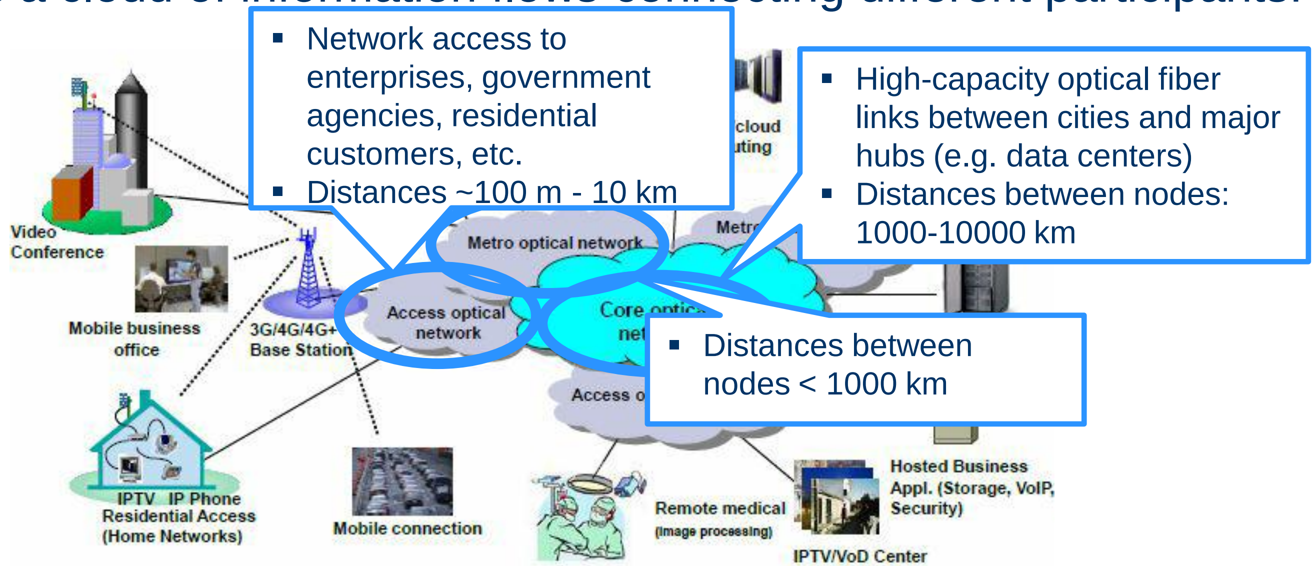
Optical Network Architectures

Overview of Optical Networks

The network as a cloud of information flows connecting different participants:



The Role of Optical Networks

Optical network segments are categorized with respect to the size of the area they cover:

- Long-haul **core networks**, also known as **Wide Area Networks (WAN)** or **interchange carrier (IXC) public networks**.
- Edge/regional/metro networks, also known as **Metropolitan Area Network (MAN**) or **local exchange carrier (LEC)**.
- **Access networks** providing peripheral links (“last-mile access”) to the end-users.

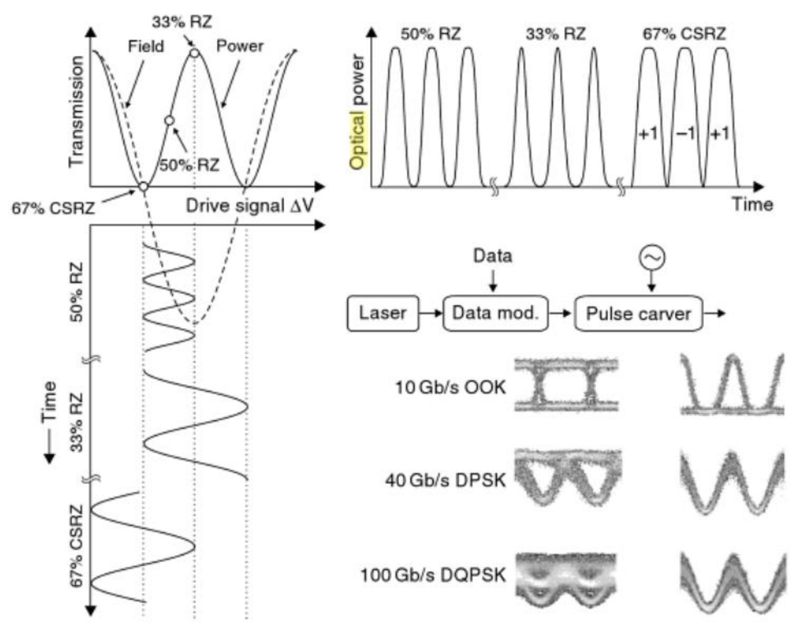
Modulation Formats: Direct Detection

Intensity Modulation – Direct Detection (IM/DD)

- First optical networks relied only on simple **On-Off Keying (OOK) binary** formats with data rates of **1**, **2.5**, **4** and **10 Gbit/s**. Both Non-Return-to-Zero (NRZ) and Return-to-Zero (RZ) pulse shaping employed.

Phase Modulation – Direct Detection (PM/DD)

- The next step was purely phase-modulated **Differential Phase Shift Keying (DPSK)** and **Differential Quadrature Phase Shift Keying (DQPSK)**, directly detected using Delay-line Interferometers (DIs).
- DPSK has the same bandwidth efficiency as NRZ/RZ-PAM, but is more resistant to fiber transmission non-linearities.
- DQPSK has (in addition) higher bandwidth efficiency (2 bits/symbol), and the rate could be increased without increasing the bandwidth.
- DPSK and DQPSK transponders capable of **10** and **40 Gbit/s** were commercialized, and still used today.

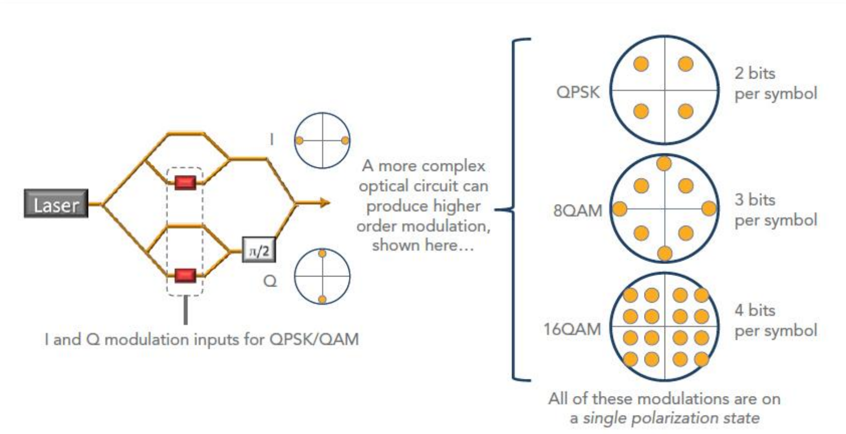


Modulation Formats: The Coherent Revolution

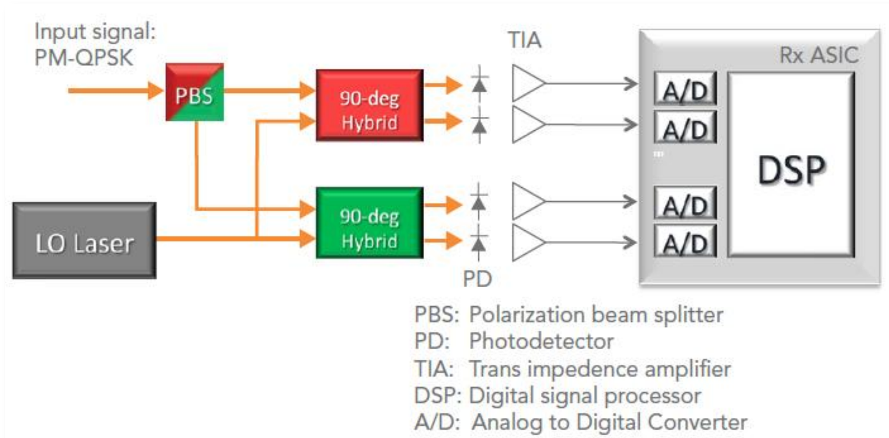
Advanced Formats Using Coherent Optical Detection

- Coherent reception uses a 90 degree hybrid and local oscillator laser to analyze the received optical signal into its In-Phase and Quadrature components: **We can detect both Amplitude and Phase modulation at the same time.**
- An **IQ modulator** is used to create advanced **Quadrature Amplitude Modulation (QAM)** formats with higher bandwidth efficiency.
- **Digital Signal Processing (DSP)** is used to mitigate transmission impairments and detect the symbols.
- While the concept is old (1990s), the processing power did not exist at the time, and coherent optical systems were not possible: The advent of very high speed digital CMOS electronics in recent years is what made the coherent revolution possible.
- The current commercial standard: **100 Gbit/s** Dual-Polarization QPSK (DP-QPSK)

QAM Transmitter



QAM Receiver

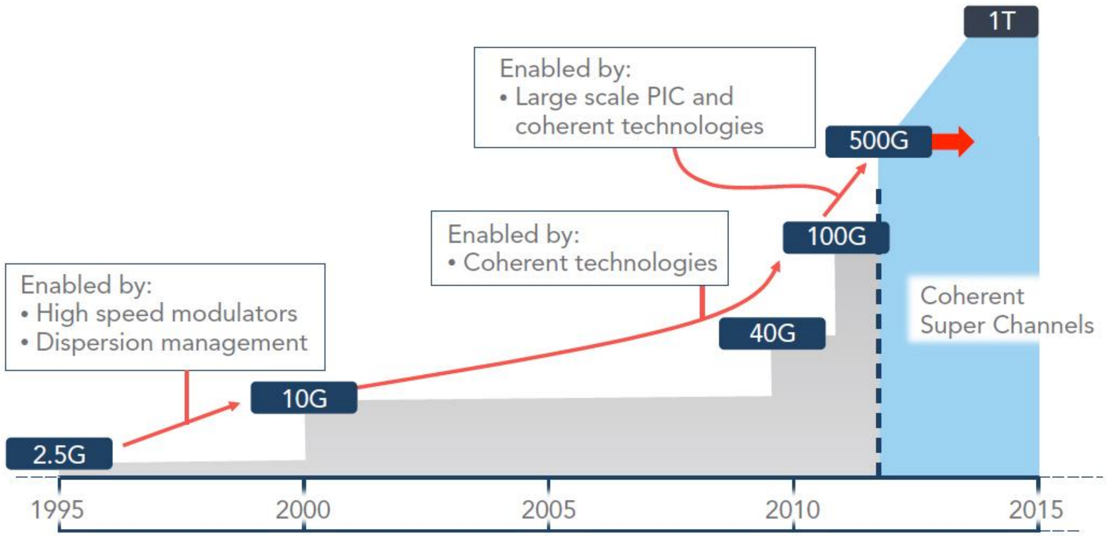


Modulation Formats: Historical Perspective and Current Deployment

- Telecom operators have deployed **100G** (DP-QPSK) channels since ~2010.
- The next step for commercial standardization is **400G** optical channels, most probably employing DP-16-QAM (twice the bandwidth efficiency compared to 100G).

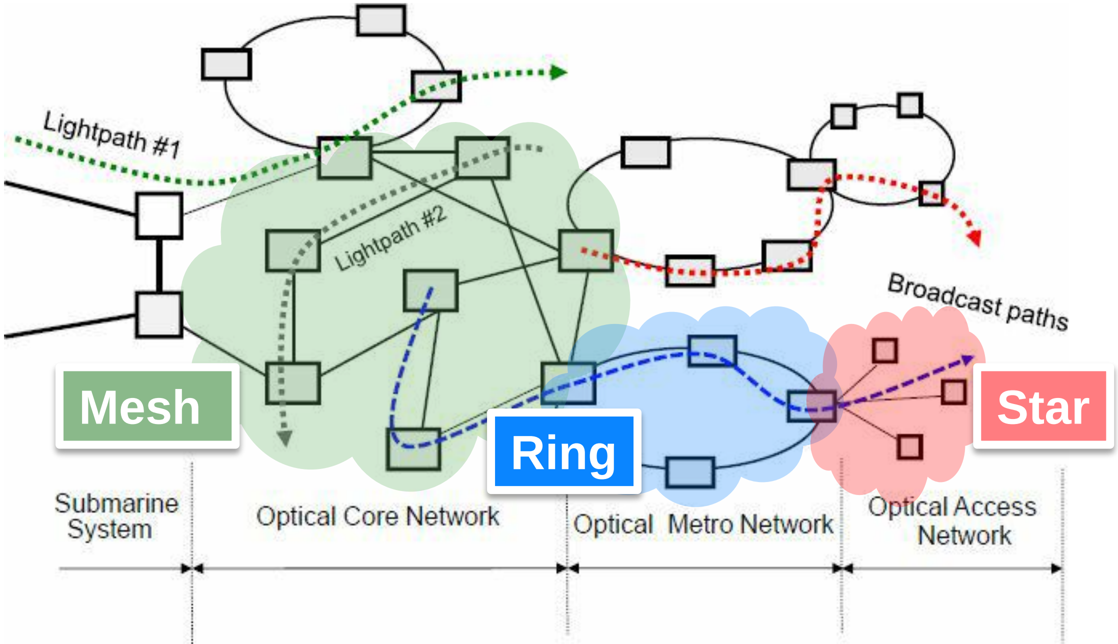
Typical deployment scenarios for each segment in current optical networks:

- OOK (1, 2.5, 4, 10 Gbit/s) in Access and Metro.
- DPSK (10, 40 Gbit/s) and DQPSK (10, 40 Gbit/s) mostly in Metro, legacy equipment still present in Core networks.
- Coherent DP-QPSK (100 Gbit/s) mostly in the Core, with some system vendors providing lower-performance and lower-cost options targeted for Metro networks
- Future optical networks are expected to be all-coherent in the Metro and Core, using higher-order QAM (16-, 32-, 64-QAM).



Network Topologies

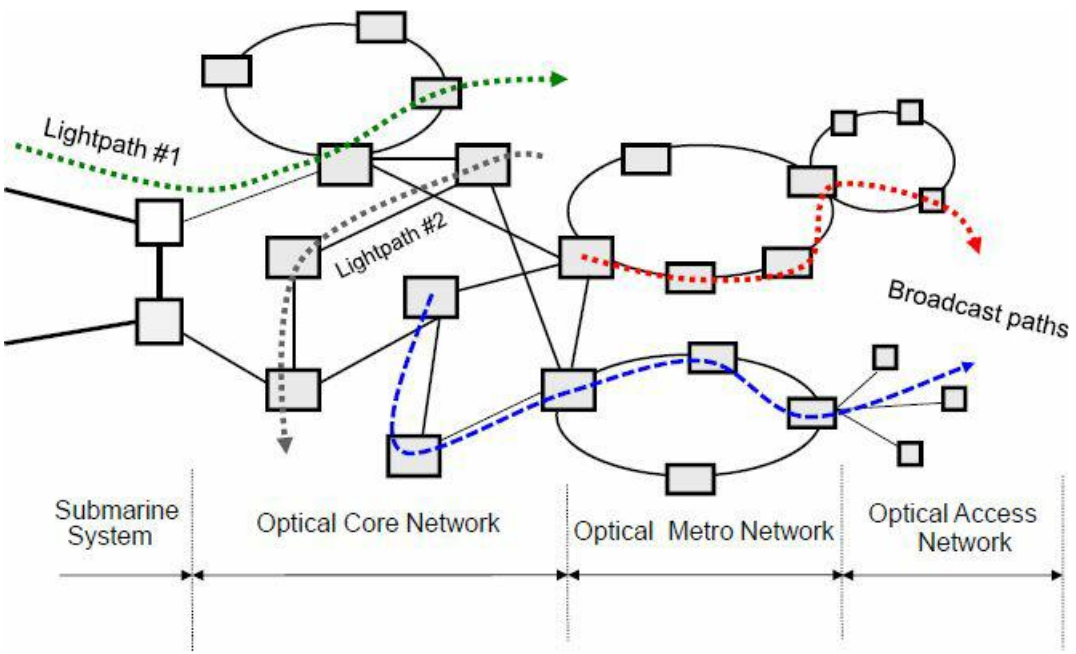
- The **physical network topology** that best supports traffic demand generally varies with the segments (Core, Metro, Access) of the optical networking structure.
- End-to-end optical signal connections (point-to-point or broadcast) are called **lightpaths** (or **optical channels**).
- A given connection is associated with **Quality of Service (QoS)** requirements (physical or network), which is then related to each individual lightpath.



Network Topologies

Lightpaths differ in lengths and information capacity that is carried along. Typically:

- Core: 40-100 Gbit/s per optical wavelength, > 1000 km
- Metro: 1-40 Gbit/s per optical wavelength, < 1000 km
- Access: < 1 Gbit/s per optical wavelength, < 10 km

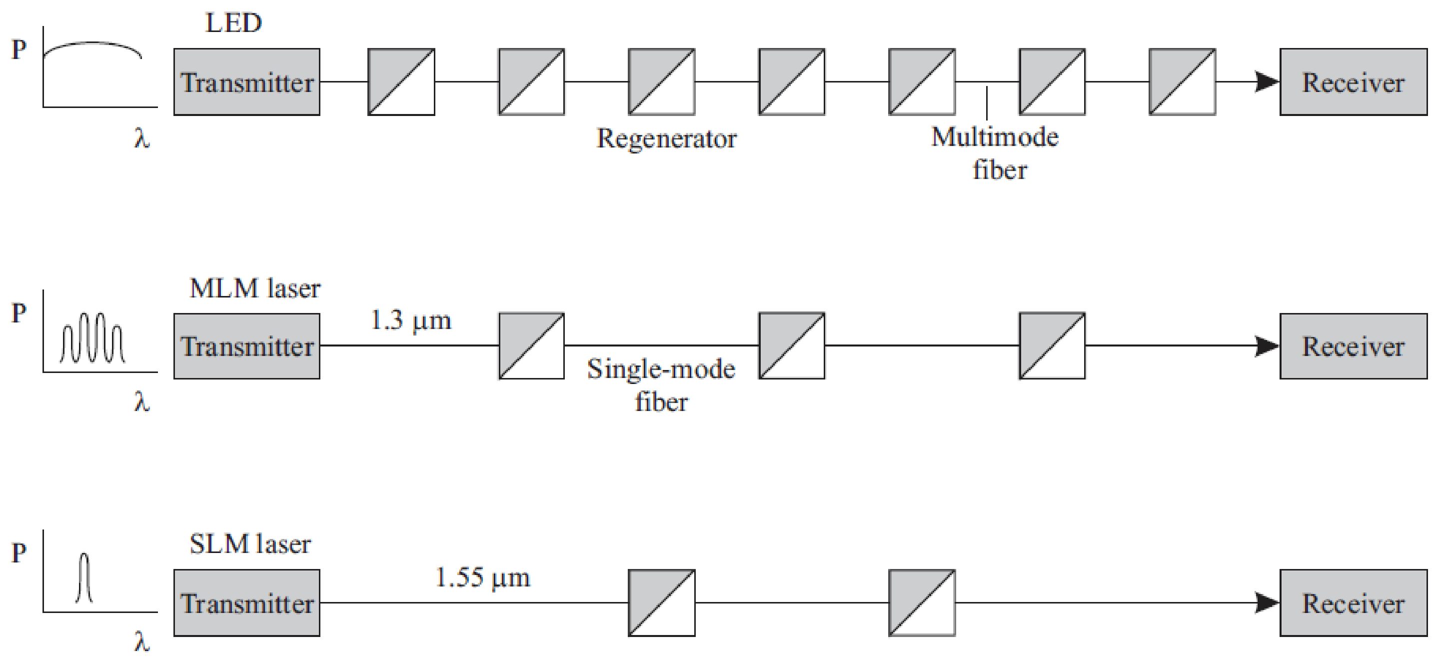


1^{st} Generation of Optical Networks

Optics for:

- Transmission (lower BER than copper links)
- Capacity

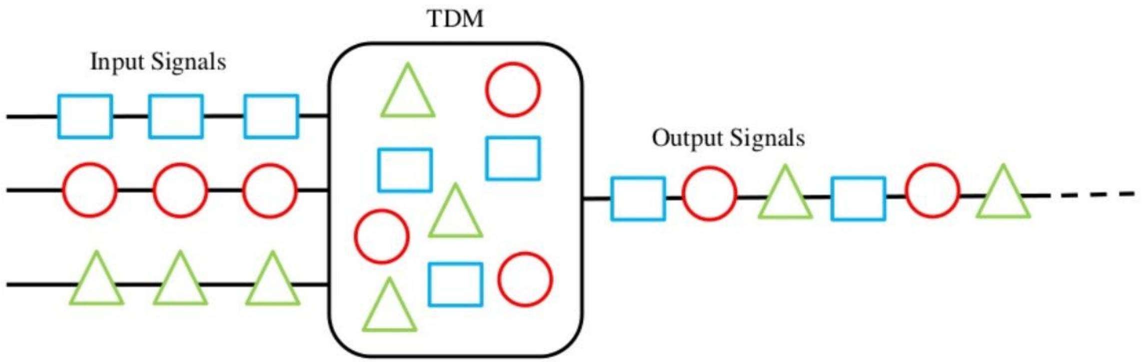
Switching and Network functions → Electronics



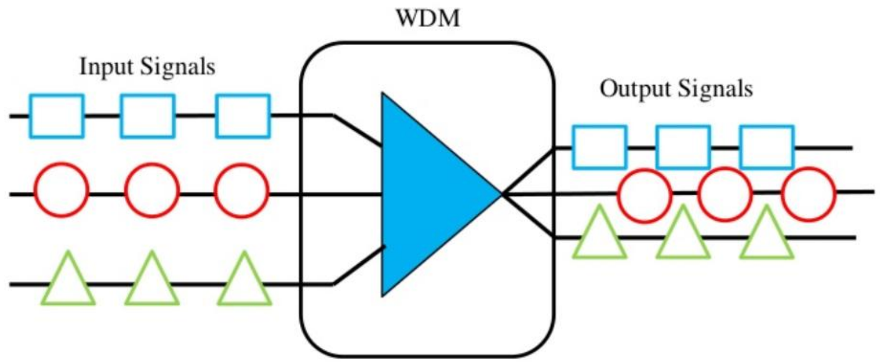
Towards to 2nd Generation: TDM and WDM

Complementary methods of increasing fiber capacity:

- **Time Division Multiplexing:** Increase the *serial* bitrate.
- **Wavelength Division Multiplexing:** Increase the number of *parallel* wavelengths.



- High-speed, high-bandwidth electronic equipment needed
- Expensive to build & maintain

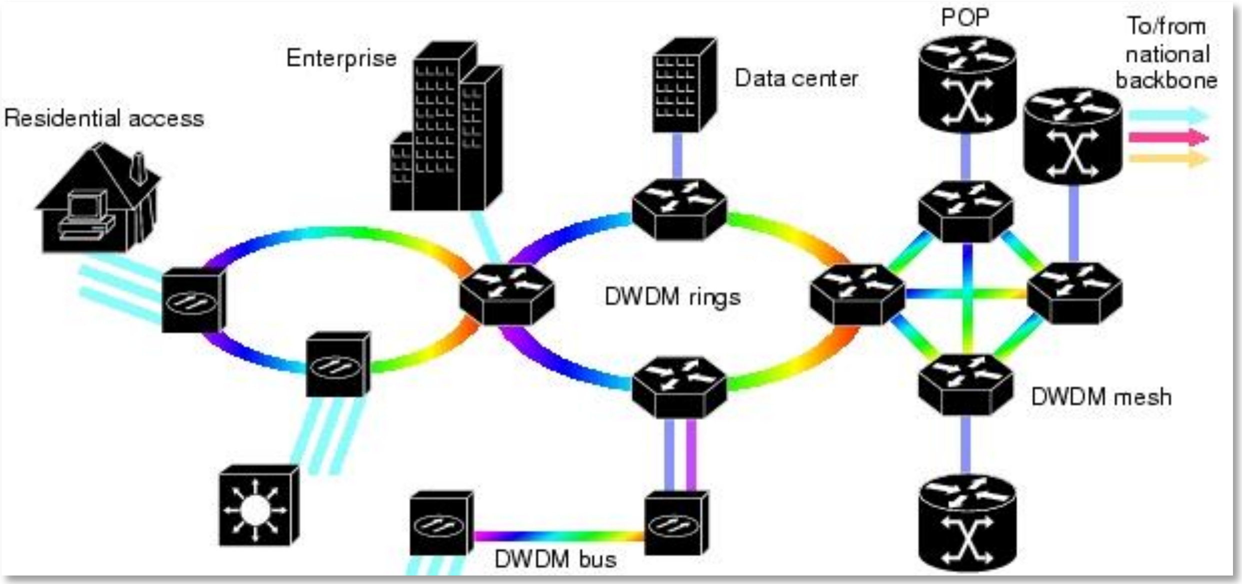


- Send data in parallel, on the **same optical fiber**
- Multiple wavelengths using lower-rate electronic/optical equipment to achieve higher throughputs overall

Wavelength Division Multiplexing

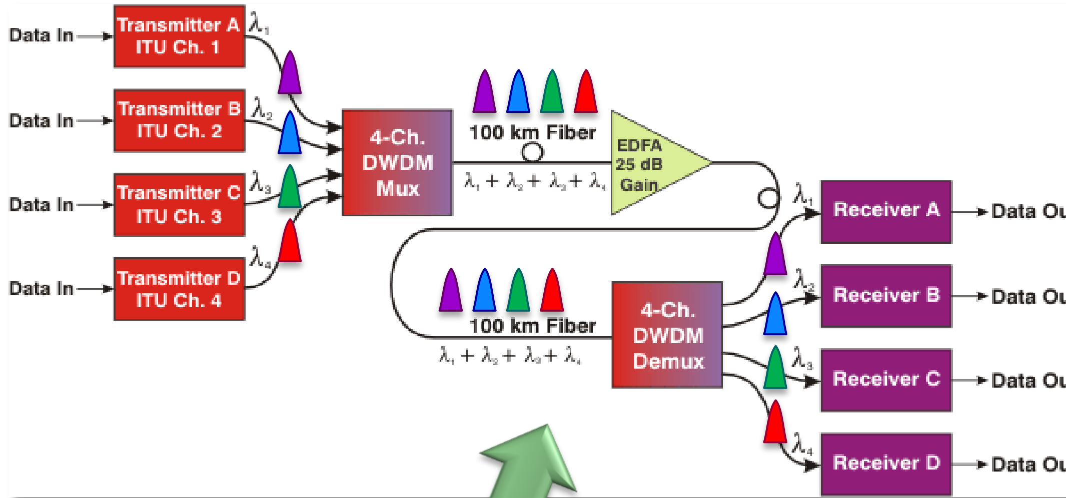
WDM technology signaled a real start to optical networking:

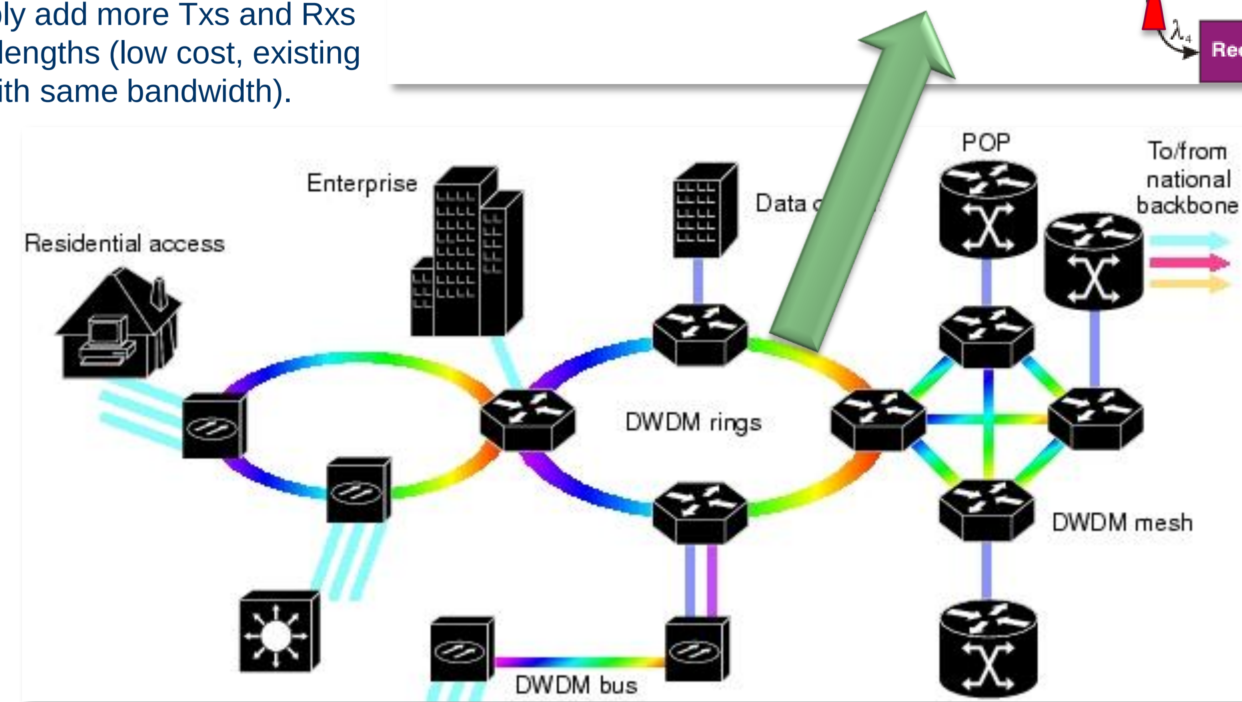
- Each wavelength within the WDM spectrum could follow a distinct lightpath – enabled **routing of optical signals along the network paths**.
- Amplification of the signals by using the stimulated emission principle.
  - ✓ No optoelectronic conversion (O-E-O) needed.
  - ✓ All-optical networks made possible.
- Possible to compensate chromatic dispersion by periodic deployment of special optical fibers, called dispersion compensating fibers (DCF).
- Amplifiers and DCFs could handle multiple wavelengths together.



Wavelength Division Multiplexing

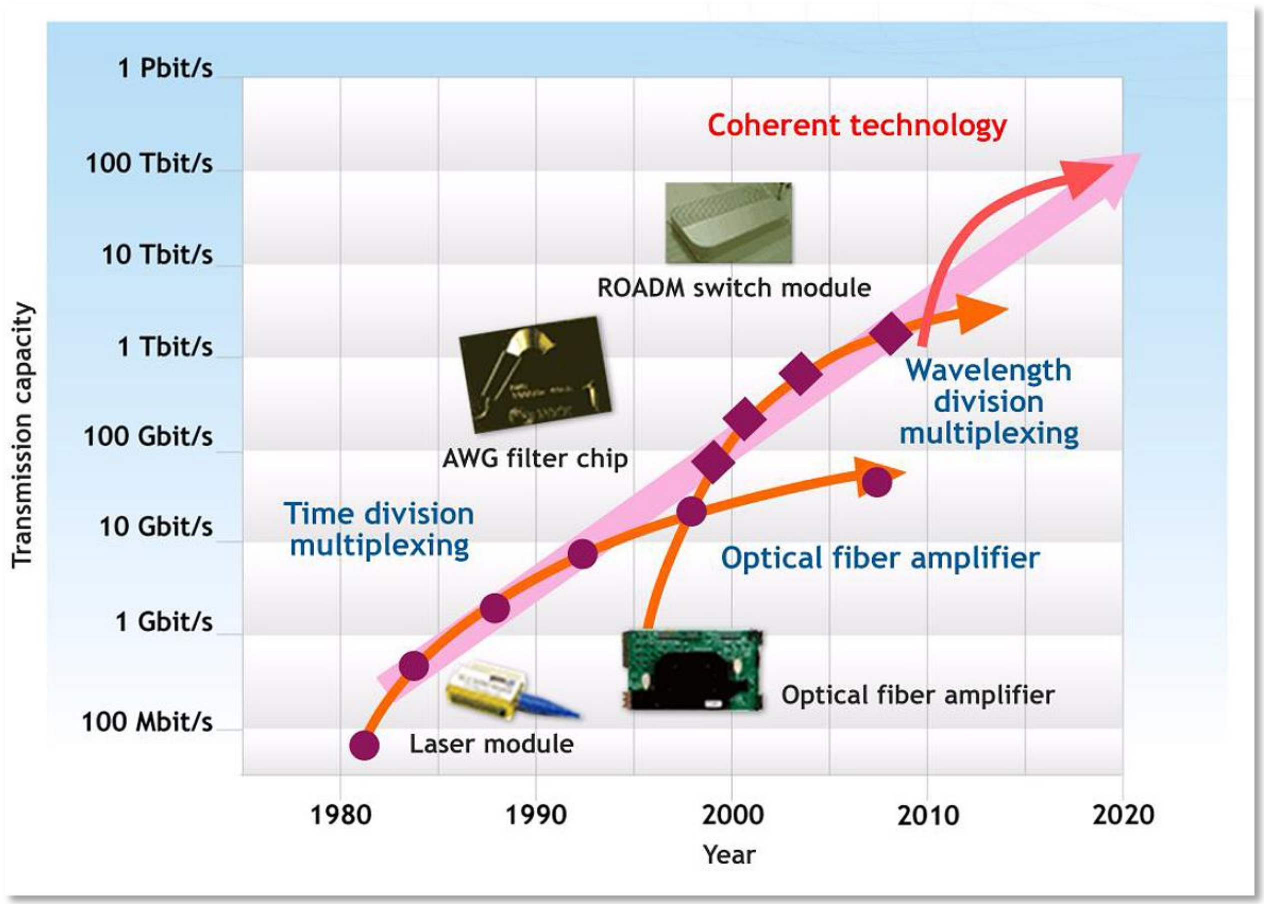
- Modern WDM optical networks rely on using **spans** between nodes.
- These consist of ~70-100 km lengths of fiber, with amplifiers (EDFAs) and DCFs.
- Total transmission reach in this way can be **several thousand kilometers** (with no O-E-O conversion needed).
- **Easy upgrades:** As more capacity is needed, simply add more Txs and Rxs on new wavelengths (low cost, existing technology with same bandwidth).





Wavelength Division Multiplexing

The result: WDM technology maturity and introduction of several complementary technologies enabled unprecedented growth in total transmission capacity, but also in transmission link length.



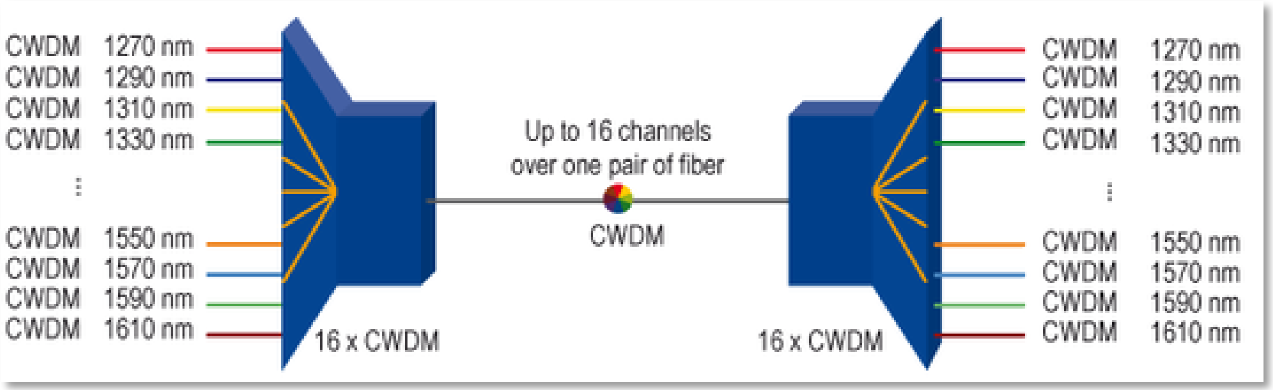
Coarse WDM

The International Telecommunications Union (ITU) G.694.2 recommendation on **Coarse Wavelength Division Multiplexing (CWDM)** for city and access networks:

- A **fixed grid of 16 channels** between 1270 nm and 1610 nm
- 20 nm spacing between channels (~2500 GHz)

\+ Large channel spacing allows the use of cheap components (e.g. low cost lasers).

− A lot of bandwidth is wasted (a typical optical channel is 1-100 GHz).



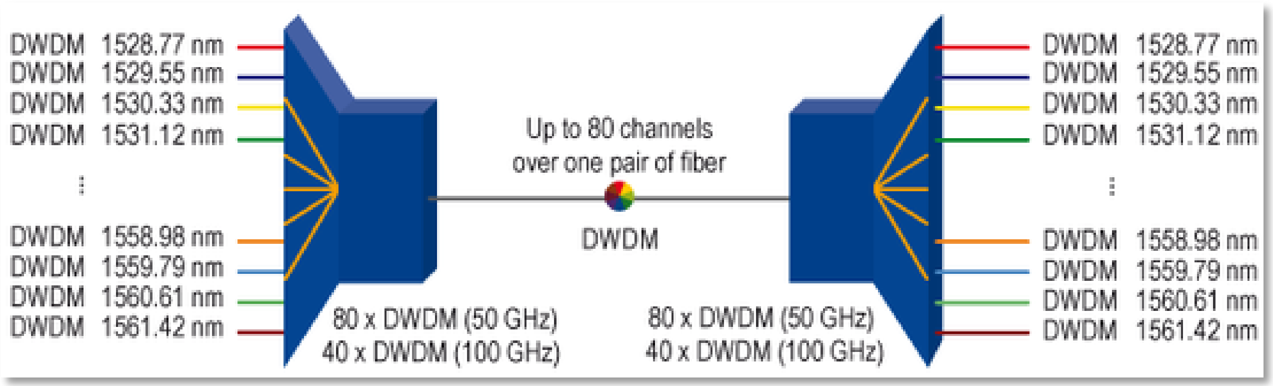
Dense WDM

ITU G.694.1 recommendation on **Dense Wavelength Division Multiplexing (DWDM)**:

- A **fixed grid of >80 DWDM wavelengths** over one pair of fiber
- DWDM channel spacing 0.8 nm (100 GHz grid) or 0.4 nm (50 GHz grid)
- Distances >1000 kms can be achieved with the use of optical amplifiers

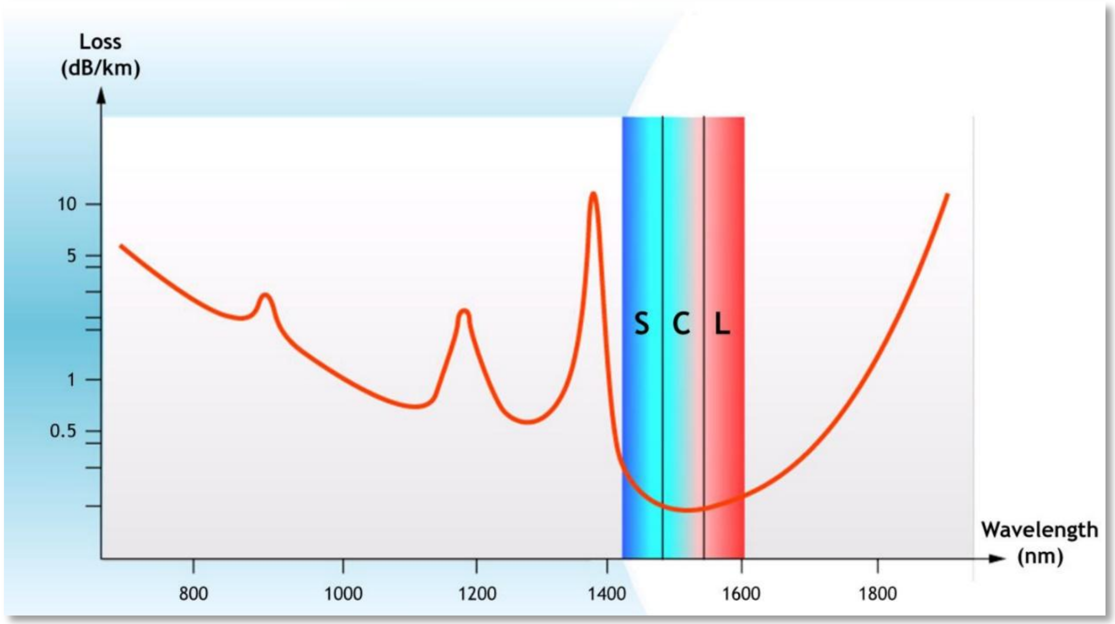
\+ Denser packing of channels than CWDM, higher spectral efficiency.

− Higher cost.



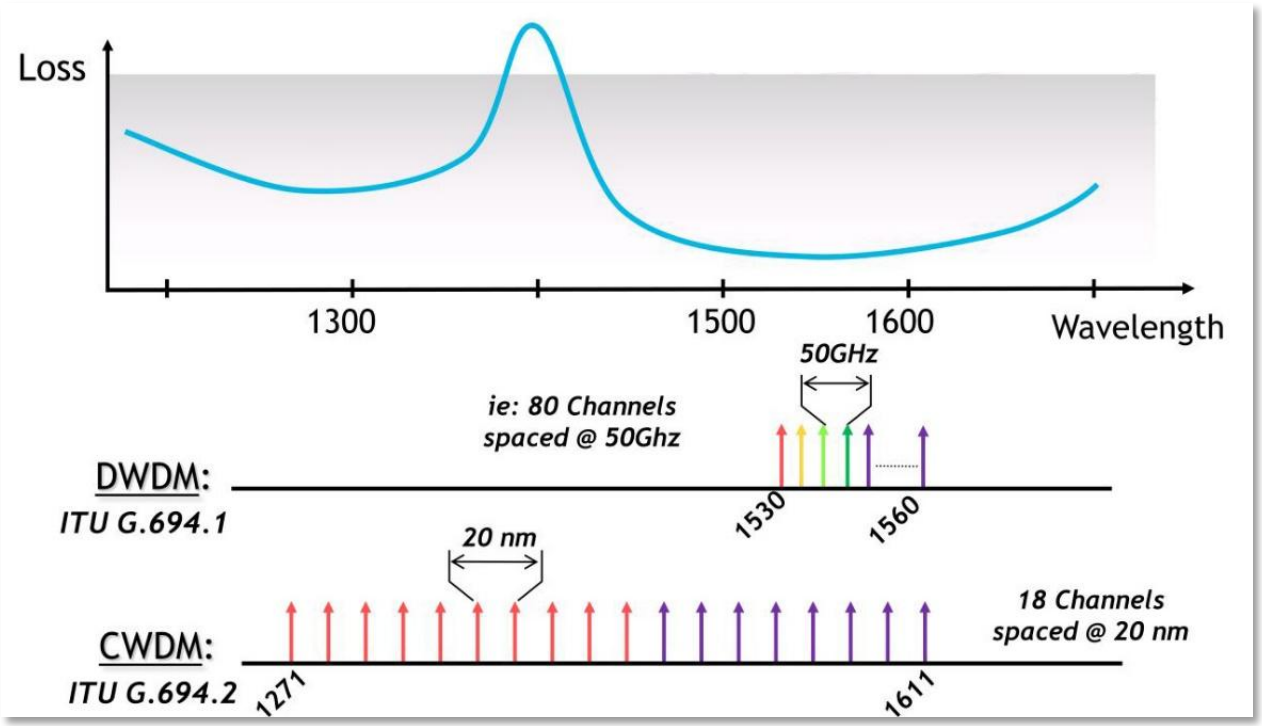
Wavelength Division Multiplexing

- Based on optical power loss of fibers, spectrum ranges have been characterized for compatibility purposes with light sources, receivers and optical components, including the optical fiber.
- According to the broad absorption minimum, the third window is best suited for DWDM technology.
- For DWDM transmission systems, three optical bands are defined:
  - The Short Band (**S-Band**): 1460 to 1530 nm
  - The Conventional Band (**C-Band**): 1530 to 1565 nm
  - The Long Band (**L-Band**): 1565 to 1625 nm



Wavelength Division Multiplexing

Fixed CWDM & DWDM ITU grids

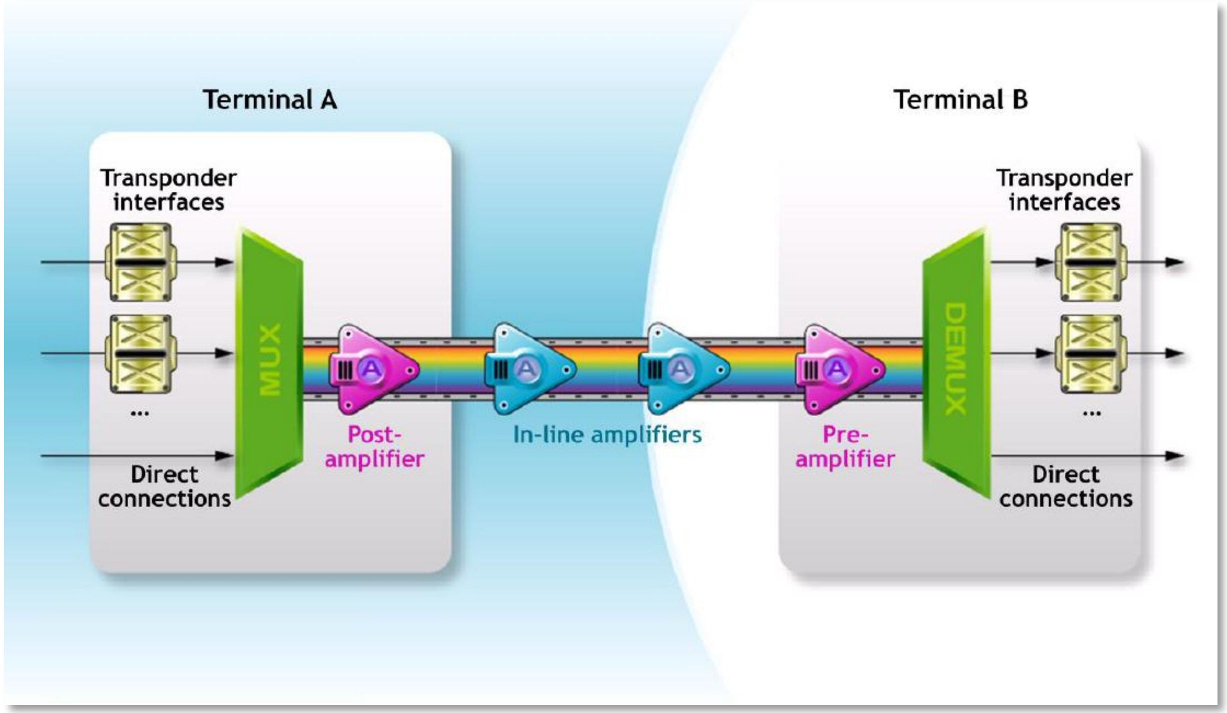


- CWDM is the cheaper alternative, traditionally used in **Metro optical network** applications (shorter distances, more links, more transceivers needed).
- DWDM is used for long-distance **Core optical networks** (in addition to **Metro**), where higher-performing, more expensive (but fewer) transceivers are needed.

DWDM Vs CWDM Summary

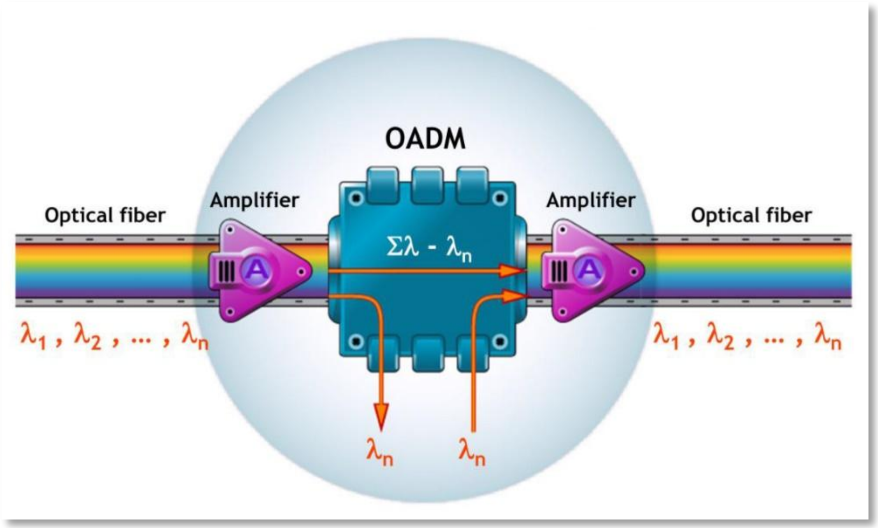
Coarse WDM	Dense WDM
Low-cost equipment	More versatile (more expensive)
Metro Networks	Metro and Core Networks
Point-to-point (P2P) topologies	P2P, ring, mesh
Up to 16 channels with 20 nm spacing	>80 channels with 50 GHz spacing
Up to ~80 km (20 dB attenuation)	Reach of several 1000 km
No optical amplification	Optical amplification with EDFAs possible
10G wavelengths sometimes not supported	100/400G channels supported

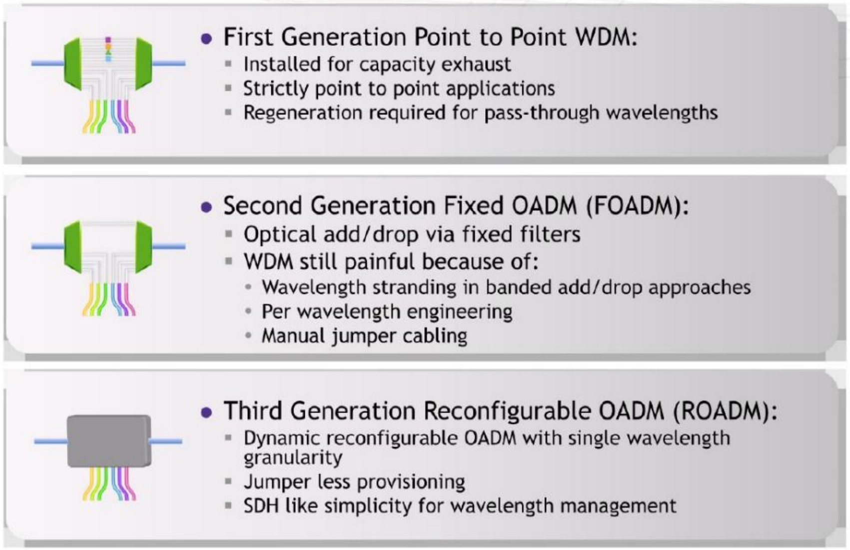
Basic Functional Blocks of a WDM Network (1/2)



- The **transponder** can receive an input optical signal and convert it into the electrical domain, and vice versa (uses optoelectronic modulators to convert electronic data into optical signals).
- The **WDM multiplexer/demultiplexer (MUX/DEMUX)** combines/separates discrete wavelengths at the transmitter/receiver sides.
- Amplifiers (EDFAs, Raman) are used for pre- (Rx-side), post- (Tx-side), and in-line (in each **fiber span**) amplification of the optical signals.

Basic Functional Blocks of a WDM Network (2/2)

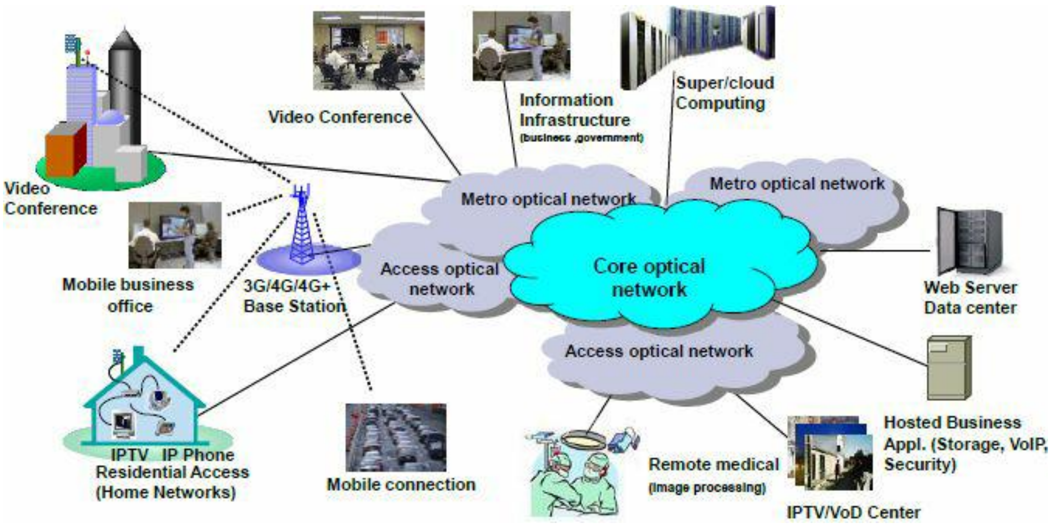




- **Reconfigurable Optical Add Drop Multiplexers (ROADMs)** are key components of all-optical networks.
- They perform optical routing by removing or inserting one or more wavelengths propagating along the fiber, **without** converting them into electrical signals.
- ROADMs are reconfigurable and dynamic multi-degree nodes, with single-wavelength granularity.

Access Optical Networks

- Access networks provide connectivity to the end-user customers (residential, commercial, government/public organizations, laboratories, wireless base stations, etc.).
- These include both wired (copper and optical), as well as wireless technologies:
  - ADSL, VDSL, GSM, UMTS, LTE, WiFi, WiMAX, etc.
- Vast majority of wired access networks in Europe and the US are over copper (e.g. ADSL), while several Asian countries (United Arab Emirates, South Korea, Hong Kong, Japan) have high penetration (up to 85% for the UAE) of optical access.



Fiber to the x (FTTx)

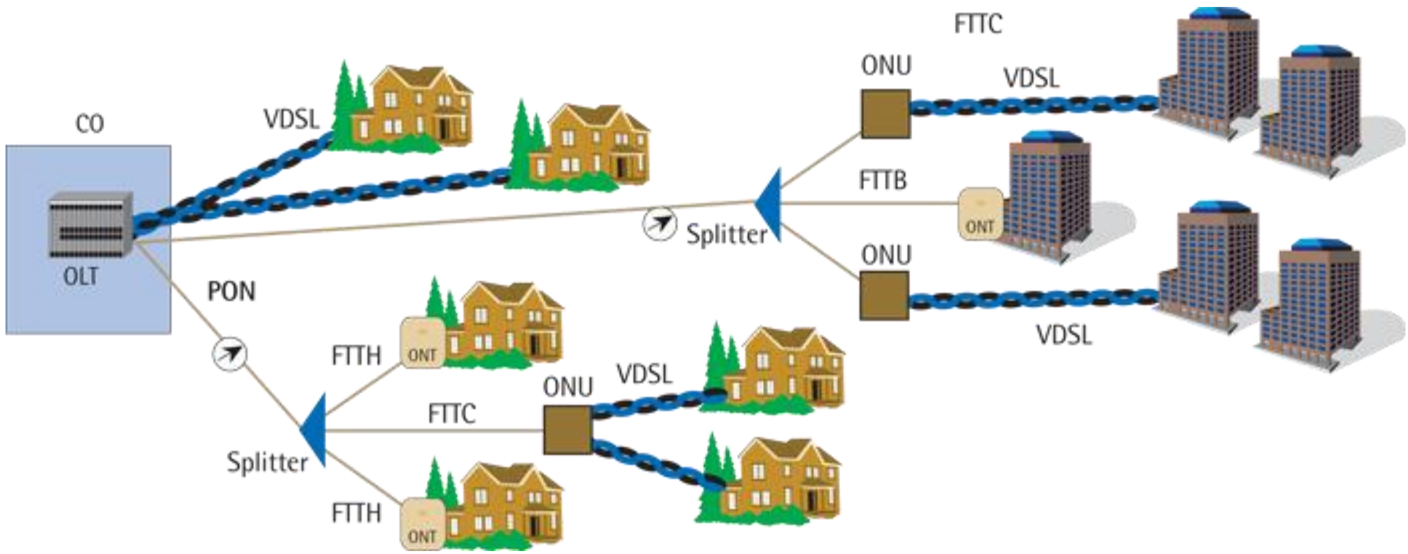
- Last-mile optical networks are referred to as **Fiber to the x (FTTx)**. For example:

  Fiber to the Node (FTTN)
  Fiber reaches a street cabinet several kilometers from the customers, with the final connections being copper. Often used in triple-play services (telephony, internet, TV).

  Fiber to the Curb (FTTC)
  Fiber reaches a street cabinet close to the customer (<300m). Final connections may be high-bandwidth wired Ethernet or wireless (WiFi).

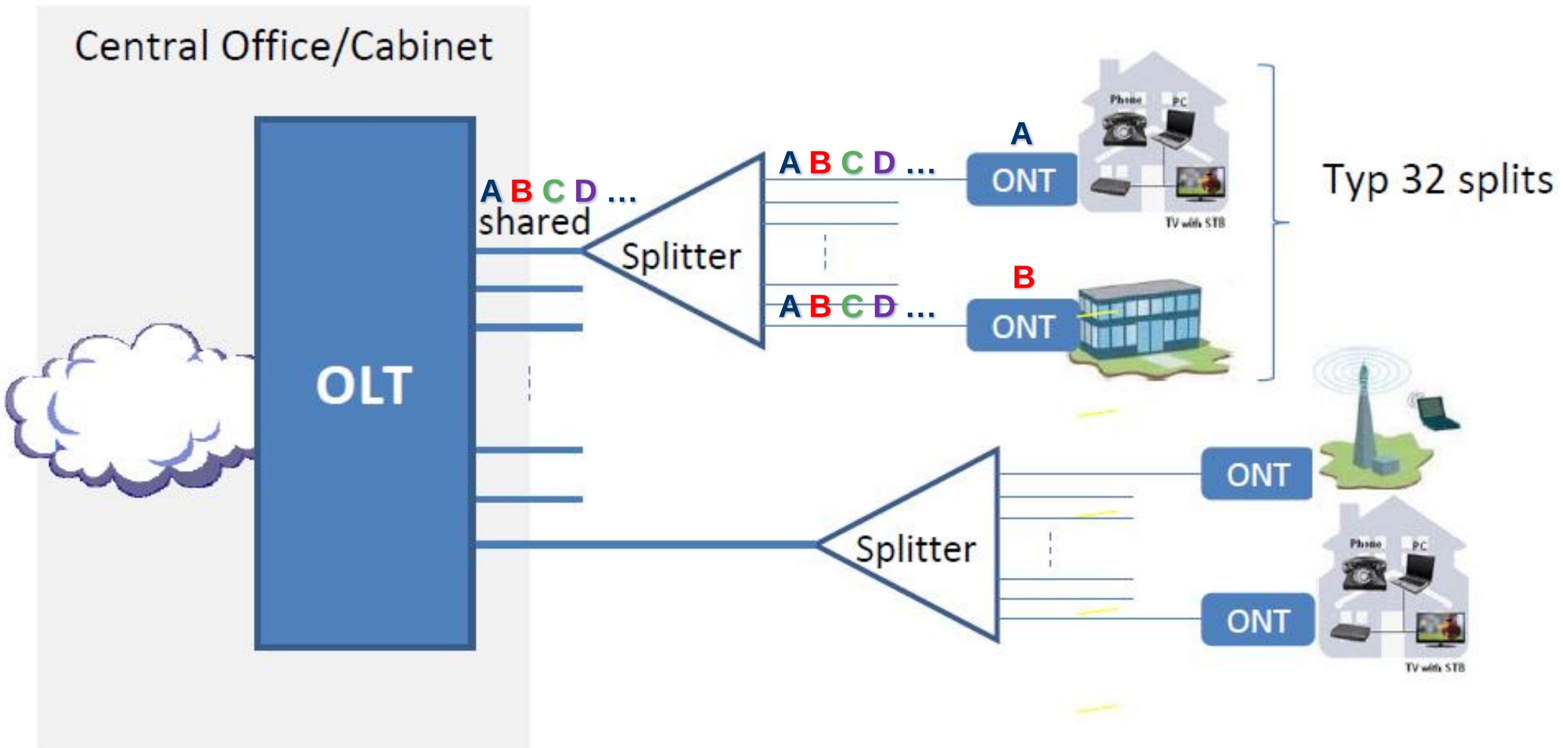
  Fiber to the Premises (FTTP) - also known as **Fiber to the Home (FTTH)** and **Fiber to the Building (FTTB):** Fiber reaches the boundary of the residential or commercial building. **Passive optical networks (PONs)** and point-to-point Ethernet are architectures that deliver triple-play services over FTTH networks directly from an operator's central office.

- **Two different architectures:** Star (Passive Optical Networks) or Point-to-Point (Active Ethernet).



Star: Passive Optical Networks (PONs)

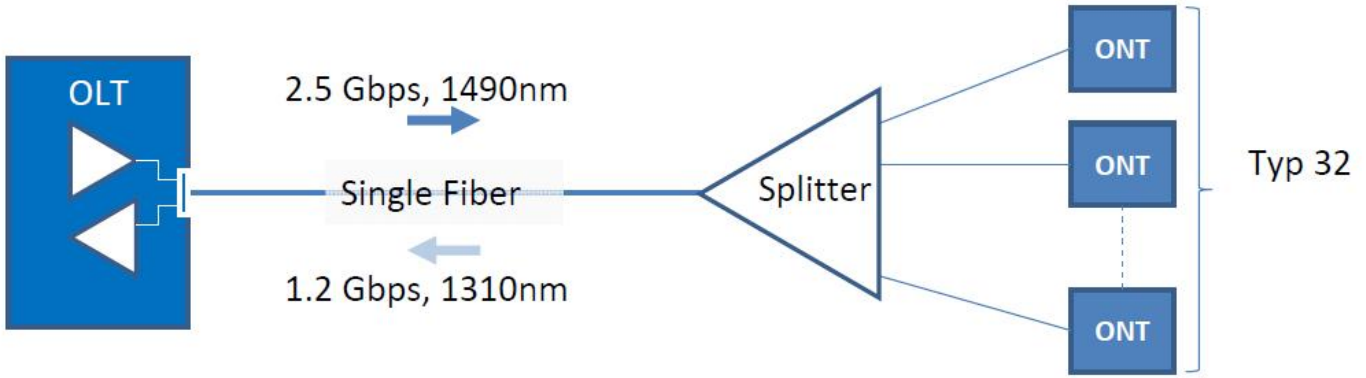
- The **Optical Line Terminal (OLT)** at the service provider's **central office (CO)** broadcasts data to several **Optical Network Terminals (ONTs)** at the customer premises through the passive fiber network.
- All ONTs receive the same broadcast data, selecting the appropriate portion corresponding to the end-user it is serving.



Current Standards: TDM-PONs

Gigabit Passive Optical Network (GPON)

- TDM architecture, 2.5 Gbit/s downstream, 1.2 Gbit/s upstream
- Typically have multiple GPON ports per OLT card, with each card serving more than 100 customers.
- Single shared fiber:
  - Fewer fibers than point-point (if splitter deployed in the field).
- Splits: Up to 128, but typ. 32 or 64.
- Typical reach: 20km with 32 splits, but some vendors provide longer reach.
- Typical optical budget 28 dB, but higher budget optics available.

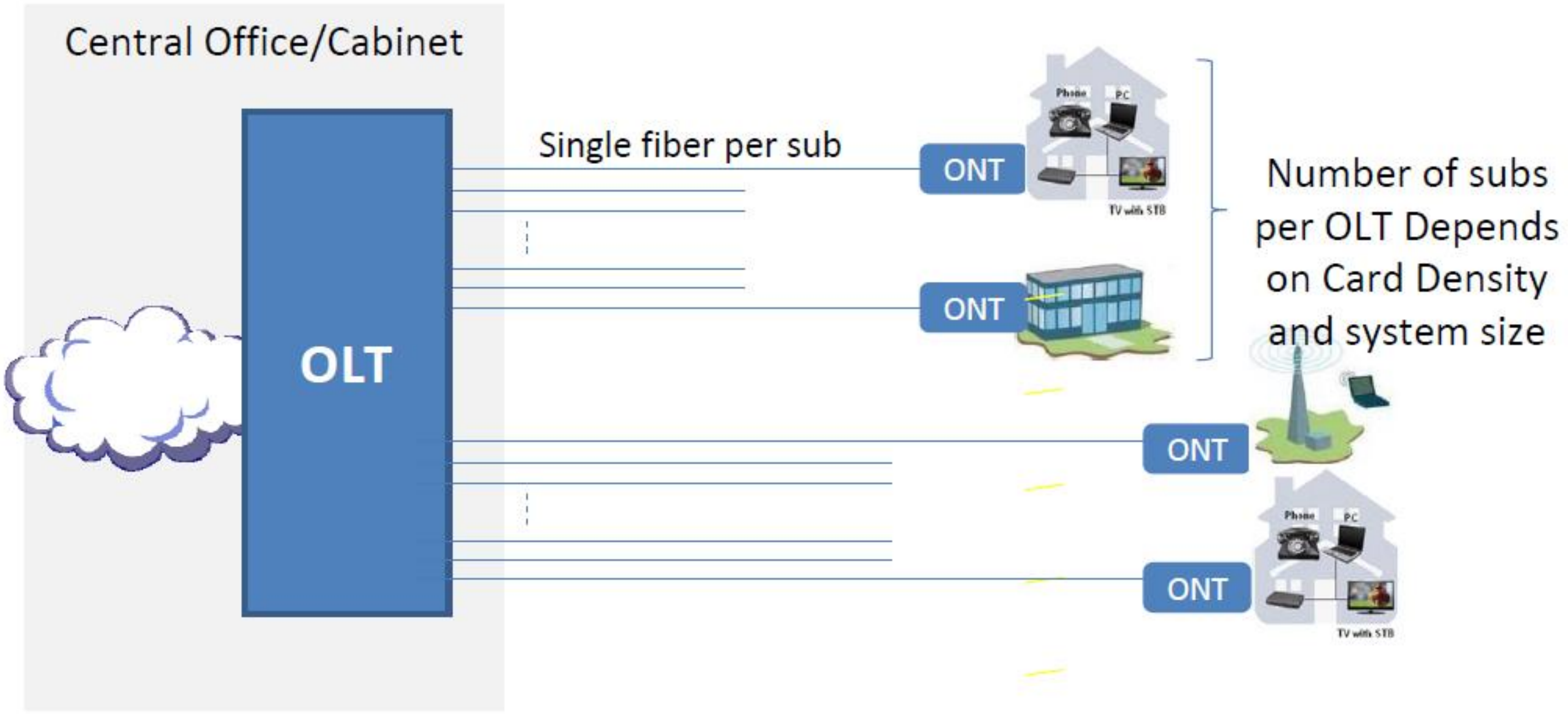


XGPON and **XGPON2** (also known as **NGPON1**)

- TDM architecture
- XG-PON is asymmetric: 10 Gbit/s downstream and 2.5 Gbit/s upstream
- XG-PON2 is symmetric: 10 Gbit/s downstream and 10 Gbit/s upstream

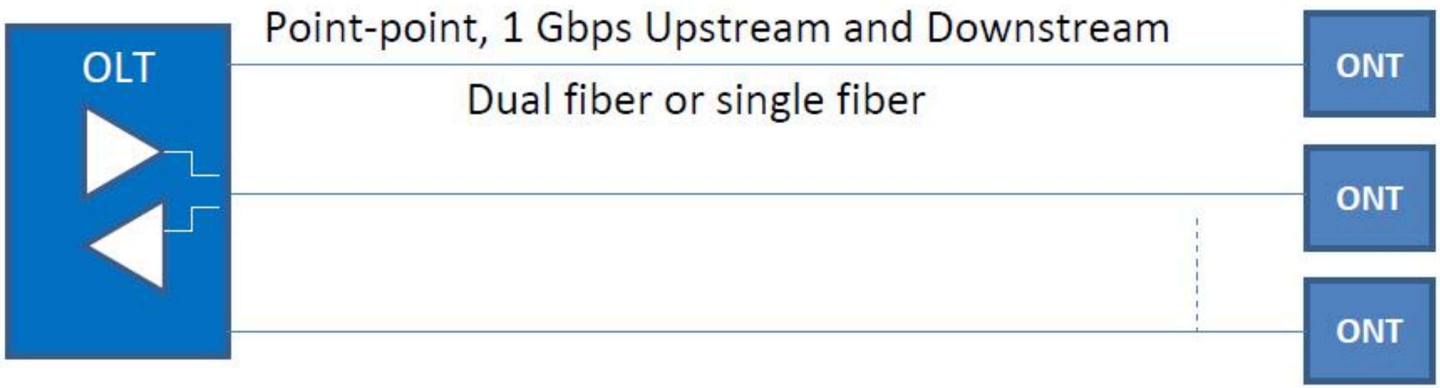
Point-to-Point: Active Ethernet

- Dedicated point-to-point connections for each ONT.
- 1 fiber per customer.



Current Standards: Active Ethernet

- “Future-proof”: Upgrade individual users by changing electronics.
- User isolation: Dedicated connection & simpler traffic management.
- Potential for simpler and lower cost ONT.
- More fiber than GPON.
- the GPON splitter at the C.O. to proof their fiber installation.
- Reach: 20-80 km depending on optics.



PON Vs Active Ethernet

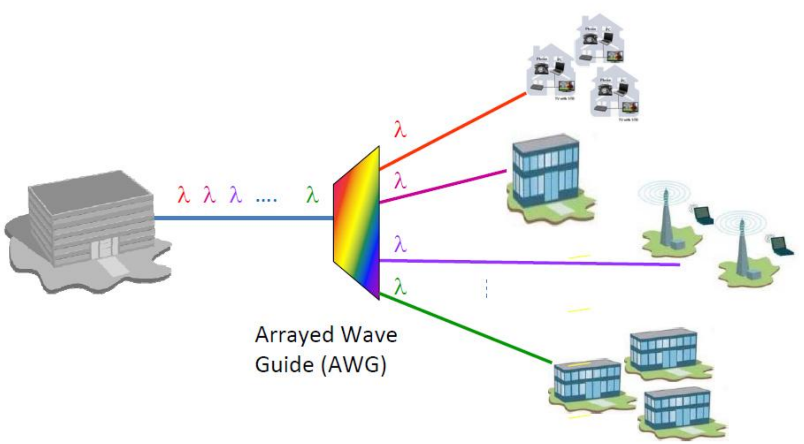
Active Ethernet	TDM-PON (GPON, XGPON)
Potential for higher capacity (limited only by TRx speed)	Higher density ONT - More subscribers per platform - Lower power per subscriber - Lower cost per subscriber
User isolation (no “rogue” ONTs can steal data)	Fewer fibers/cables in the central office (and feeder/exchange) - More subscribers per fiber - Lower mean time to repair (MTTR)
Simpler traffic management	Prevailing architecture for large telecom providers
Potential for lower complexity ONT	Evolution to WDM-PON standards

Future Standards: TDM/WDM-PON

Why move to WDM-PON?

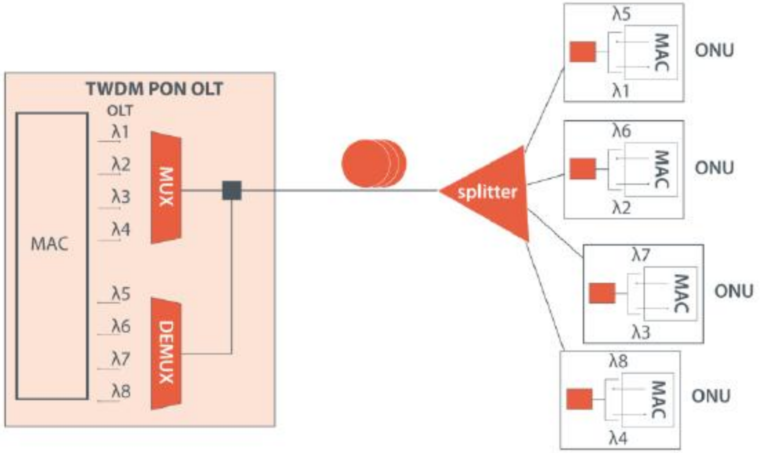
- Combines good qualities of TDM and point-to-point: Effectively delivers point-to-point performance with fiber density comparable to TDM-PON.
- 32-40 users per fiber, 1 user per wavelength.
  - TDM-PON: 10G/32 users = 312 Mbps/user over single fiber
  - WDM-PON: 1 Gbps per wavelength = 1 Gbps/user over single fiber
- Hybrid approaches are also possible, such as an XGPON or GPON per wavelength.

WDM-PON



- Pure WDM
- Wavelength selection is done with an AWG, and only 1 wavelength reaches each ONT

TDM/WDM-PON

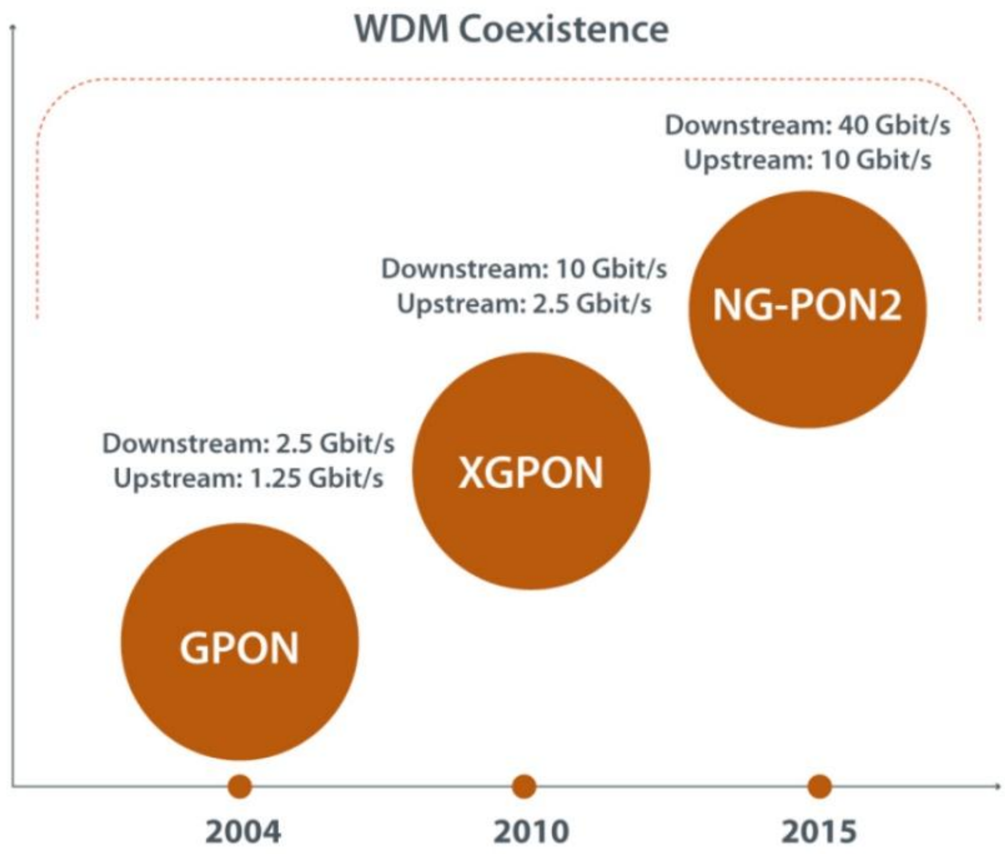


- Both TDM and WDM
- Passive splitting, all wavelengths reach ONTs
- Wavelength selection done at ONTs

Future Standards: NG-PON2

NG-PON2 (currently being specified, expected in 2015)

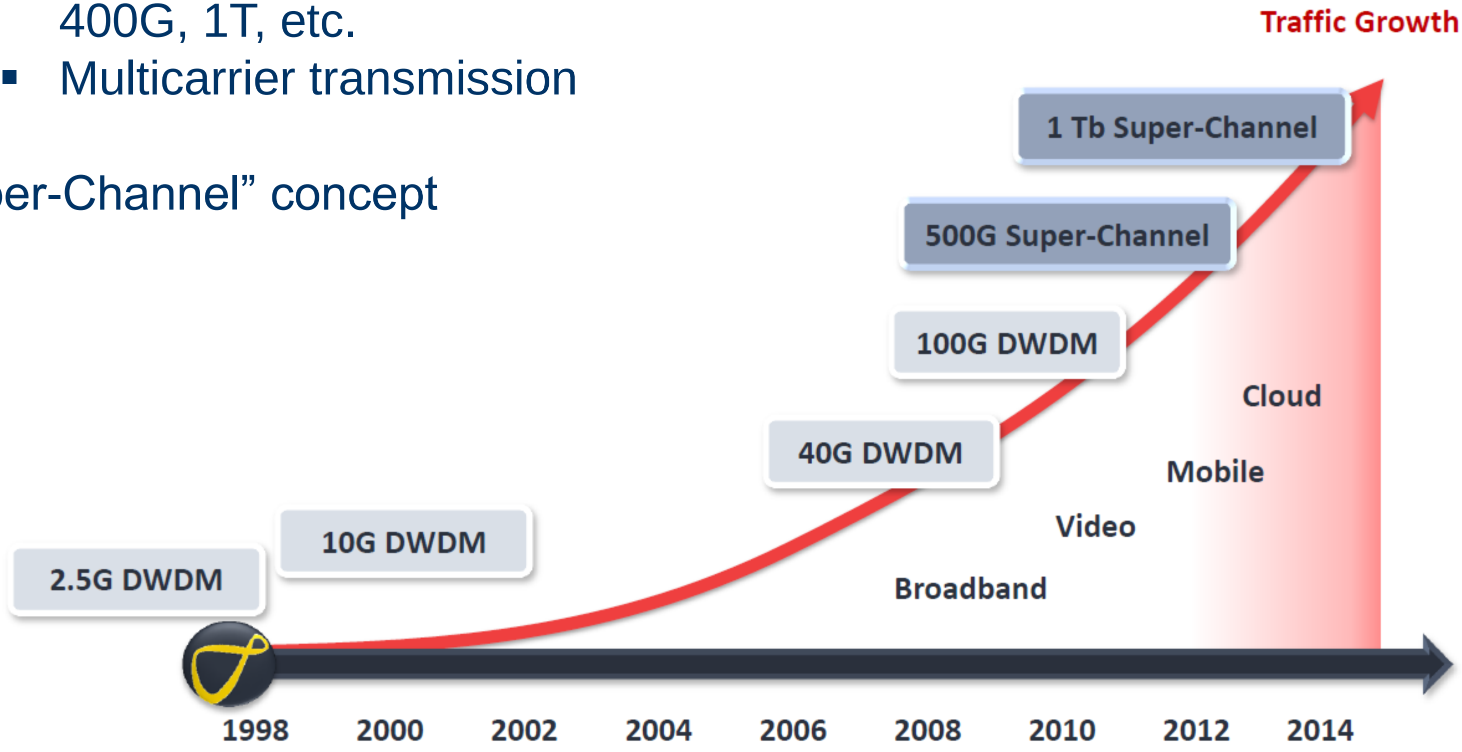
- 40 Gbit/s downstream, 10 Gbit/s upstream
- Several options: WDM, Ultra-Dense WDM-PON (UDWDM), OFDM, TDM, TDM/WDM, Hybrid system with 4 x XGPON multiplexing.



The Future: Flexible Networks (1)

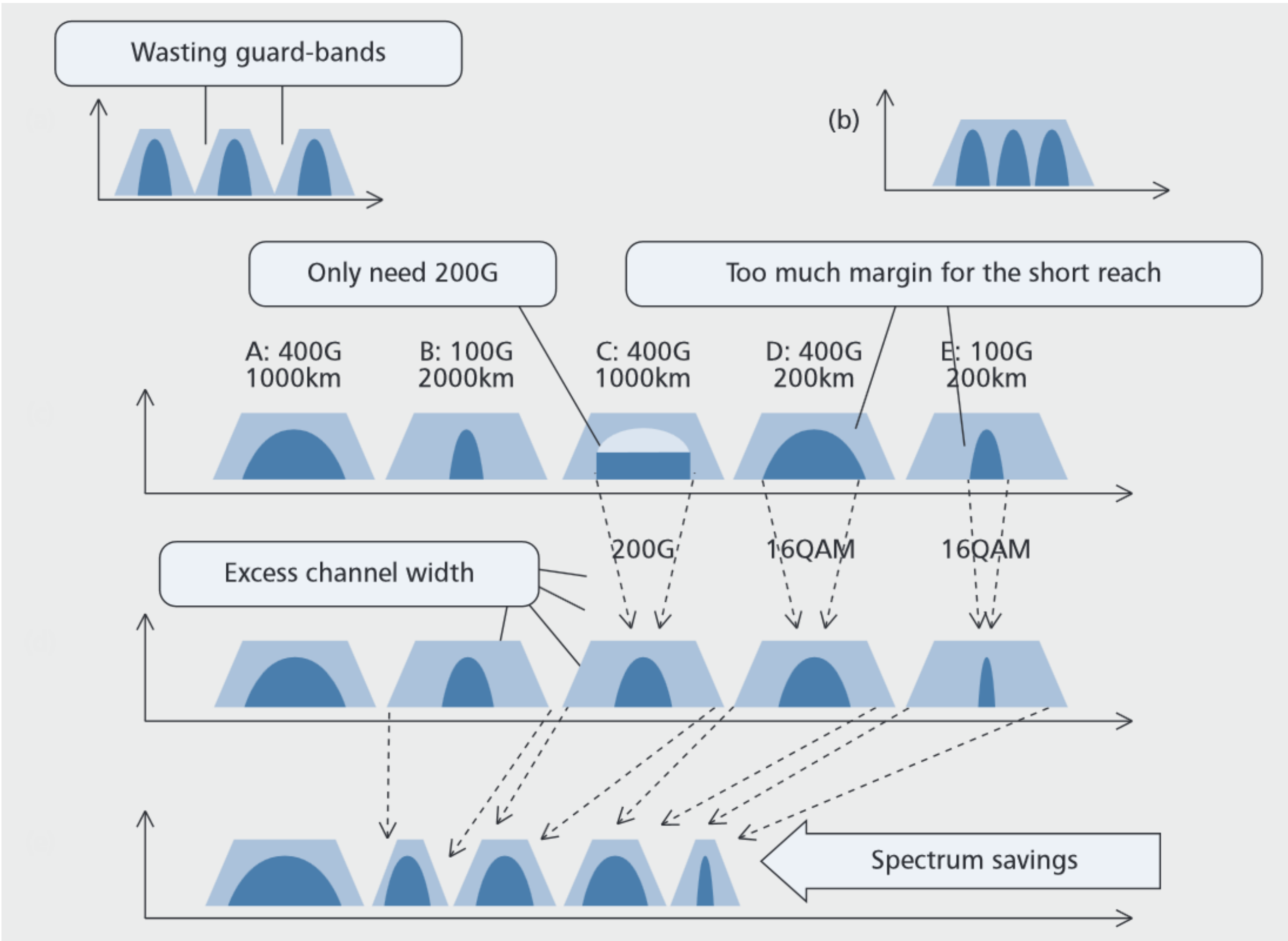
- Exponential Traffic Growth makes the traditional WDM schemes to reach its **capacity** and **reach** limits.
- Demands:
  - Less rigid ('Elastic') Spectrum Specifications (channel spacing <50 GHz AND >100 GHz)
  - Variety of Modulation Formats (coherent QAM) and rates: 100G, 400G, 1T, etc.
  - Multicarrier transmission

"Super-Channel" concept



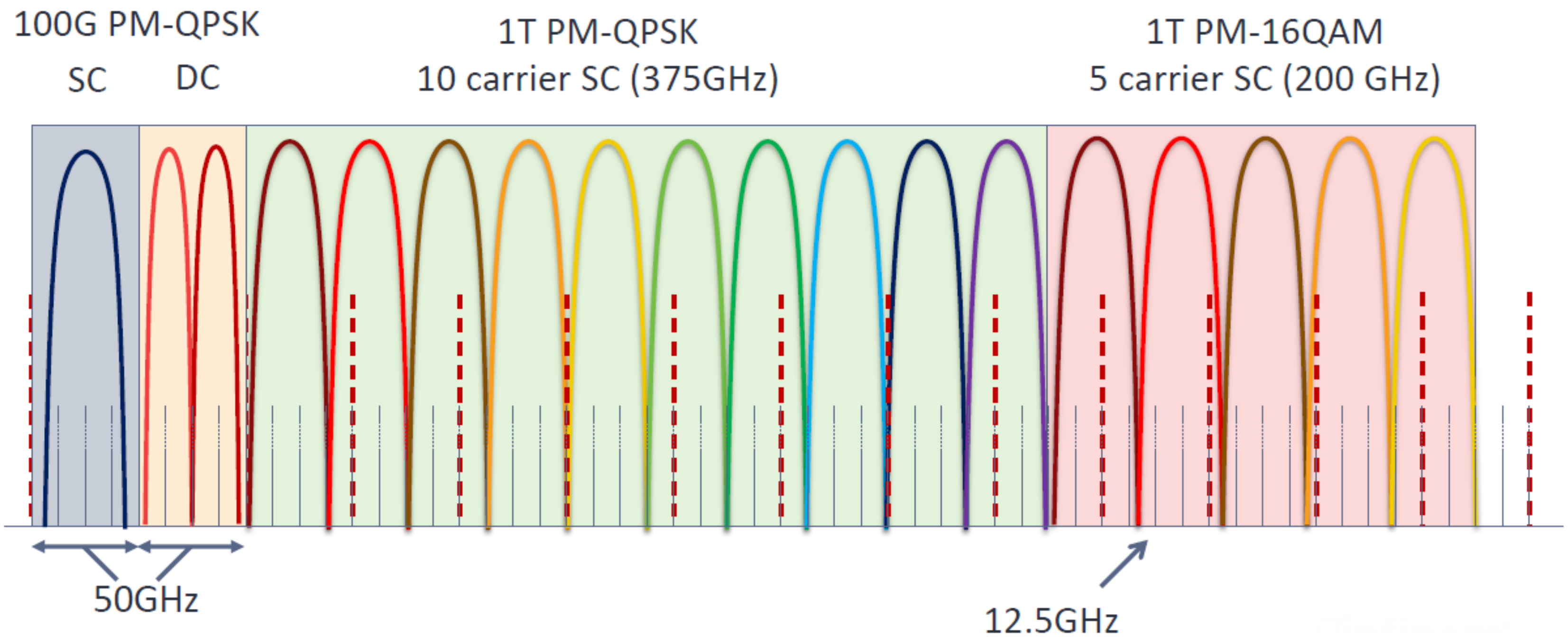
The Future: Flexible Networks (2)

- Flexible DWDM Grid (ITU-T G.694.1) – **FlexGrid** standard
- **12.5 GHz** spectral granularity is able to support variable transmission rates >100Gb/s



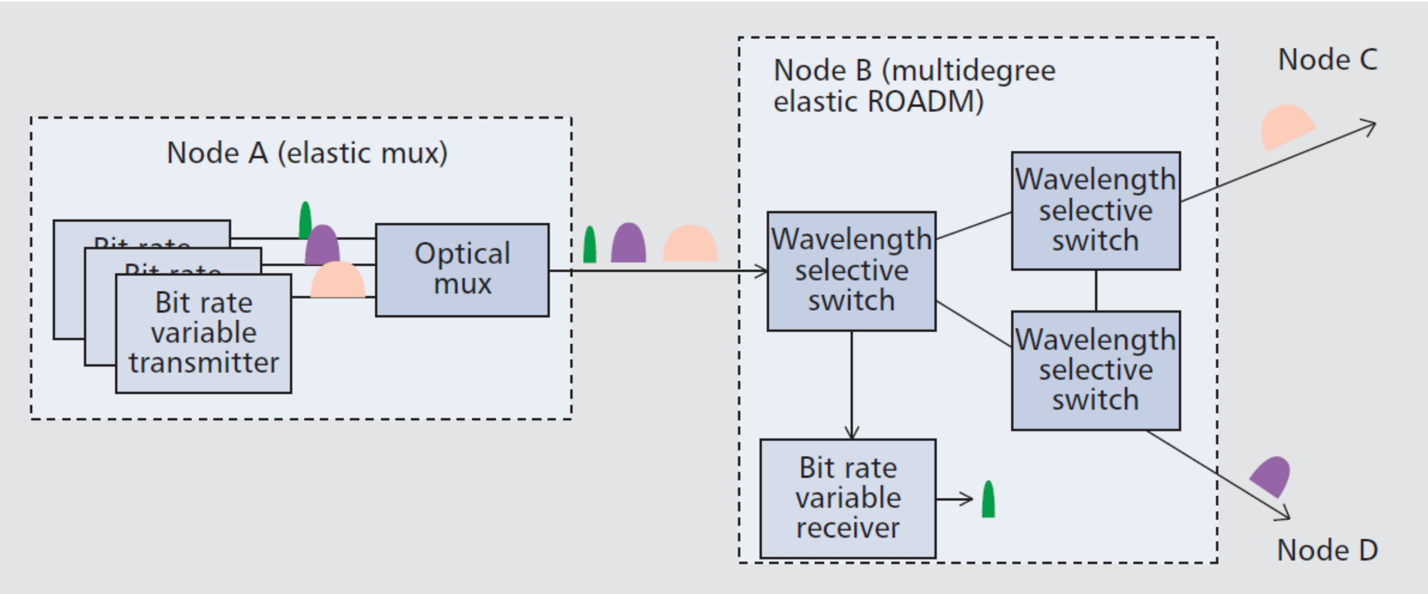
The Future: Flexible Networks (3)

- Super-Channel approach to achieve higher bit rates.
- Multiple carriers with center frequencies and bandwidths defined by the Flex-Grid.
- More efficient use of the bandwidth, little bandwidth wasted in guard channels.
- Reclaim 25% ‘wasted’ spectrum from 50 GHz fixed-grid.



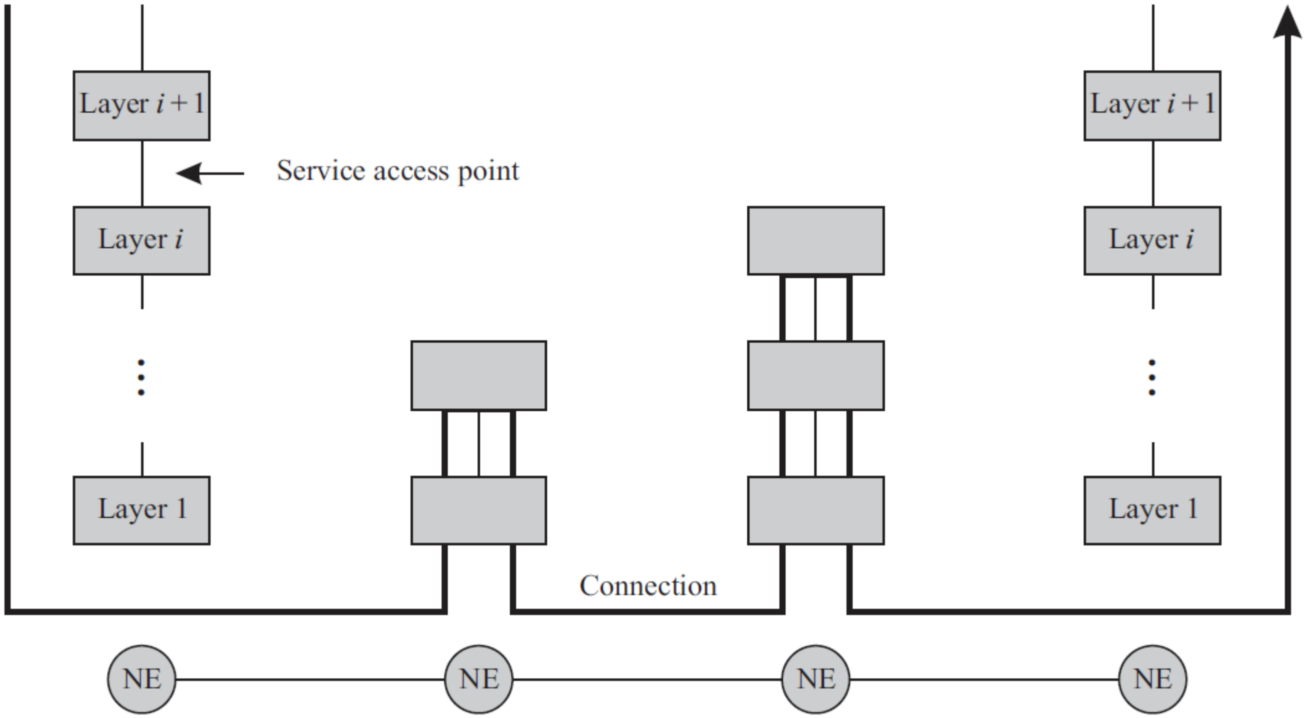
The Future: Flexible Networks (4)

- Variable-bitrate transponders supporting multiple formats and rates.
- Traffic demands of various characteristics (bit rate, reach) can be handled by the network with a maximization of the spectral efficiency.
- E.g. use 100G QPSK for longer reach, switch to 16-/64-QAM for shorter distances with better SNR.
- Respond to changing network conditions by adapting formats.
- Maximizes bandwidth efficiency, network utilization → lower cost, lower energy consumption.



Layered Hierarchy of a Network (1)

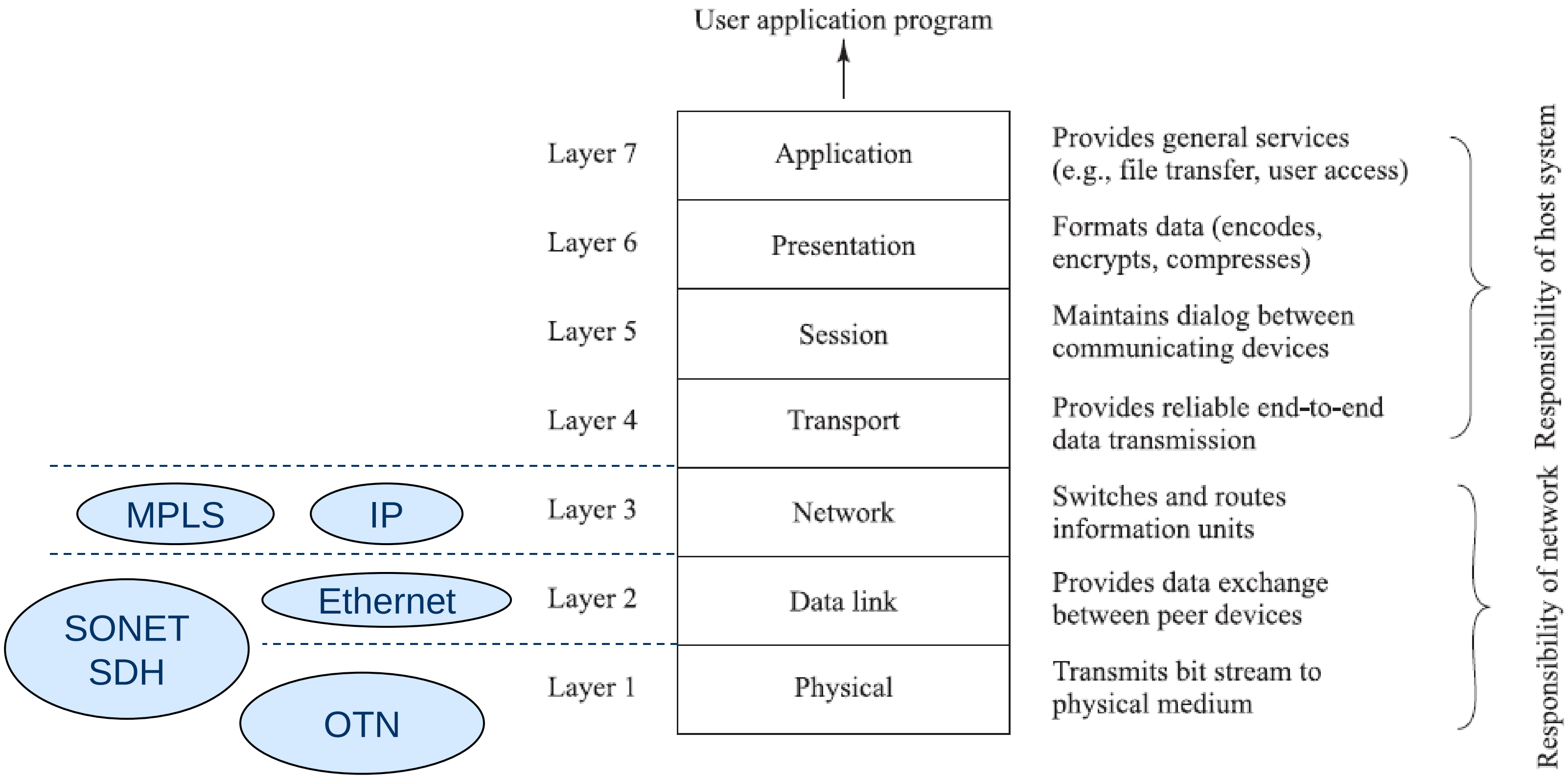
- Networks contain a variety of *different functions* being performed by *different components* from *different vendors* **all interworking together**.
- In order to simplify our view of the network, it is desirable to break up the functions of the network into different ***layers***.



NE: Network Element

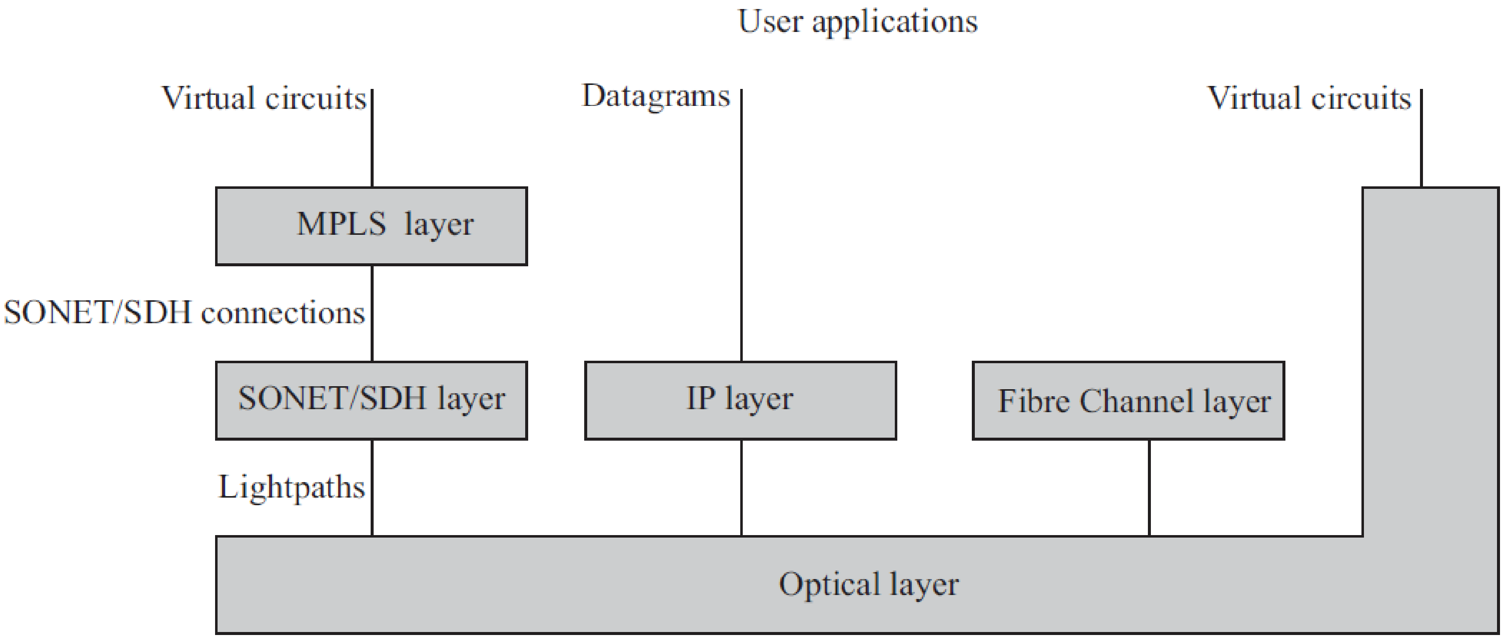
Layered Hierarchy of a Network (2)

- The classic OSI layered hierarchy



Optical Layer in Layered Hierarchy (1)

- The optical layer is a *server* layer that provides services to other *client* layers.
- Client layers residing above a second-generation optical network layer include:
  - IP
  - Ethernet
  - SONET/SDH
  - OTN
  - other possible protocols (e.g. Fiber Channel)



Optical Layer in Layered Hierarchy (2)

- The transmission rates standards of the higher layers “affected” the transmission standards of the optical layer

SONET Signal	SDH Signal	Bit Rate (Mb/s)
STS-1		51.84
STS-3	STM-1	155.52
STS-12	STM-4	622.08
STS-24		1244.16
STS-48	STM-16	2488.32
STS-192	STM-64	9953.28
STS-768	STM-256	39, 814.32

OTN (G.709)	Line Rates
OTU1:	2.666 Gb/s
OTU2:	10.709 Gb/s
OTU3:	43.018 Gb/s

Data/asynchronous bandwidth channels	*Bit rate*
Gb Ethernet	1 Gb/s
10 Gb Ethernet	10 Gb/s
40 Gb Ethernet	40 Gb/s

Optical Transport Network (OTN)

- The **Optical Transport Network** (OTN), a.k.a. ***G.709***, was designed to transport data packet traffic such as IP and Ethernet over fiber optics, as well as legacy traffic and in particular SONET/SDH.
- It is called the *digital wrapper* technology because it wraps any client signal in overhead information for operations, administration, and management.
- Capabilities of:
  - FEC
  - Management
  - Protocol Transparency
  - Asynchronous Timing

OTN hierarchy