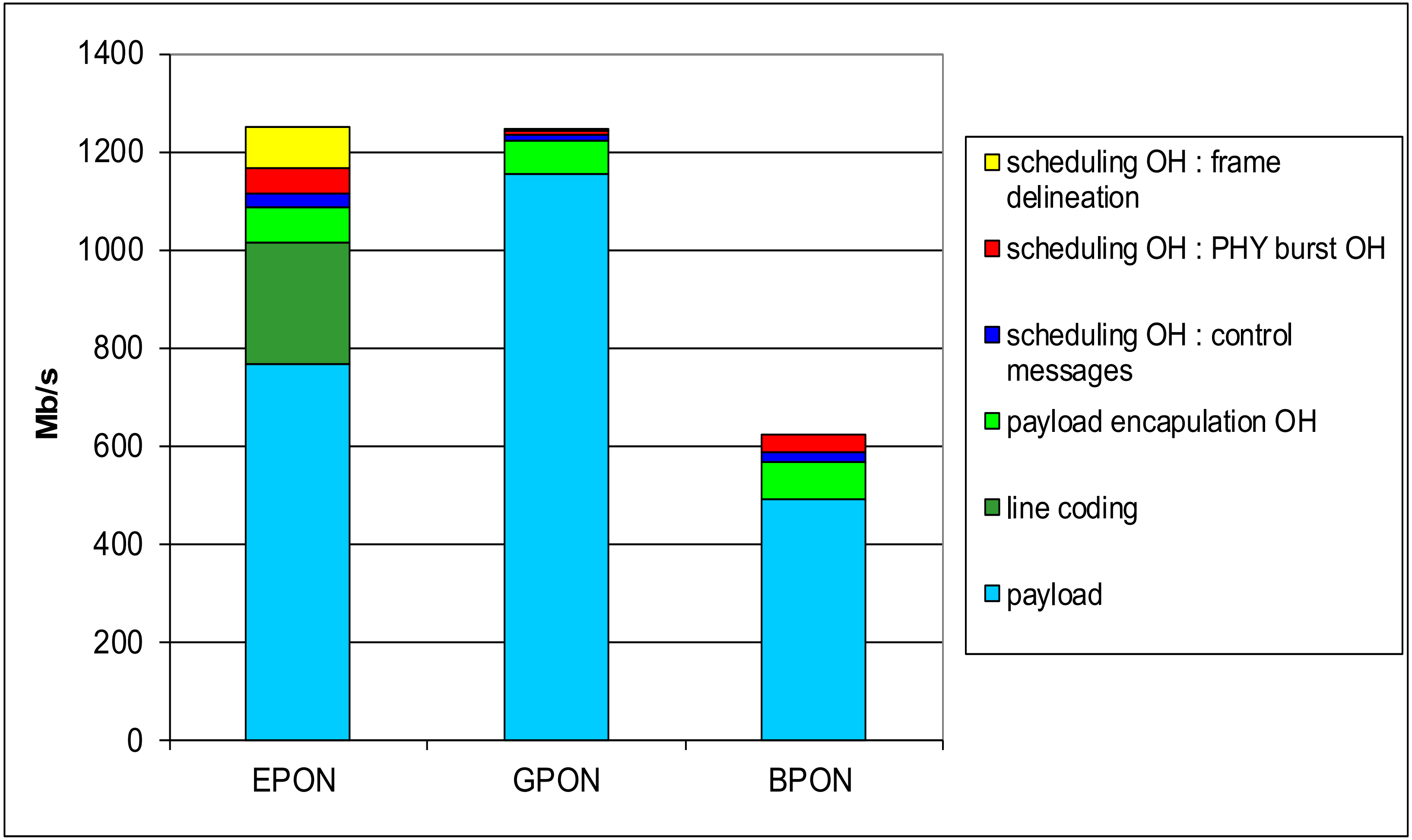


Downstream
PCBd
PSync
PLOAM BIP
US BW Map
Payload Section
Alloc ID
Start
End
Alloc ID
Start
End
Alloc ID
Start
End
1
100
300
2
400
500
3
504
600
Slot 100
Slot 300
Slot 400
Slot 500
Slot 504
Slot 600
ONT 1
ONT 2
ONT 3
Upstream

Technical Standards Comparison

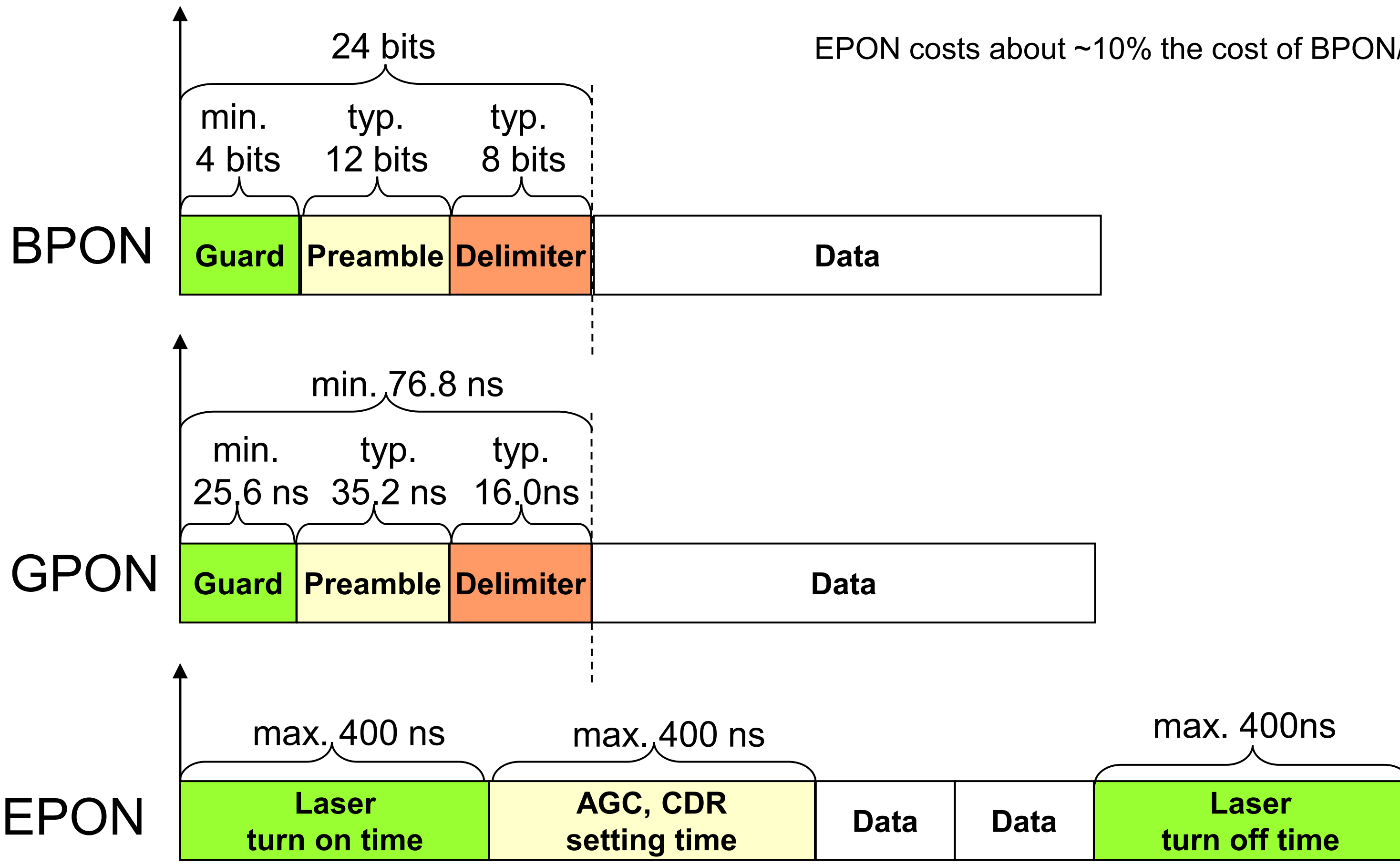
Technology	Standard	Downstream/ Upstream Bandwidth	# ONT served	Lambda	Framing/ Protocol	Distance
APON/BPON (ATM PON/ Broadband PON)	ITU-T G.983.x	155, 622 or 1244 Mbit/s down 155 or 622 Mbit/s up	Limited by power budget and ONU addressing limits: 16 to 32 splitter	1490 nm Down 1310 nm Up (1550 nm Down for RF video)	ATM	20 km
GPON (Gigabit PON)	ITU-T G.984	1.2 or 2.4 Gbit/s down 155, 622, 1.2 or 2.4 Gbit/s up	Up to 64(physical) Up to 128 (logical)	1490 nm Down 1310 nm Up (1550 nm Down for RF video)	GEM: G-PON Encapsulation Method (supports Ethernet), ATM	10/20 km (up to 60 km)
EPON (Ethernet PON)*	IEEE 802.3ah	Symmetric 1.25 Gbit/s	Up to 16	1550 nm Down 1310 nm Up	Ethernet	10/20 km
10GEPON (10 Gigabit Ethernet PON)	IEEE 802.3av (Working Task Force)	10 Gbit/s down 1 Gbit/s up (symmetric 10 Gbit/s in the future?)	32 (maybe more?)	1480-1500 nm Down ? 1260-1360 nm Up ? 1550-1560 Video overlay ?	Ethernet	20 km

Transmission Efficiency



Header's Comparison

EPON costs about ~10% the cost of BPON/GPON

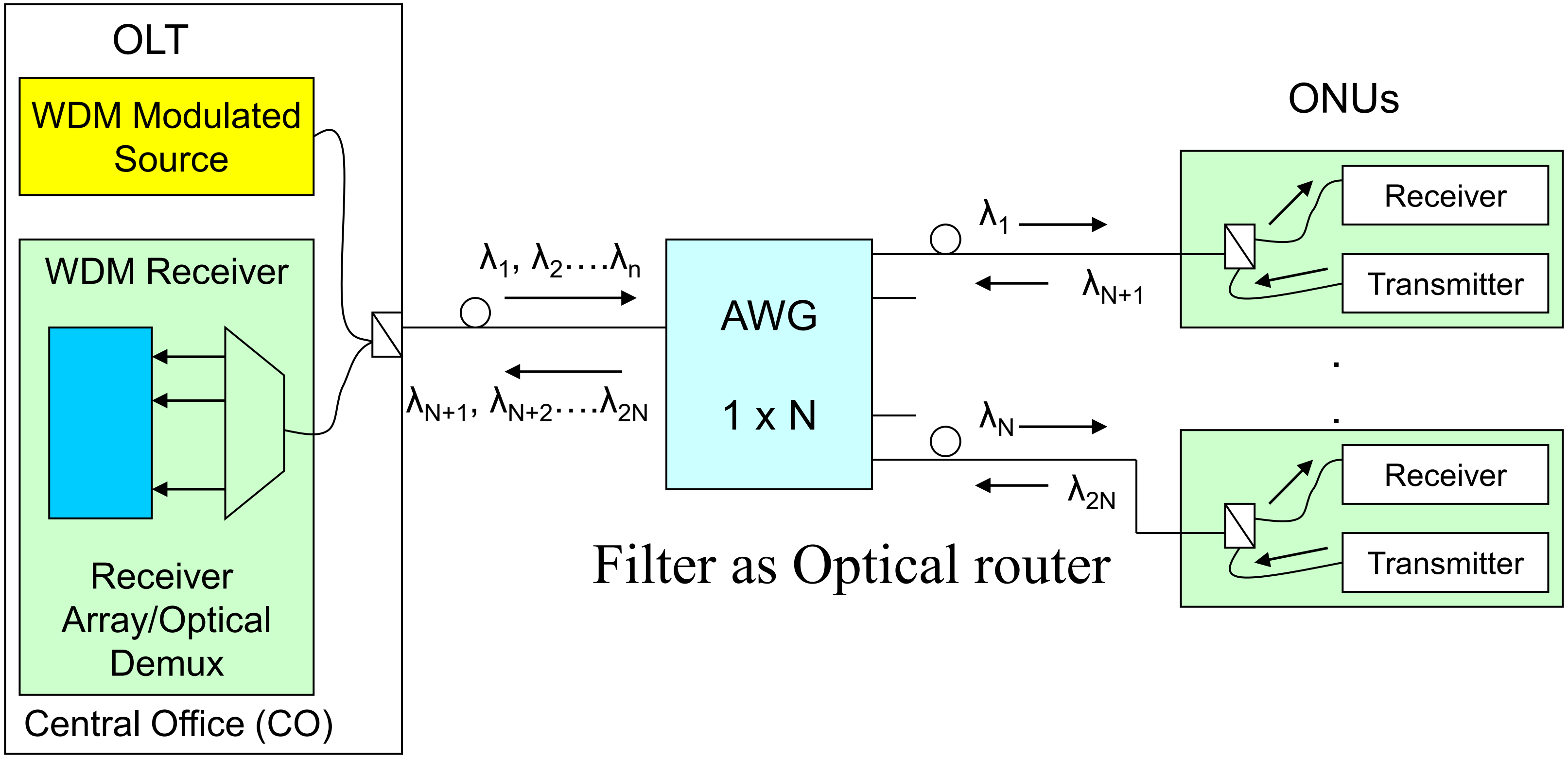


AGC: Automatic Gain Control; CDR: Clock and Data Recovery

Laser turn on time overlaps the laser turn off time of the previous burst

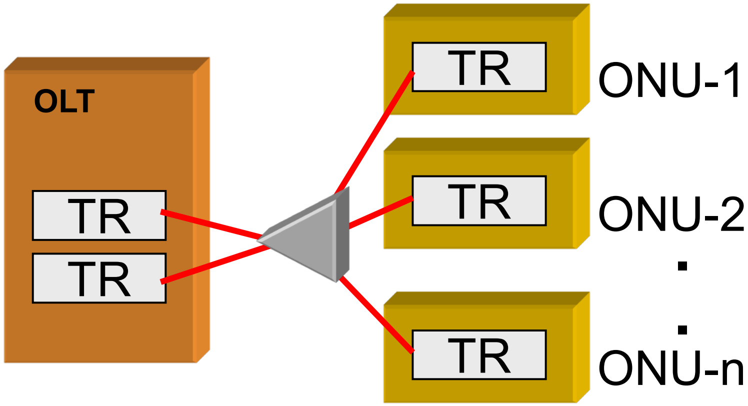
Simple WDM-PON

- Number of ONUs limited by wavelengths
- Point-to-point topology
- Long-reach (almost point-to-point reach)



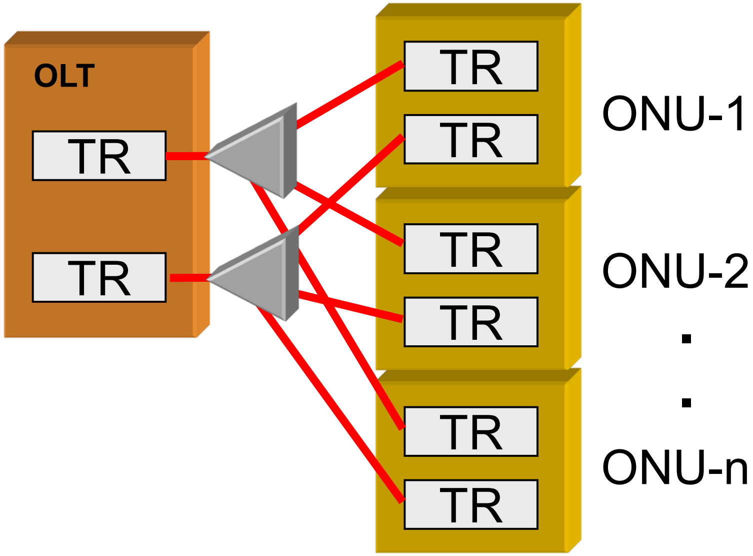
Filter as Optical router

Protection Mechanisms



B type
1+1 protection of OLT

- Cost-effective
- Redundant feeder
- Redundant OLT transceivers

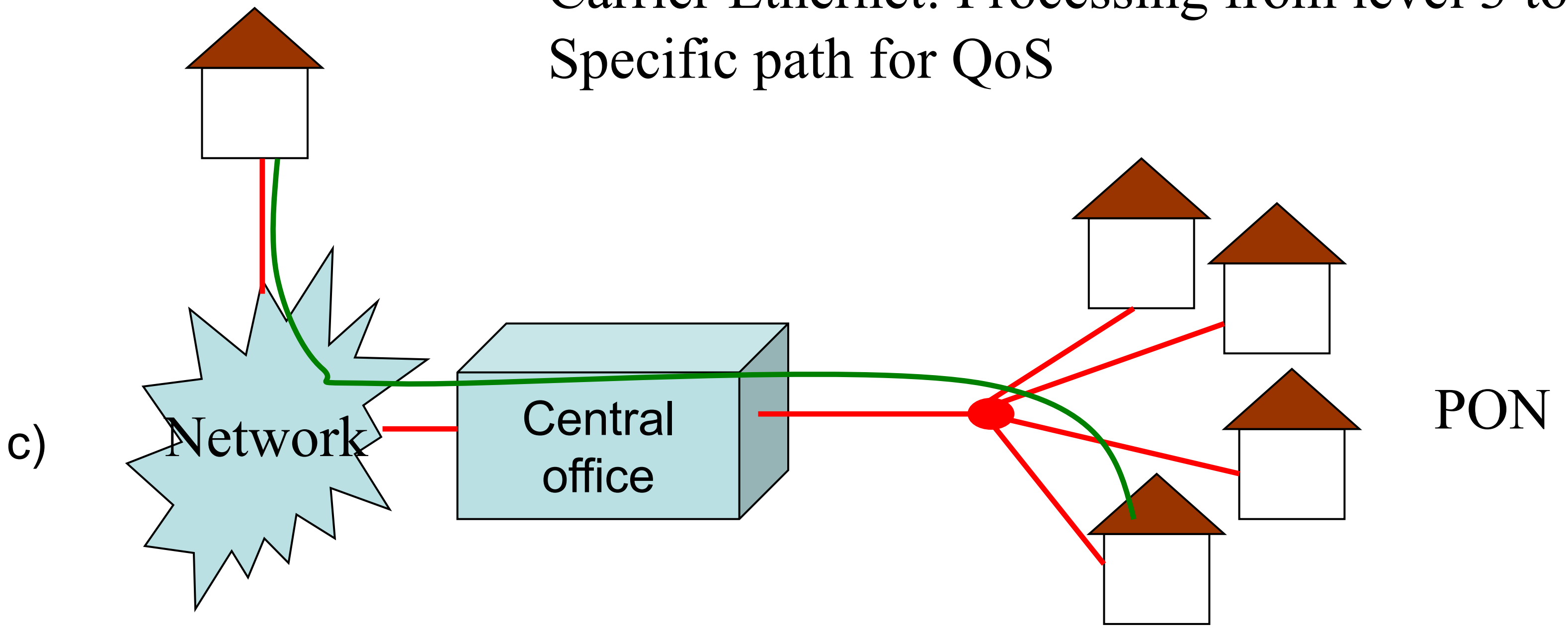


C type
1+1 protection of PON

- Most secure and expensive
- Redundant feeder and drops
- Redundant transceivers

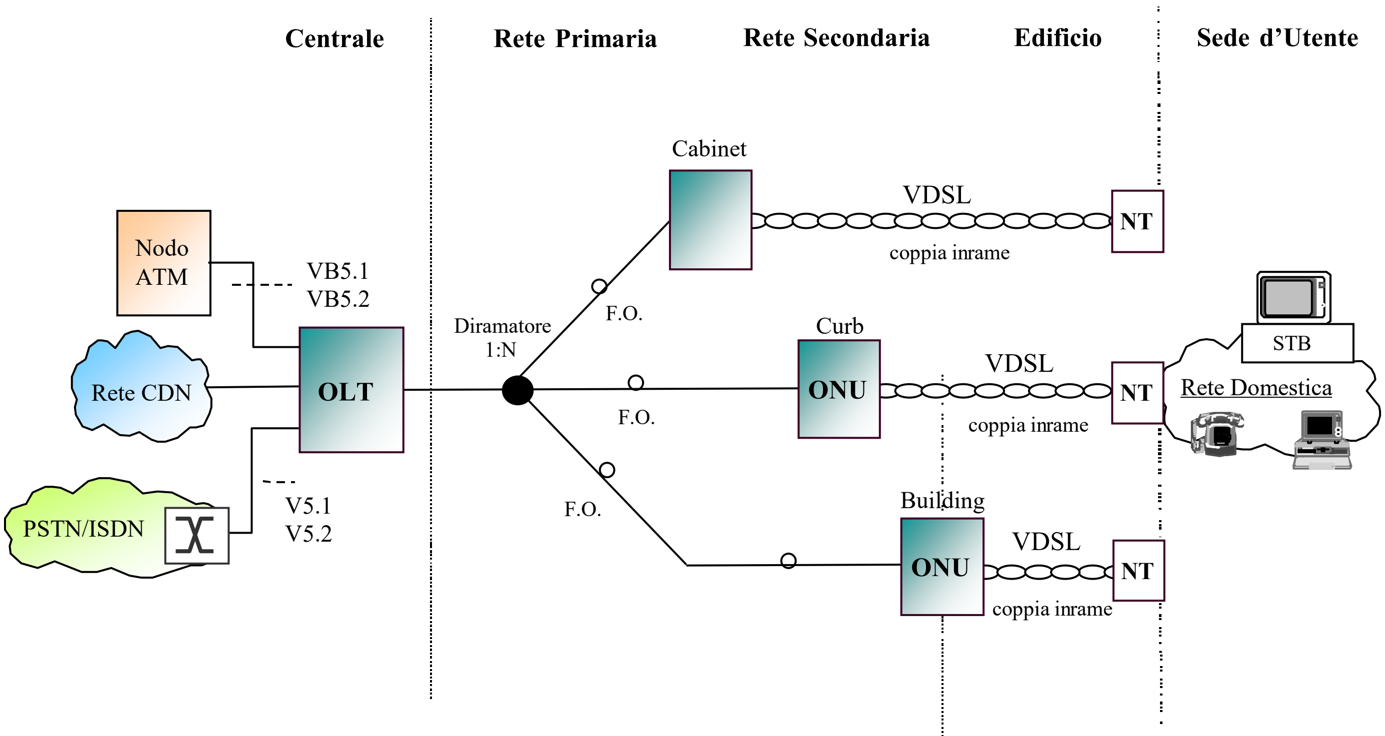
Carrier Ethernet for PON (EPON)

Carrier Ethernet: Processing from level 3 to 2
Specific path for QoS



VLANTAG, VPLS, Q-in-Q, MAC in MAC, PBT

Elements of a PON



OLT: Optical Line

VDSL: Very high bitrate Subscriber Loop

STB: Set Top Box

ONU: Optical Network Unit

NT : Network Termination

International development overview

- China
  - GPON and EPON are being tested in China : future PON growth mainly depends on Chinese market evolution
  - Beijing, Wuhan, Shanghai e Guangzhou are the cities with the greatest FTTX deployment
- Japan
  - The number of xDSL users has decreased for the first time at the end of 2006, while FTTH users have grown by 10% in 2006 last trimester.
  - At the end of 2006, out of 26 million Broadband lines, FTTH accounted for 30% of the total amount.
- South Korea
  - In July 2007, 500.000 FTTH users
  - Almost 4 million FTTB “apartment LANs”

International development overview

- USA
  - Large average cable-length
  - Large investments form cable operators, that account for a relevant share of the broadband market
  - No unbundling required for new fiber infrastructures.
- Brazil, Colombia, Argentina, Chile
  - Less than 300.000 FTTH users
- Australia, New Zeeland, Kuwait, Russia, United Arab Emirates, Pakistan
  - Less than 2 million FTTH users

Ref: EXFO, may 2007

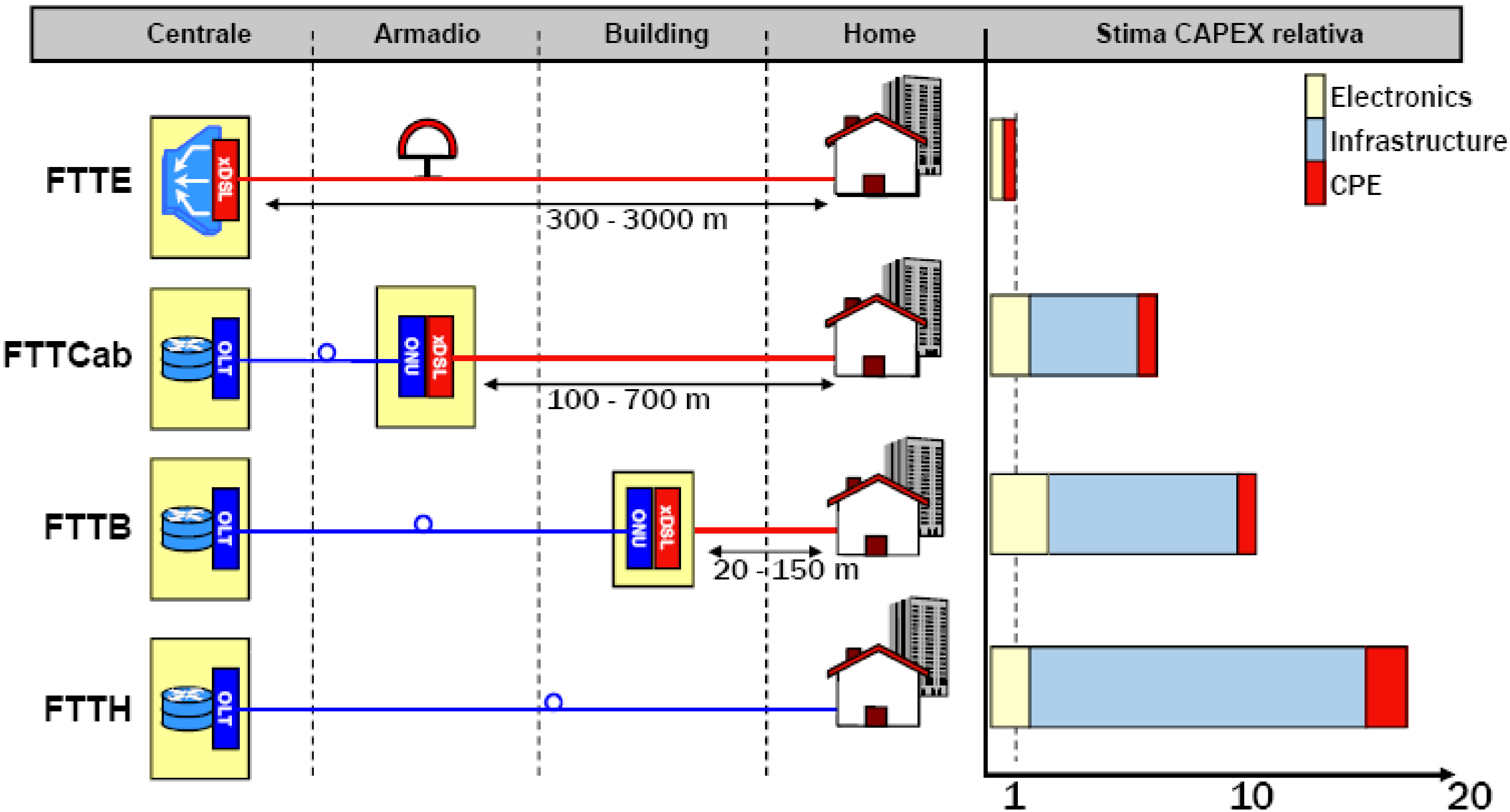
International development overview

- Mostly in Northern Europe, local administrations are building the infrastructure, with equal access conditions for service providers

- The leading incumbents are deploying extended FTTCab/VDSL infrastructure plans.

- Sweden: more than 500.000 FTTH users
- France, UK: more than 600.000 FTTH users
- Italy : more than 250.000 FTTH users
- Denmark: more than 400.000 FTTH users
- Holland : more than 500.000 FTTH users

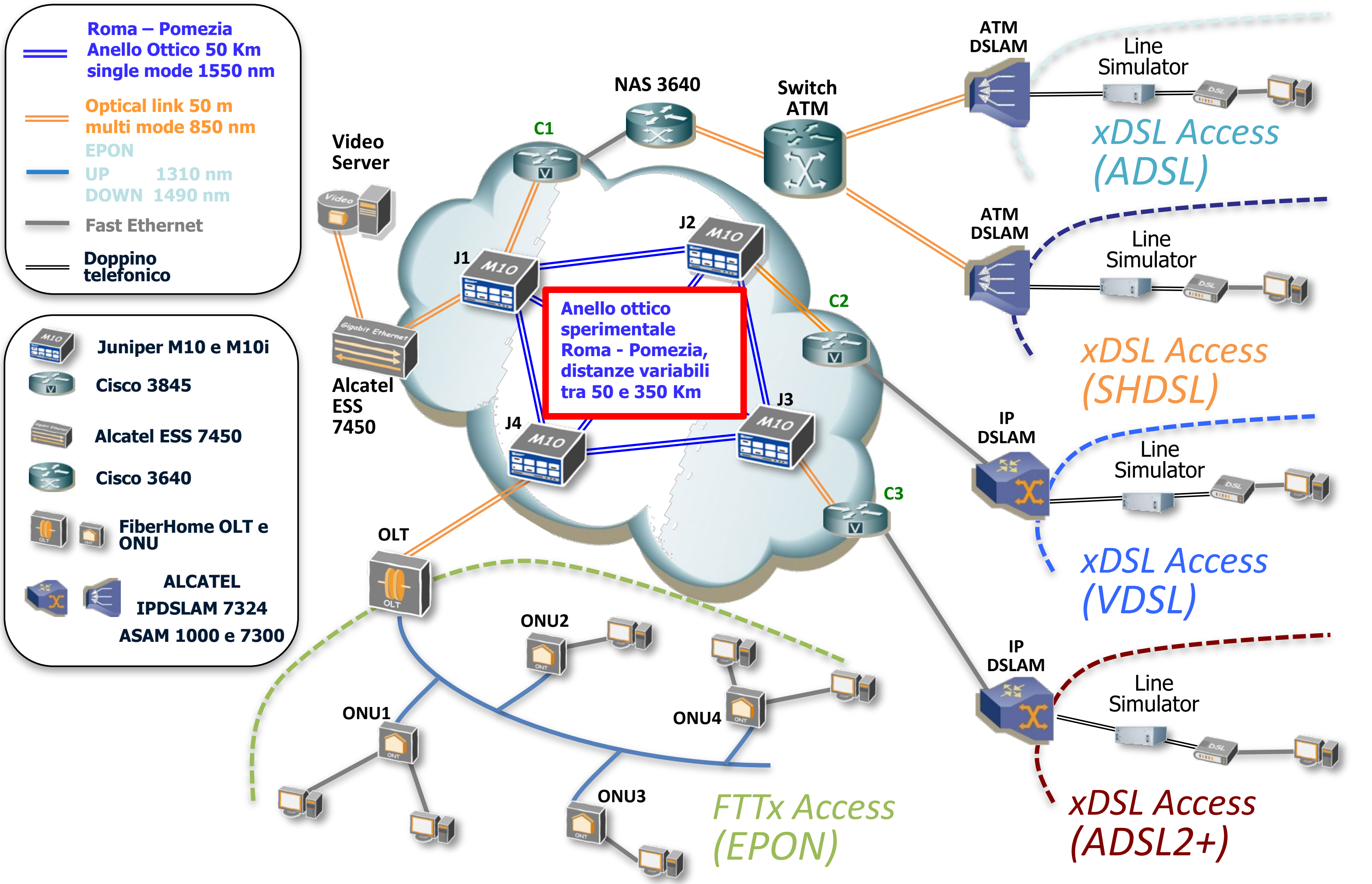
FTTx costs


Centrale
Armadio
Building
Home
Stima CAPEX relativa
FTTE
xDSL
300 - 3000 m
FTTCab
OLT
ONU
xDSL
100 - 700 m
FTTB
OLT
ONU
xDSL
20 - 150 m
FTTH
OLT
Electronics
Infrastructure
CPE
1
10
20

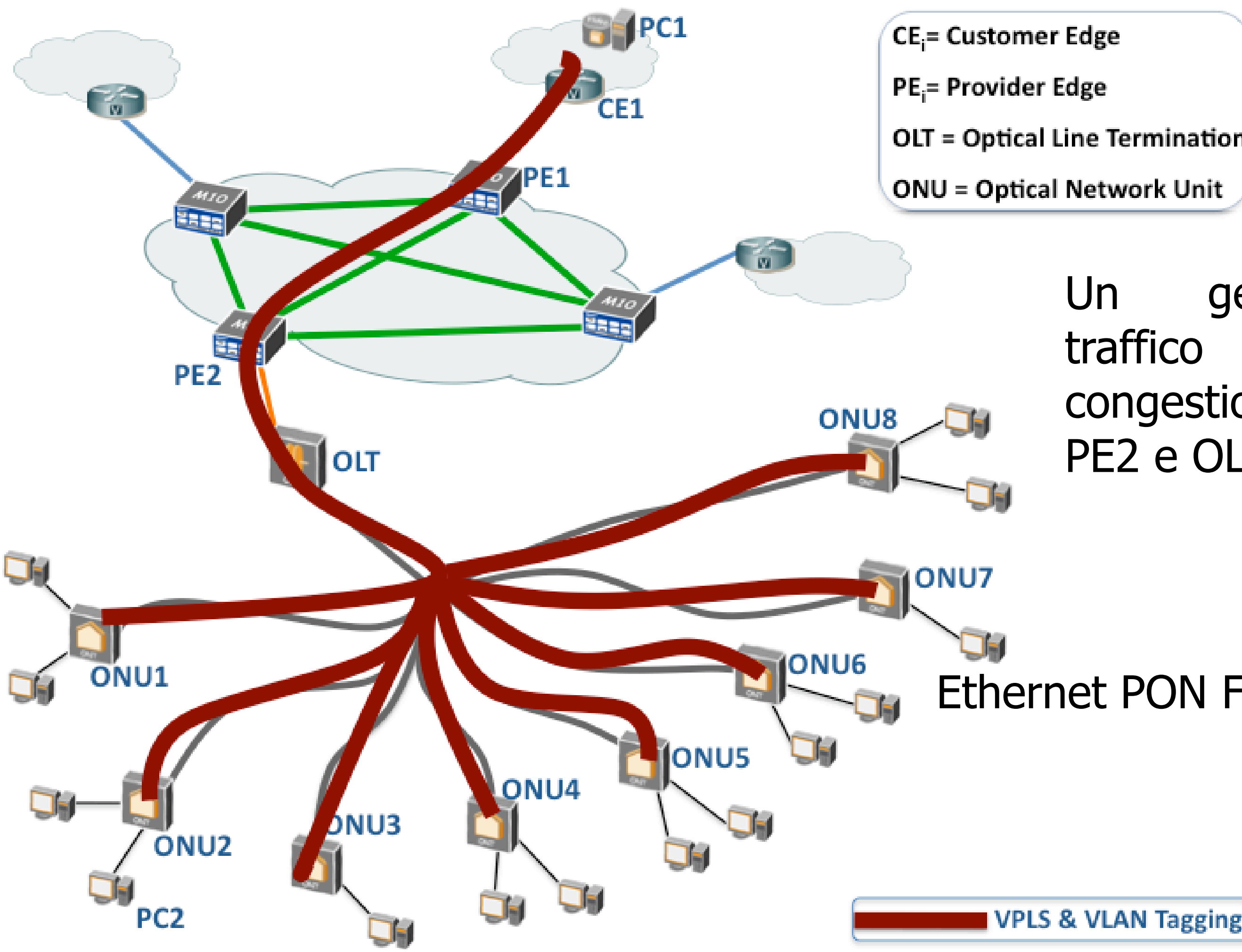
FUB study on NGN economics

- 1400 Mega Euro for digital Divide end (connection of central office to babckbone)
- FTTC/B/H for all? No 2 Mb/s for all but 20 Mb/s for almost all and >50 Mb/s for many
- 10 million of users based on FTTB: total cost 15000 Mega Euro!
- Unbundling problems:
  - For OLO no PON, yes Point-to-point
  - We say yes PON since:
    - » with logical unbundling now and WDM later!
    - » Too cost to include devices in central office and fibres in current ducts
    - » With PON we can shift OLO location from central office to

FUB Experiments on EPON



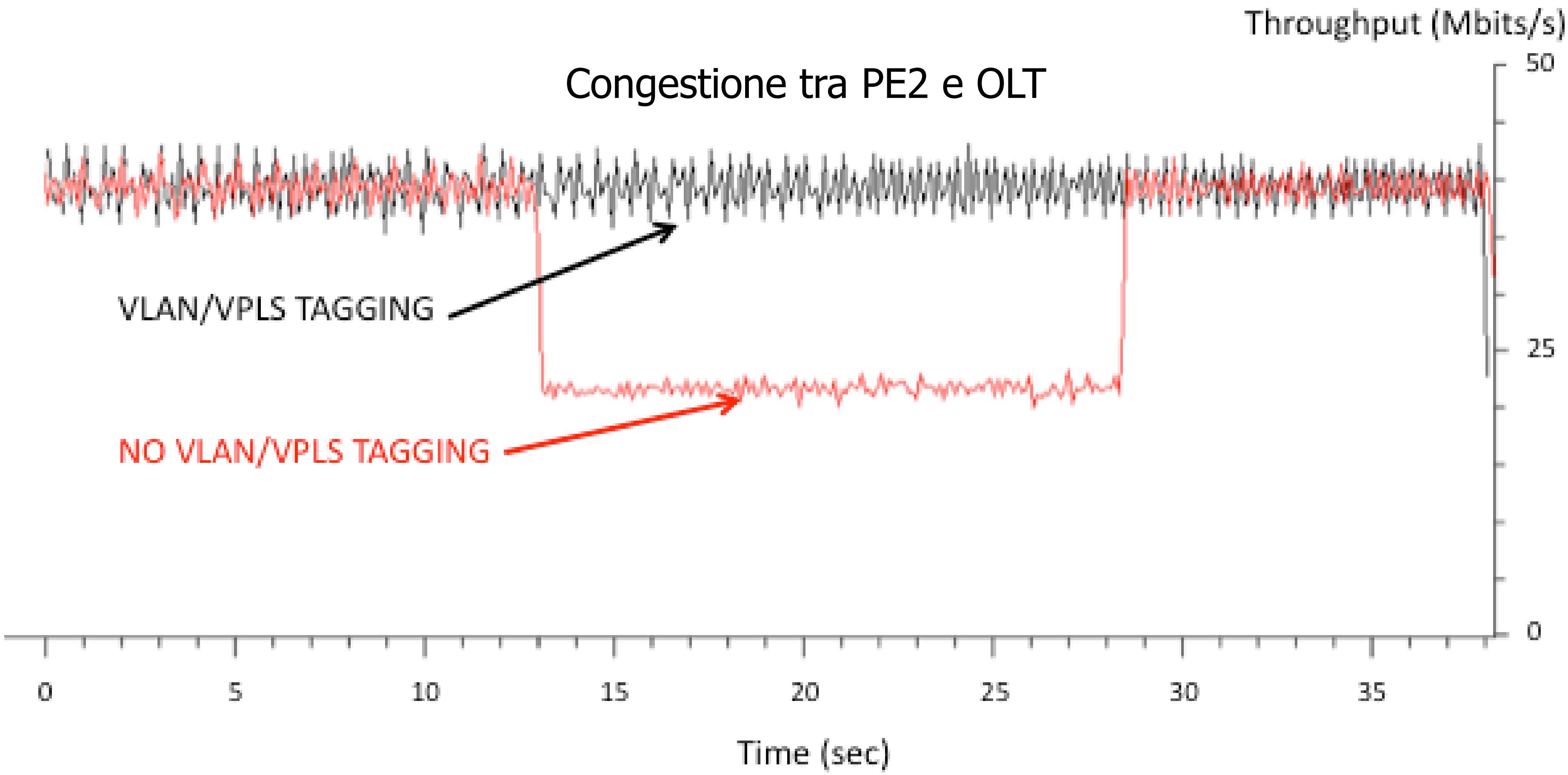
Logical network by means of VPLS&VLAN Tagging



Un generatore di traffico permette un congestionamento tra PE2 e OLT

Ethernet PON FiberHome

Throughput in downstream



Conclusions

- FTTx necessary for NGN
- PON is the best current solution
- Problems for investments and network properties