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FIBER-OPTIC COMMUNICATIONS

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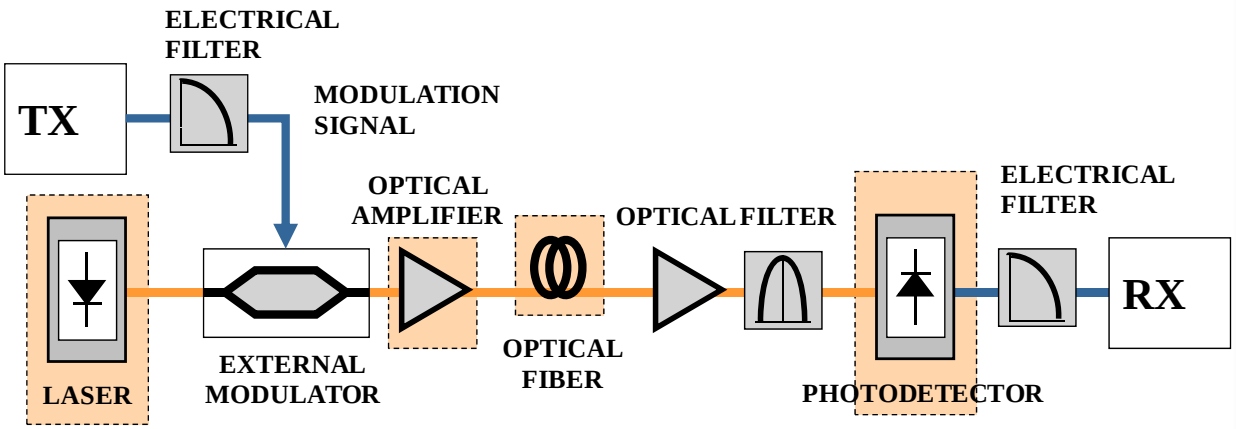
INTRODUCTION

Simplified Fiber-Optic System Example



F.O. SYSTEMS CLASSIFICATION

TECN.
- Analog (HFC)
- Digital

MOD.
- Intensity Modulation – Direct Detection (IM-DD)
- Phase Modulation – Differential Detection (DPSK)
- Coherent Detection Systems (ASK, PSK, FSK)

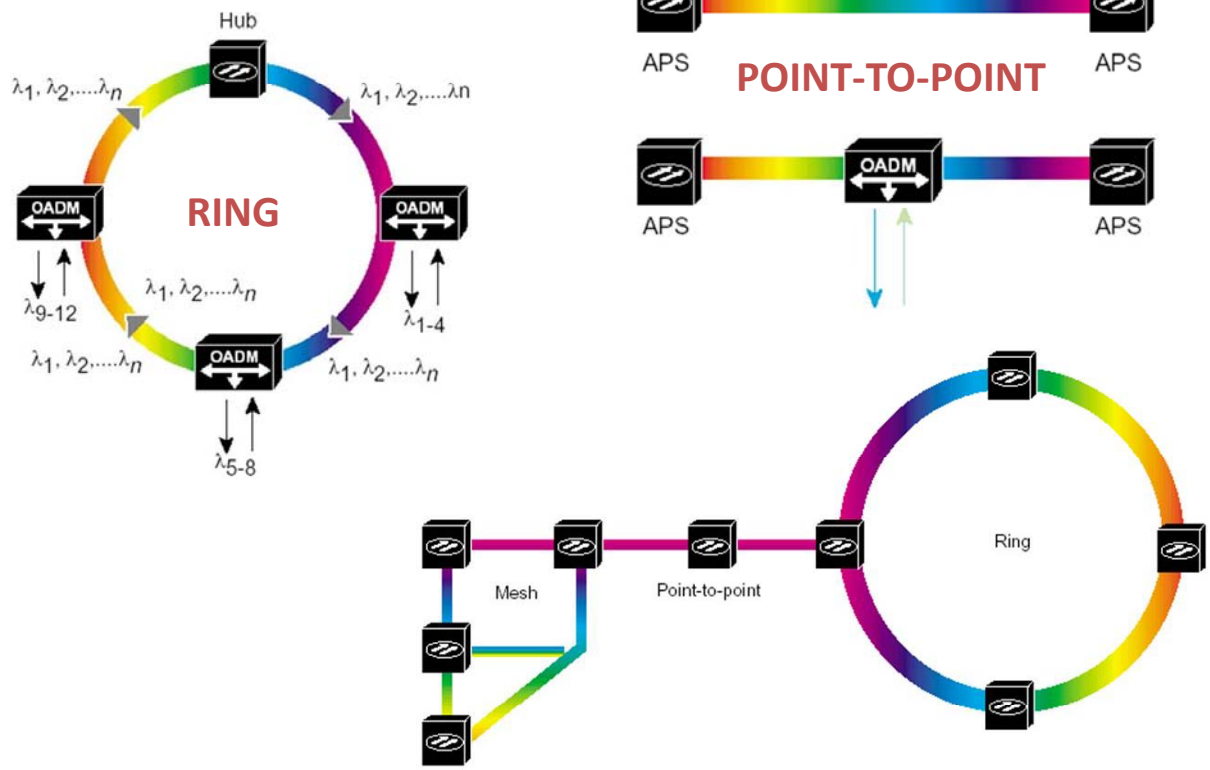
MUX.
- Time Multiplexation (ETDM, OTDM)
- Frequency / Wavelength Multiplex. (FDM , WDM)
- Polarization Multiplexation (PolDM)

REACH
- Long-Haul → Terrestrial, Submarine
- Metro / Access

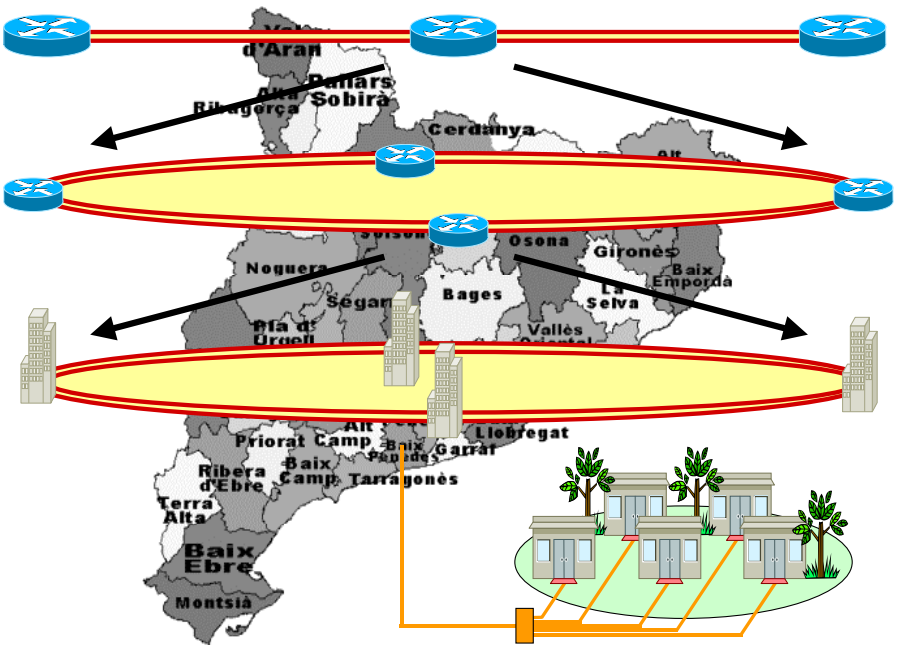
Characteristic Parameters

- Link Length(L) ← Power Budget (atennuation)
- Bandwidth(BW) ← dispersion
- Signal-to-Noise Ration (SNR) ← Shot, Thermal, ASE
- Bit Error Ratio (BER)
- Transmission Bit Rate (R_B)
- Number of Channels (Capacity)

Network Topology



FIBER-OPTIC LOCALIZATION



Longh-Haul (1000 km)

Regional (100 km)

Metropolitan (20 km)

Access (10 km)

Which Communication Media ?

Atmosphere

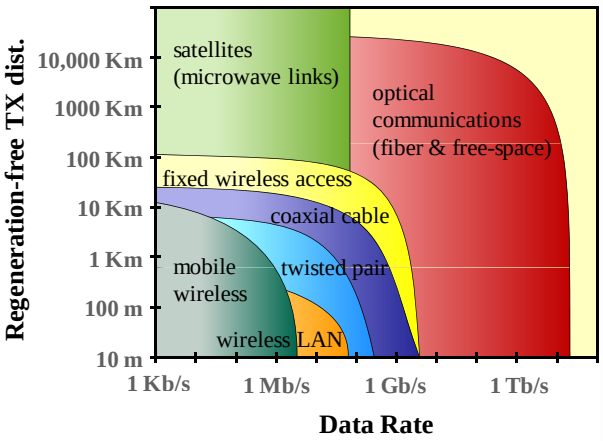
- **Radio transmission**
- **Microwave line-of-sight links (100 Mbit/s, 50 km)**
- **Satellite (100 Mbit/s, around the world)**

Cables

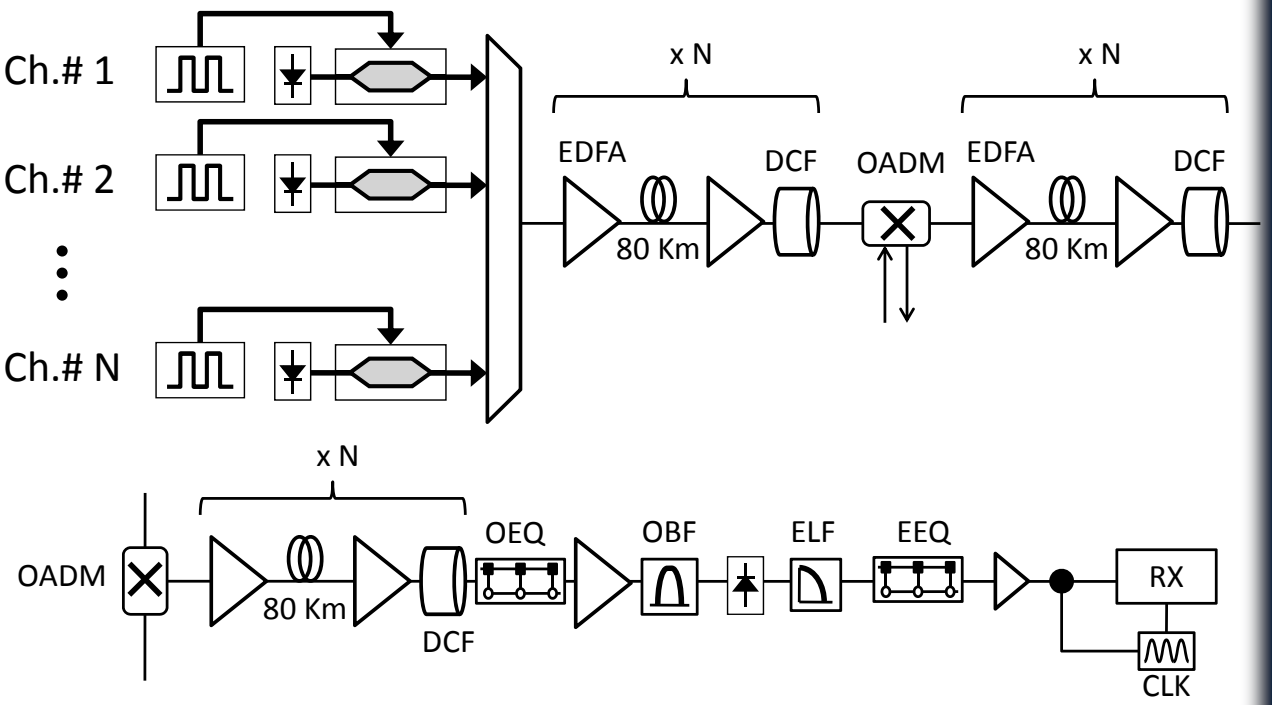
- **Twisted-pair cable (2 Mbit/s, 2 km)**
- **Coaxial cable (>500 Mbit/s, few km)**
- **Undersea cable (50 Mbit/s)**

Optical Fiber

- **High transmission bandwidth and low loss**
  - 10 Gbit/s over 100 km (single fiber, single transmission wavelength without amplifier)
  - > 200 Gbit/s using multiple wavelength carriers
  - > 20,000 km at 10 Gbit/s using amplifiers
- **Free of electromagnetic interference**
- **Small size and low weight**
- **Increased data security**



TRANSPORT NETWORKS (LONG HAUL)



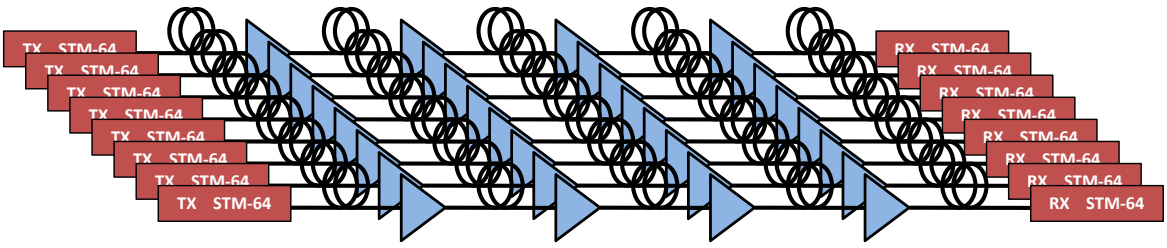
Some Recent Record Fiber-Optic Transmission Results

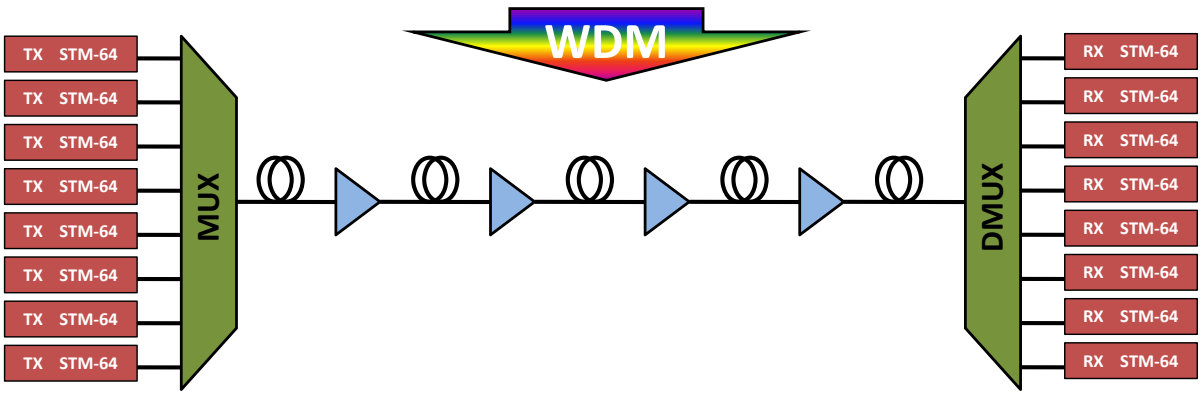
Ref.	Capacity	Distance	Capacity × Distance
[1]	10.9 Tb/s (273 ch × 40 Gb/s)	117 km	1.3 Pb/s·km
[2]	10.2 Tb/s (256 ch × 42.7 Gb/s)	300 km	3.1 Pb/s·km
[3]	6.0 Tb/s (149 ch × 42.7 Gb/s)	6,100 km	36 Pb/s·km
[4]	2.6 Tb/s (64 ch × 42.7 Gb/s)	4,000 km	10 Pb/s·km
[5]	1.6 Tb/s (40 ch ×42.7 Gb/s)	10,000 km	16 Pb/s·km

[1] K. Fukuchi, T. Kasamatsu, M. Morie,R. Ohhira, T. Ito, K. Sekiya, D. Ogasahara, and T. Ono, B10.92-Tb/s (273 40-Gb/s) triple-band/ultra-dense WDM optical repeatered transmission experiment,[in Proc. Optical Fiber Communication Conf. (OFC), 2001, Paper PD24.
[2] Y. Frignac, G. Charlet, W. Idler, R. Dischler, P. Tran, S. B. S. Lanne, C. Martinelli, G. Veith, A. Jourdan, J.-P. Hamaide, and S. Bigo, BTransmission of 256 wavelength division and polarization-division multiplexed channels at 42.7 Gb/s (10.2 Tb/s capacity) over 3 100 km of TeraLight fiber,[in Proc. Optical Fiber Communication Conf. (OFC), 2002, Paper FC5.
[3] G. Charlet, E. Corbel, J. Lazaro, A. Klekamp, R. Dischler, P. Tran, W. Idler, H. Mardoyan, A. Konczykowska, F. Jorge, and S. Bigo, BWDM transmission at 6 Tbit/s capacity over transatlantic distance and using 42.7 Gb/s differential phase-shift keying without pulse carver,[in Proc. Optical Fiber Communication Conf. (OFC), 2004, Paper PDP36.
[4] A. H. Gnauck, G. Raybon, S. Chandrasekhar, J. Leuthold, L. S. C. Doerr, A. Agarwal, S. Banerjee, D. Grosz, S. Hunsche, A. M. A. Kung, D. Maywar, M. Movassaghi, X. Liu, C. Xu, X. Wei, and D. M. Gill, B2.5 Tb/s (64 42.7 Gb/s) transmission over 40 100 km NZDSF using RZ-DPSK format and all-Raman amplified spans,[in Proc. Optical Fiber Communication Conf. (OFC), 2002, Paper FC2.
[5] C. Rasmussen, T. Fjelde, J. Bennike, F. Liu, S. Dey, P. M. B. Mikkelsen, P. Serbe, P. V. der Wagt, Y. Akasaka, D. Harris, D. Gapontsev, V. Ivshin, and P. Reeves-Hall, BDWDM 40 G transmission over transpacific distance (10,000 km) using CSRZ-DPSK and enhanced FEC and all- Raman amplified 100 km Ultrawave fiber spans,[in Proc. Optical Fiber Communication Conf. (OFC), 2001, Paper PD18.

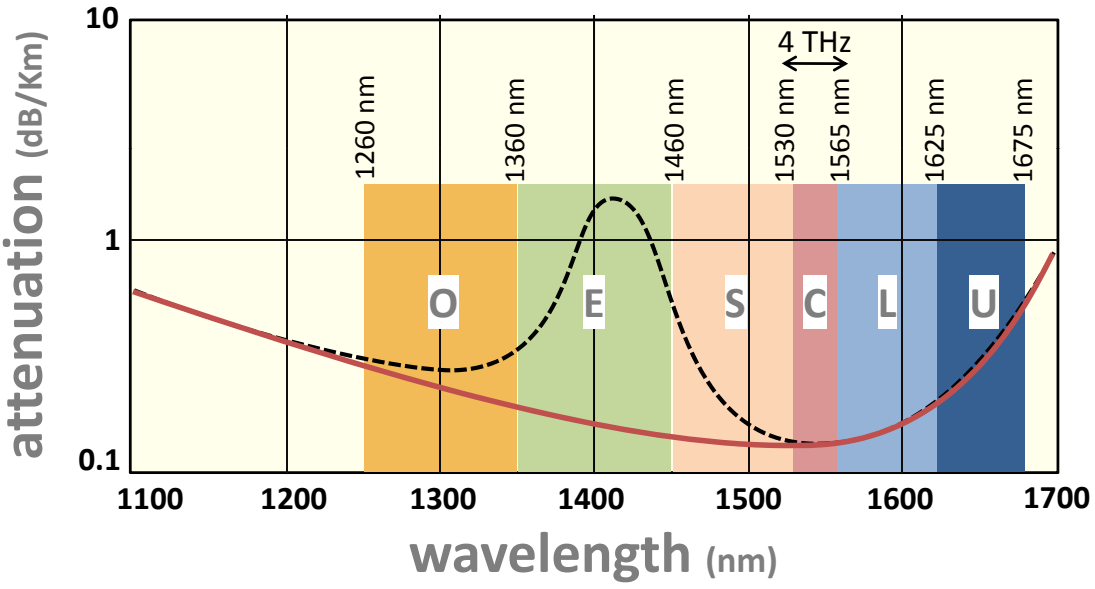
WDM WAVELENGTH DIVISION MULTIPLEXING

8 channels x 10 Gb/s = 80 Gb/s





WDM transmission Bands



O – original	C – conventional (erbium)	L – long wavelength
E – extended	S – short wavelength	U – ultralong wavelength

WDM versions

ITU-T G.671

coarse WDM (CWDM) A class of WDM devices having a channel wavelength spacing less than **50 nm** but greater than **1000 GHz** (about 8 nm at 1550 nm and 5.7 nm at 1310 nm). Devices within this class can cover several spectral bands.

dense WDM (DWDM) A class of WDM devices having a channel spacing less than or equal to **1000 GHz**. Devices within this class can cover one or more spectral bands.

wide WDM (WWDM) A class of WDM devices having a channel wavelength spacing greater than or equal to **50 nm**. This device class typically separates a channel in one conventional transmission window (e.g., 1310 nm) from another (e.g., 1550 nm).

The Ethernet LX-4 10 Gbit/s physical layer standard is an example of a CWDM system in which four wavelengths near 1310 nm, each carrying a 3.125 gigabit(Gb)-per-second data stream, are used to carry 10 gigabit-per-second of aggregate data.

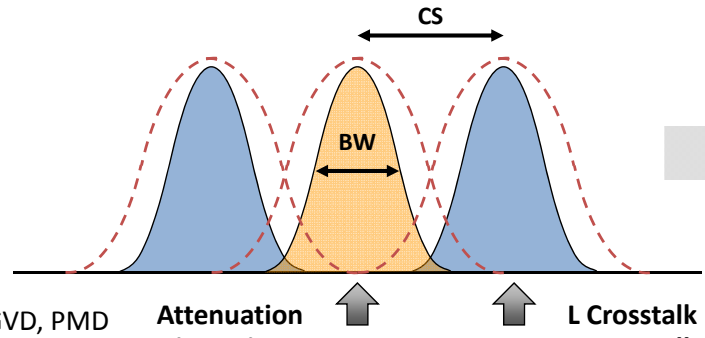
DWDM Grid (ITU-T G.694.1)

$193.1 + N \times 0.1/2^M$ [THz] N = int. , M = [0, 1, 2, 3]

100 GHz Grid

Frequency (THz)	Wavelength (nm)	Frequency (THz)	Wavelength (nm)	Frequency (THz)	Wavelength (nm)
196.1	1528.77	194.6	1540.56	193.1	1552.52
196.0	1529.55	194.5	1541.35	193.0	1553.33
195.9	1530.33	194.4	1542.14	192.9	1554.13
195.8	1531.12	194.3	1542.94	192.8	1554.94
195.7	1531.90	194.2	1543.73	192.7	1555.75
195.6	1532.68	194.1	1544.53	192.6	1556.56
195.5	1533.47	194.0	1545.32	192.5	1557.36
195.4	1534.25	193.9	1546.12	192.4	1558.17
195.3	1535.04	193.8	1546.92	192.3	1558.98
195.2	1535.82	193.7	1547.72	192.2	1559.79
195.1	1536.61	193.6	1548.51	192.1	1560.61
195.0	1537.40	193.5	1549.32	192.0	1561.42
194.9	1538.19	193.4	1550.12	191.9	1562.23
194.8	1538.98	193.3	1550.92	191.8	1563.05
194.7	1539.77	193.2	1551.72	191.7	1563.86

Main Impairments



Old Fiber Plant

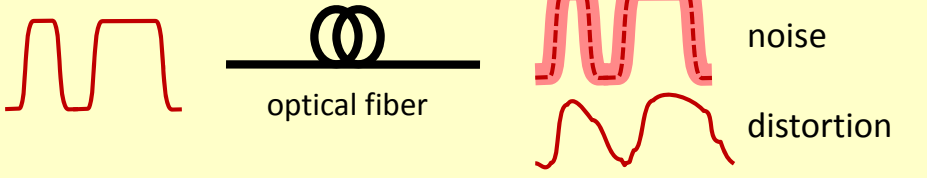
GVD, PMD
SPM, Intra XPM. Intra FWM
ASE, Shot, Thermal, Phase
MUX, OXC

Attenuation
Dispersion
NL Effects
Noise
Filtering

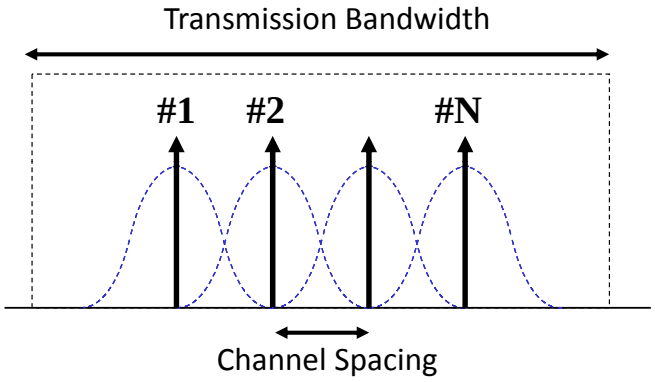
L Crosstalk
NL Crosstalk

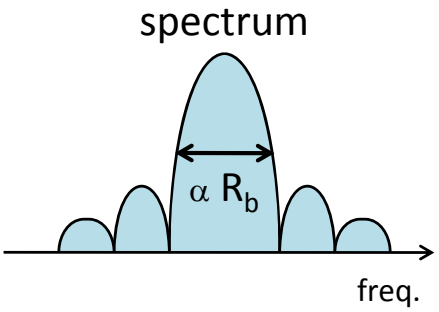
Inter XPM. Inter FWM

channel effects



System Capacity





Capacity = Channels x Bit Rate

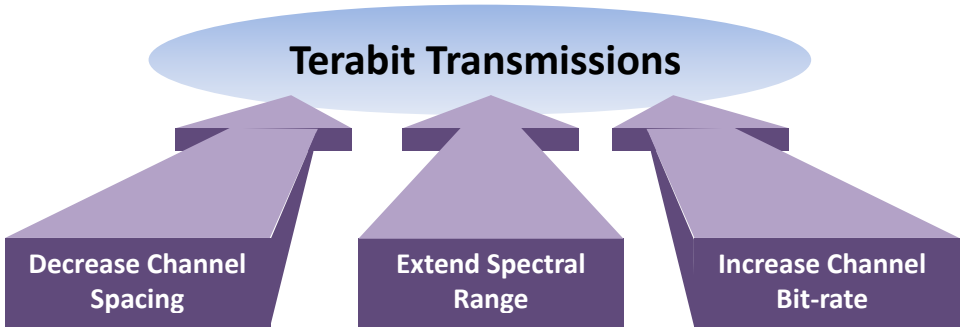
Channels = Bandwidth / Spacing

Capacity = Bandwidth x Bit Rate / Spacing

Spectral Efficiency

$$\eta \equiv \frac{R_B}{CS} \left[\frac{b/s}{Hz}\right]$$

System Capacity



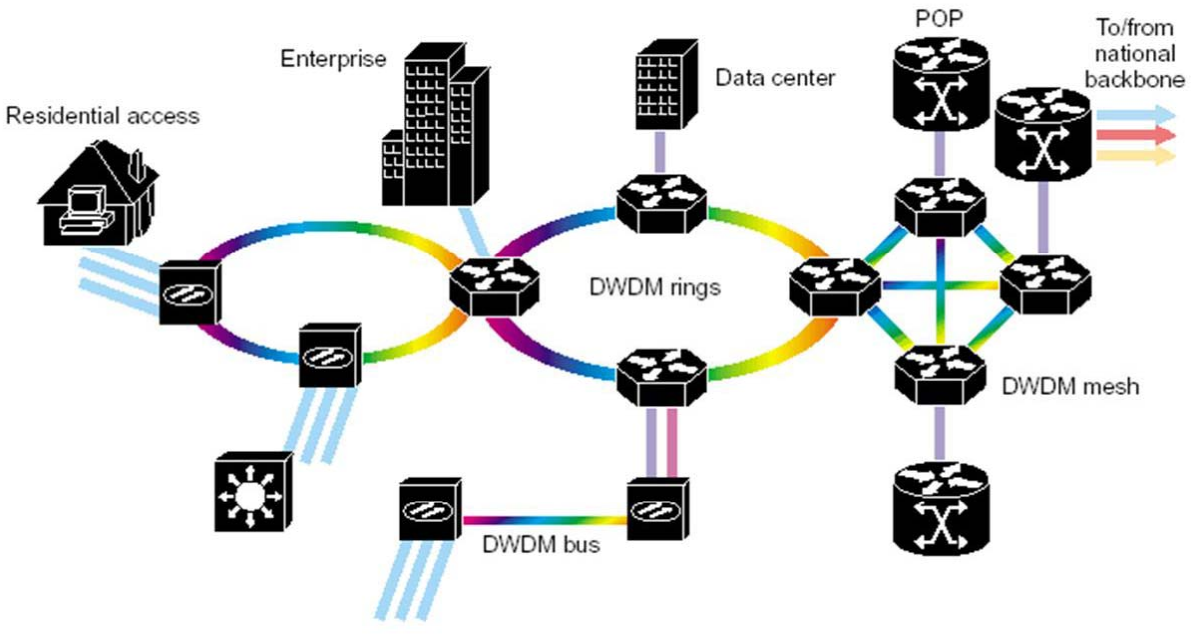
Decrease Channel Spacing	Extend Spectral Range	Increase Channel Bit-rate
200 GHz	30 nm	2.5 Gb/s
100 GHz	80 nm	10 Gb/s
50 GHz	120 nm	40 Gb/s
25 GHz	150 nm	100 Gb/s

Status of commercial equipment (per fiber)	Year 1995	Year 2000	Year 2005	Year 2010
TDM line bit-rate	2.5 Gb/s	2.5-10 Gb/s	10-40 Gb/s	10-40-100 Gb/s
WDM channels	8	64-128	128-256	128-256
Channel Spacing	200 GHz	100-50 GHz	50-25 GHz	25 GHz
Overall Capacity	20 Gb/s	1 Tb/s	5 Tb/s	10 Tb/s

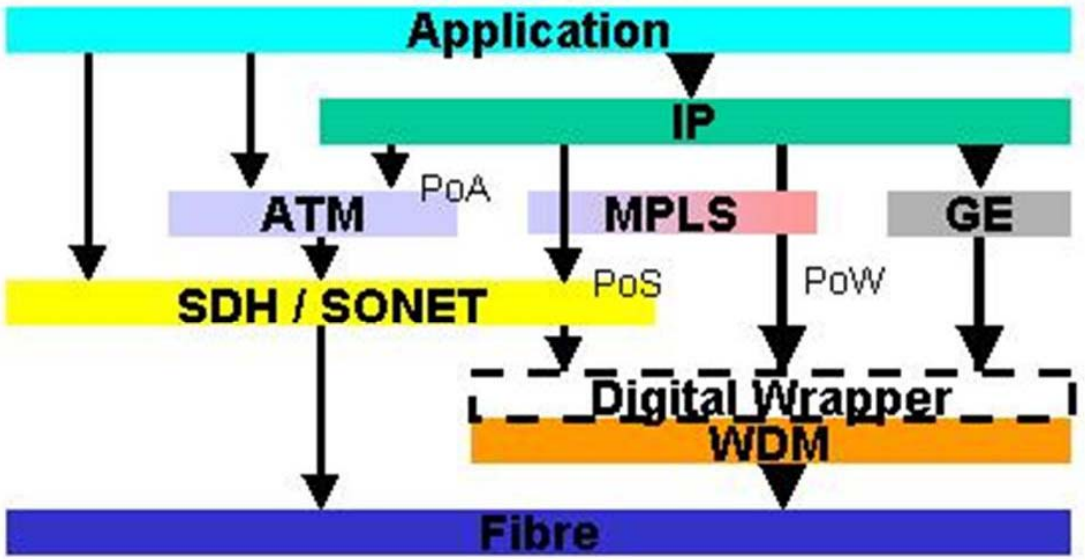
Key technologies

1. **Low-loss optical components** (including transmission fiber, dispersion-compensating devices, and optical switching/routing elements) to minimize the need for optical amplification and reduce the associated amplification noise.
2. **Low-noise optical amplifiers** (such as distributed Raman amplifiers) to lower the noise accumulated along transmission lines.
3. **Advanced optical fibers** to reduce **linear signal distortions** and enable higher speed transmissions.
4. **Advanced optical fibers** to reduce **nonlinear signal distortions** and enable higher signal launch powers.
5. **Broadband optical amplifiers** to increase the available transmission bandwidth.
6. **Advanced modulation formats** are used to trade off noise resilience, fiber propagation characteristics, and resilience to narrowband optical filtering due to multiple passes through OADMs. Reduced channel spacing.
7. **Optical / Electronic distortion compensation** to increase the resilience to Chromatic Dispersion, Polarization Mode Dispersion or fiber nonlinearities.
8. **Error correction codes** as FEC allow for operation at poorer channel bit error ratio (BER), which relaxes the requirements on the OSNR at the receiver.

METROPOLITAN NETWORKS

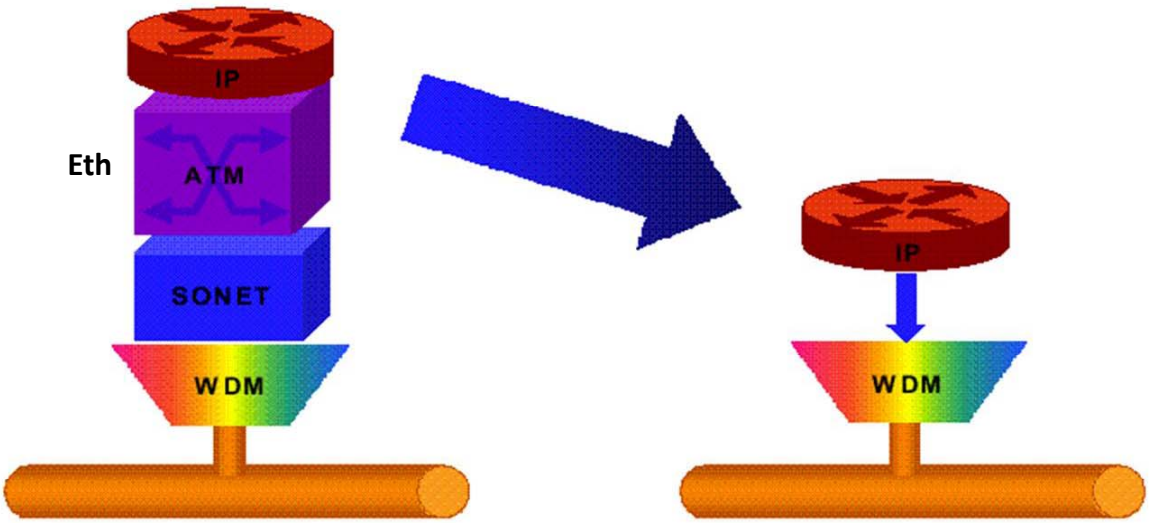


Protocol layering

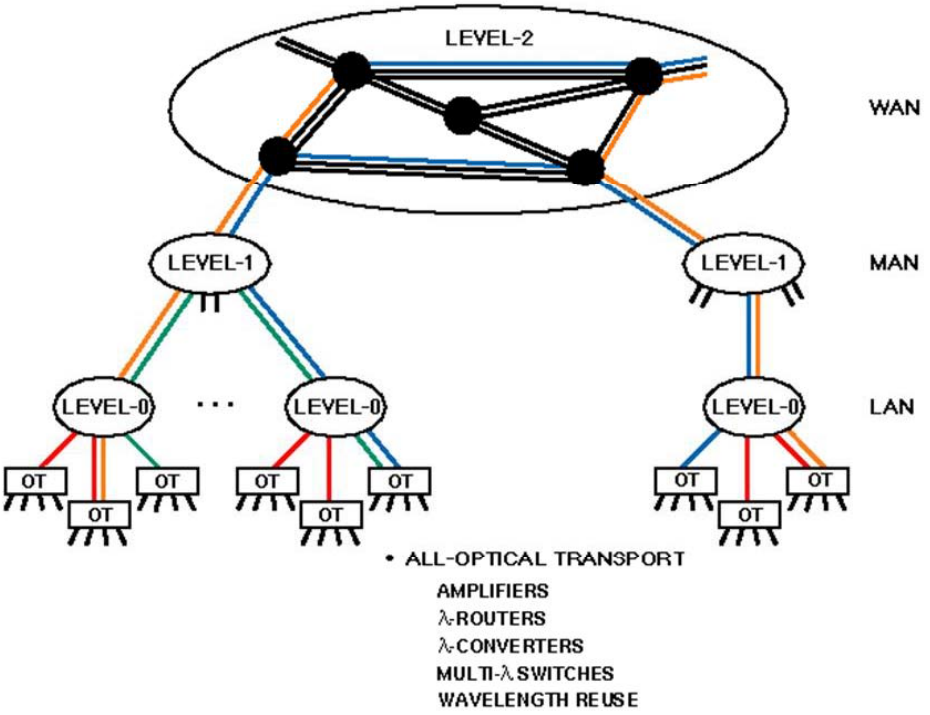


PoA - Packet over ATM PoW - Packet over WDM
GE - Gigabit Ethernet PoS - Packet over SDH

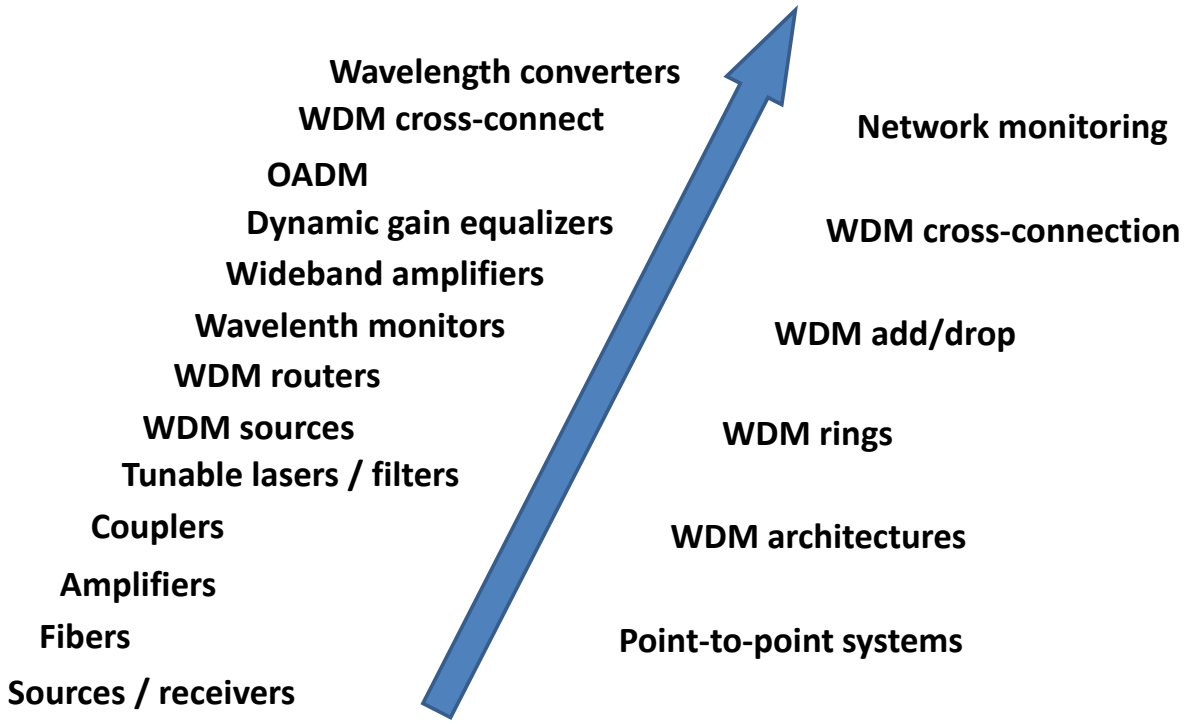
IPoWDM



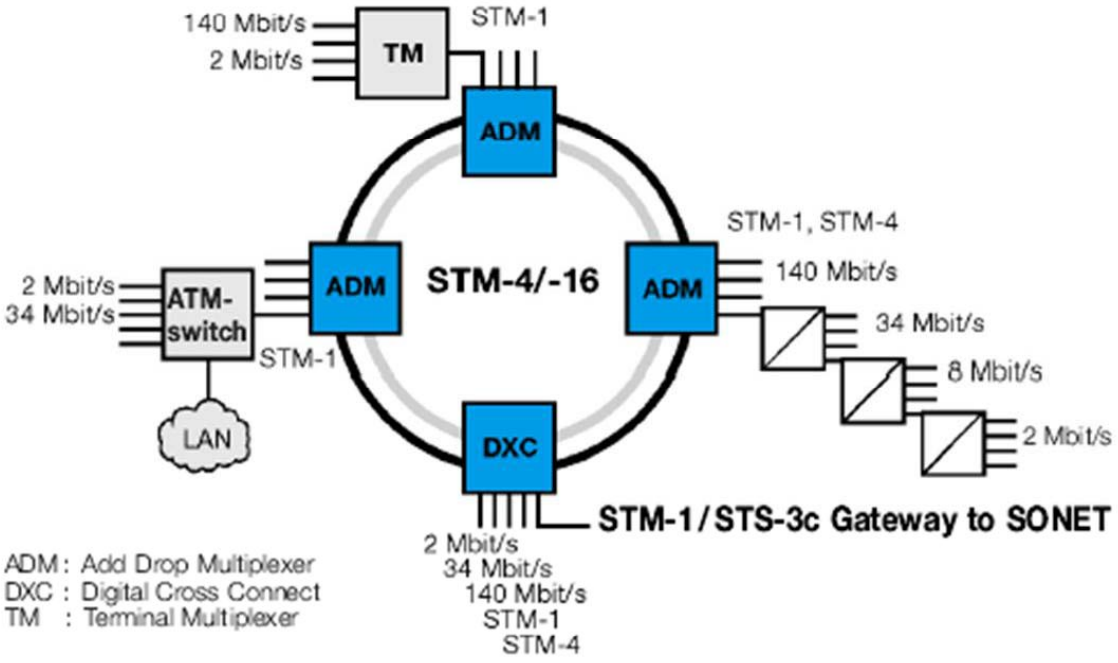
WDM ALL-OPTICAL NETWORK CONCEPT



KEY DEVICES vs. TECHNOLOGY



SONET / SDH



Long-Haul Networks Technology

SONET / SDH

SONET Optical Carrier Level	SONET Frame Format	SDH level and Frame Format	Payload Rate (kbit/s)	Line Rate (kbit/s)
OC-1	STS-1	STM-0	48,960	51,840
OC-3	STS-3	STM-1	150,336	155,520
OC-12	STS-12	STM-4	601,344	622,080
OC-24	STS-24	STM-8	1,202,688	1,244,160
OC-48	STS-48	STM-16	2,405,376	2,488,320
OC-96	STS-96	STM-32	4,810,752	4,976,640
OC-192	STS-192	STM-64	9,621,504	9,953,280
OC-768	STS-768	STM-256	38,486,016	39,813,120
OC-1536	STS-1536	STM-512	76,972,032	79,626,120
OC-3072	STS-3072	STM-1024	153,944,064	159,252,240

10G
40G

Point-to-point links
Electronic Routing
Circuit-Oriented

→ IP/GMPLS – OCS networks → OBS, OPS networks

ITU-T main recommendations

- ITU-T Recommendation **G.652** (2005), *Characteristics of a single-mode optical fibre and cable.*
- ITU-T Recommendation **G.653** (2006), *Characteristics of a dispersion-shifted single-mode optical fibre and cable.*
- ITU-T Recommendation **G.654** (2006), *Characteristics of a cut-off shifted single-mode optical fibre and cable.*
- ITU-T Recommendation **G.655** (2006), *Characteristics of a non-zero dispersion-shifted single-mode optical fibre and cable.*
- ITU-T Recommendation **G.662** (2005), *Generic characteristics of optical amplifier devices and subsystems.*
- ITU-T Recommendation **G.663** (2000), *Application related aspects of optical amplifier devices and subsystems.*
- ITU-T Recommendation **G.671** (2005), *Transmission characteristics of optical components and subsystems.*
- ITU-T Recommendation **G.691** (2006), *Optical interfaces for single channel STM-64 and other SDH systems with optical amplifiers.*
- ITU-T Recommendation **G.692** (1998), *Optical interfaces for multichannel systems with optical amplifiers.*
- ITU-T Recommendation **G.693** (2005), *Optical interfaces for intra-office systems.*
- ITU-T Recommendation **G.694.1** (2002), *Spectral grids for WDM applications: DWDM frequency grid.*
- ITU-T Recommendation G.707/Y.1322 (2007), *Network node interface for the synchronous digital hierarchy (SDH).*
- ITU-T Recommendation **G.709/Y.1331** (2003), *Interfaces for the Optical Transport Network (OTN).*
- ITU-T Recommendation **G.803** (2000), *Architecture of transport networks based on the synchronous digital hierarchy (SDH).*
- ITU-T Recommendation **G.872** (2001), *Architecture of optical transport networks.*
- ITU-T Recommendation **G.957** (2006), *Optical interfaces for equipments and systems relating to the synchronous digital hierarchy.*
- ITU-T Recommendation **G.959.1** (2006), *Optical transport network physical layer interfaces.*

Metro / Access Networks: Ethernet IEEE

Fast ethernet

100BASE-T -- A term for any of the three standard for 100Mbps ethernet over twisted pair cable. Includes 100BASE-TX, 100BASE-T4 and 100BASE-T2.
100BASE-TX -- also uses two pair, but requires cat-5 cable. Similar star-shaped configuration to 10BASE-T. 100Mbps.
100BASE-T4 -- 100Mbps ethernet over Category 3 cabling (as used for 10BASE-T installations). Uses all four pairs in the cable. Now obsolete, as Category 5 cabling is the norm. Limited to half-duplex.
100BASE-T2 -- No products exist. 100Mbps ethernet over Category 3 cabling. Supports full-duplex, and uses only two pairs. It is functionally equivalent to 100BASE-TX, but supports old cable.
100BASE-FX -- 100Mbps ethernet over fibre.

Gigabit ethernet

1000BASE-T -- 1Gbps over cat-5 copper cabling.
1000BASE-SX -- 1Gbps over fiber.
1000BASE-LX -- 1Gbps over fiber. Optimized for longer distances over single-mode fiber.
1000BASE-CX -- A short-haul solution (up to 25m) for running 1Gbps ethernet over special copper cable. Predates 1000BASE-T, and now obsolete.

10 gigabit ethernet

The new 10 gigabit ethernet standard encompasses seven different media types for LAN, MAN and WAN. It is currently specified by a supplementary standard, IEEE 802.3ae, and will be incorporated into a future revision of the IEEE 802.3 standard.
10GBASE-SR -- designed to support short distances over deployed multi-mode fiber cabling, it has a range of between 26m and 82m depending on cable type. It also supports 300m operation over a new 2000MHz.km multi-mode fiber.
10GBASE-LX4 -- uses wavelength division multiplexing to support ranges of between 240m and 300m over deployed multi-mode cabling. Also supports 10km over single-mode fiber.
10GBASE-LR and 10GBASE-ER -- these standards support 10km and 40km respecively over single-mode fiber.
10GBASE-SW, 10GBASE-LW and 10GBASE-EW. These varieties use the WAN PHY, designed to interoperate with OC-192 / STM-64 SONET/SDH equipment. They correspond at the physical layer to 10GBASE-SR, 10GBASE-LR and 10GBASE-ER respecively, and hence use the same types of fiber and support the same distances. (There is no WAN PHY standard corresponding to 10GBASE-LX4.)
10 gibabit ethernet is very new, and it remains to be seen which of the standards will gain commercial acceptance.

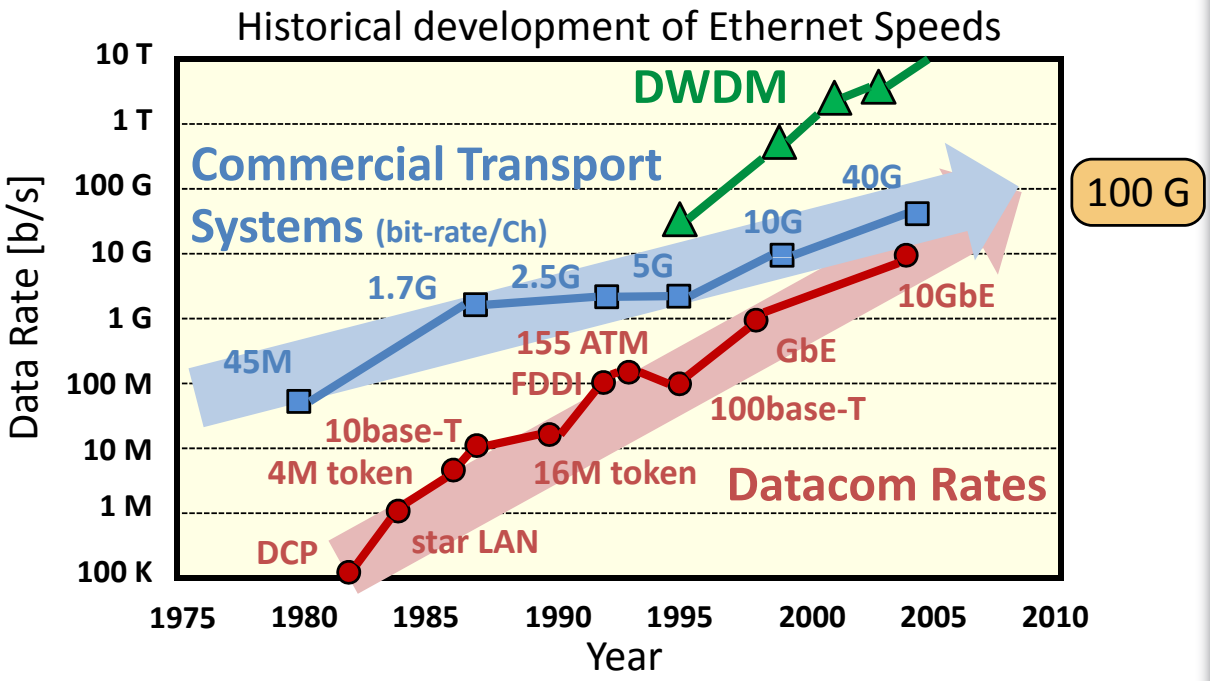
100 G Ethernet

100 Gigabit Ethernet or **100GbE** is an Ethernet standard presently under early development by the IEEE. The fastest existing standard is 10 gigabit Ethernet. In late November 2006, an IEEE study group agreed to target 100 Gbit/s Ethernet as the next version of the technology.
The IEEE 802.3 Higher Speed Study Group (HSSG) has adopted several objectives which direct their current work. These include 100GbE optical fiber Ethernet standards of both at least 100 meters (330 feet) and at least 10 kilometers (6 miles), full-duplex operation only, and using current frame format and size standards.
In July 2007, the study group presented a Project Authorization Request (PAR) to the 802 Standards Executive Committee for a new IEEE 802.3ba standard which includes both 40 GBit/s and 100 GBit/s data rates. The lower speed will run over a variety of media. The higher speed will require single-mode fiber but will allow distances of up to 40 km (25 mi).
The HSSG study group on November 16 2006 specifically adopted as objectives:

- Support a speed of 100 Gbit/s at the MAC/PLS interface
- Support at least 10 m on copper
- Support at least 100 m on OM3 multi-mode optical fiber
- Support at least 10 km on single-mode optical fiber (SMF)
- Support at least 40 km on SMF
- Support full-duplex operation only
- Preserve the 802.3 / Ethernet frame format at the MAC Client service interface
- Preserve minimum and maximum FrameSize of current 802.3 Std
- Support a bit error ratio better than or equal to 10^{-12} at the MAC/PLS service interface

On December 5 2007, the IEEE formally established IEEE 802.3ba as the designation for a 100-Gbps and 40-Gbps Ethernet communications standard.

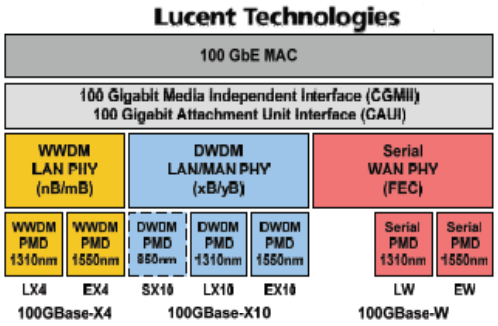
100 G Ethernet



100G Ethernet Transport options

Number of wavelengths	Bit rate per wavelength
10	10 Gb/s
4	25 Gb/s
2 ½ [1]	40 Gb/s
1	100 Gb/s

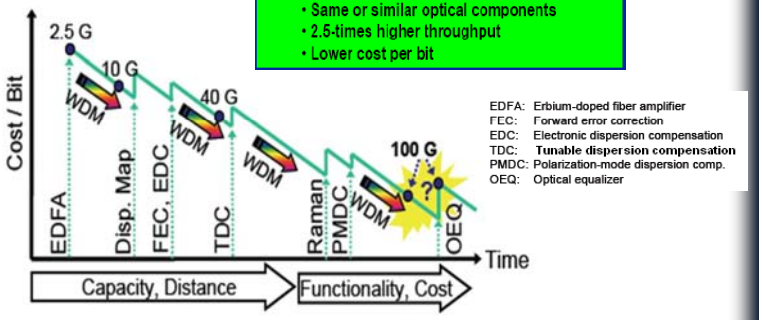
[1] Using techniques like Virtual concatenation (VCAT)



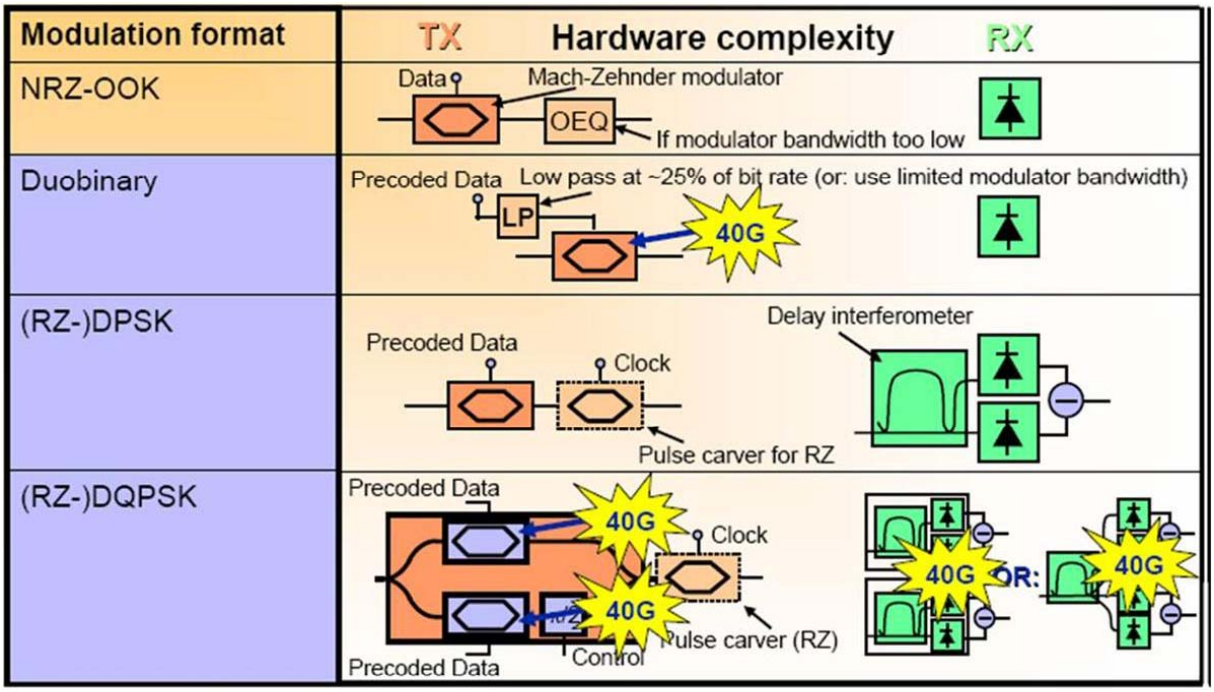
Choice depends on:

- Cost per bit
- Wavelength management and networking aspects
- 100G <u>parallel</u> for LAN + MAN
  - 4 x 25G for LAN
  - 10 x 10G for MAN
- 100G <u>serial</u> for WAN

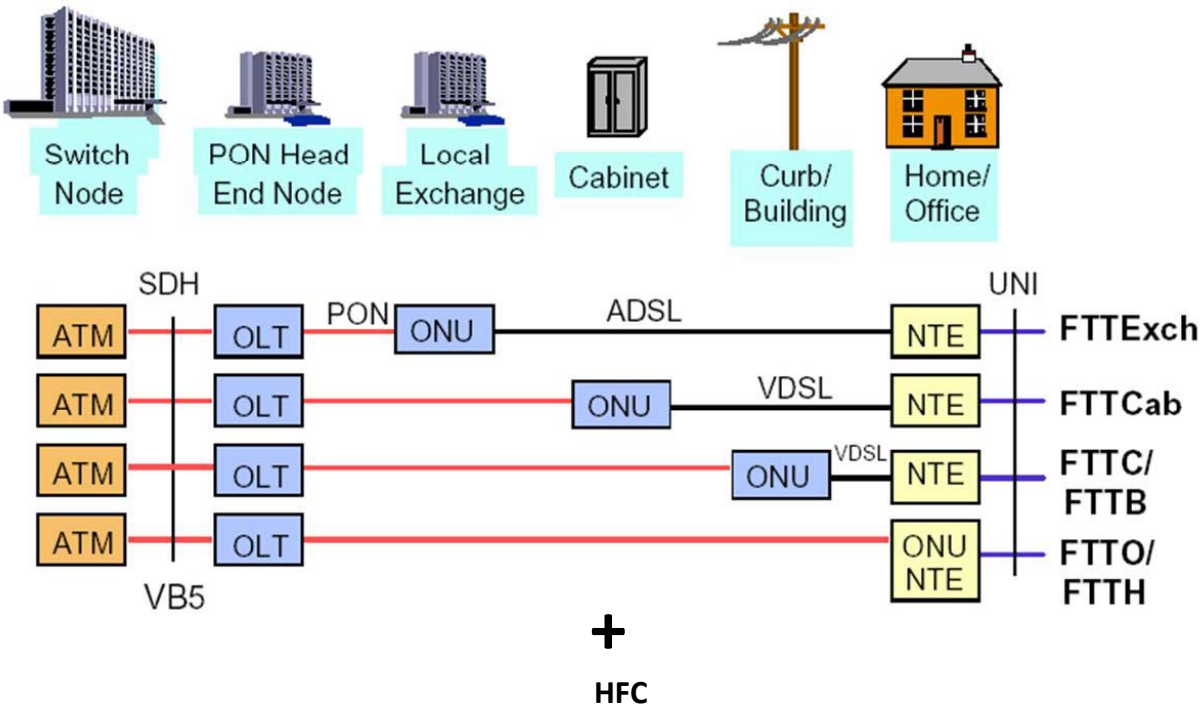
100G serial transport for the WAN could be more cost-effective than 40G
- Same or similar optical components
- 2.5-times higher throughput
- Lower cost per bit



100G Ethernet Will Require More ComplexTx/Rx Designs



ACCESS NETWORKS

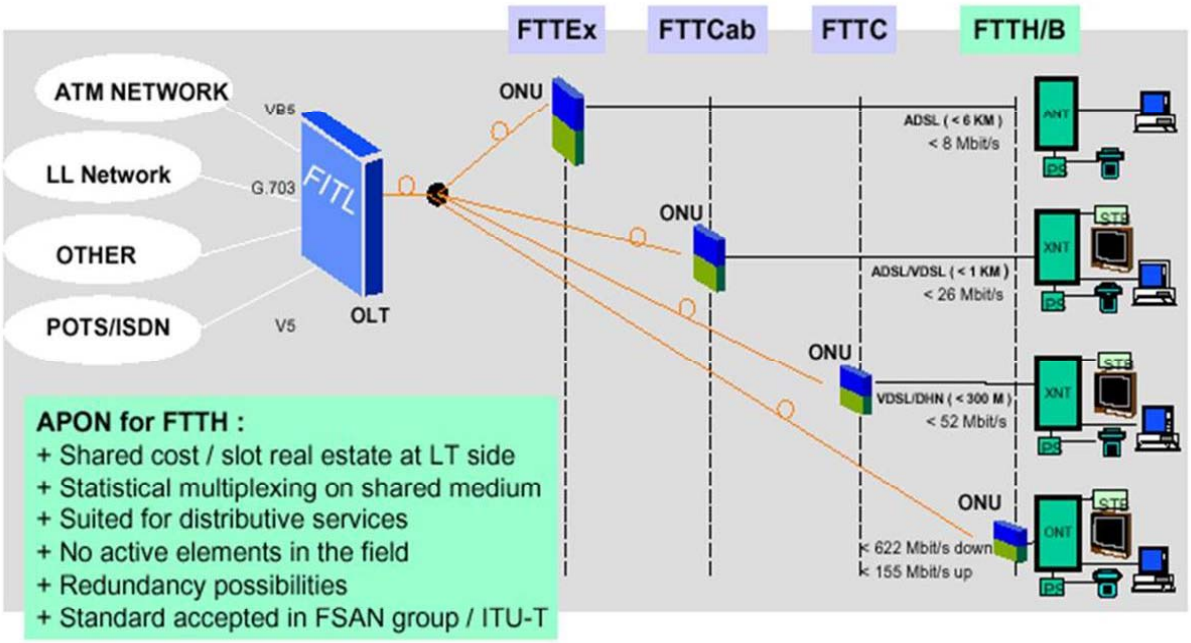


Residential Service Requirements

Application	Downstream	Upstream
HDTV (3 per home at 20 Mb/s) standard TV → 4.5 Mb/s	60 Mb/s	< 1 Mb/s
Online Gaming	2-20 Mb/s	2-20 Mb/s
VoIP Telephone (3 per home at 100 Kb/s)	0.3 Mb/s	0.3 Mb/s
Data / email ...	10 Mb/s	10 Mb/s
DVD rental (download time < 10 minutes)	14 Mb/s	< 1 Mb/s
TOTAL	**~ 100 Mb/s**	**~ 30 Mb/s**

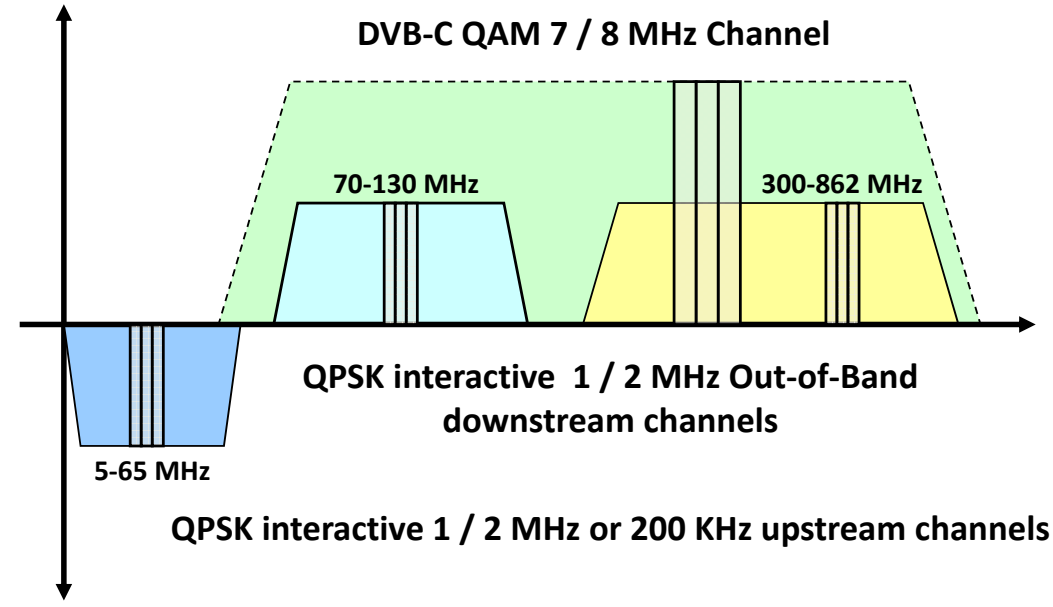
Fiber-to-the Home (FTTH)

FTTx



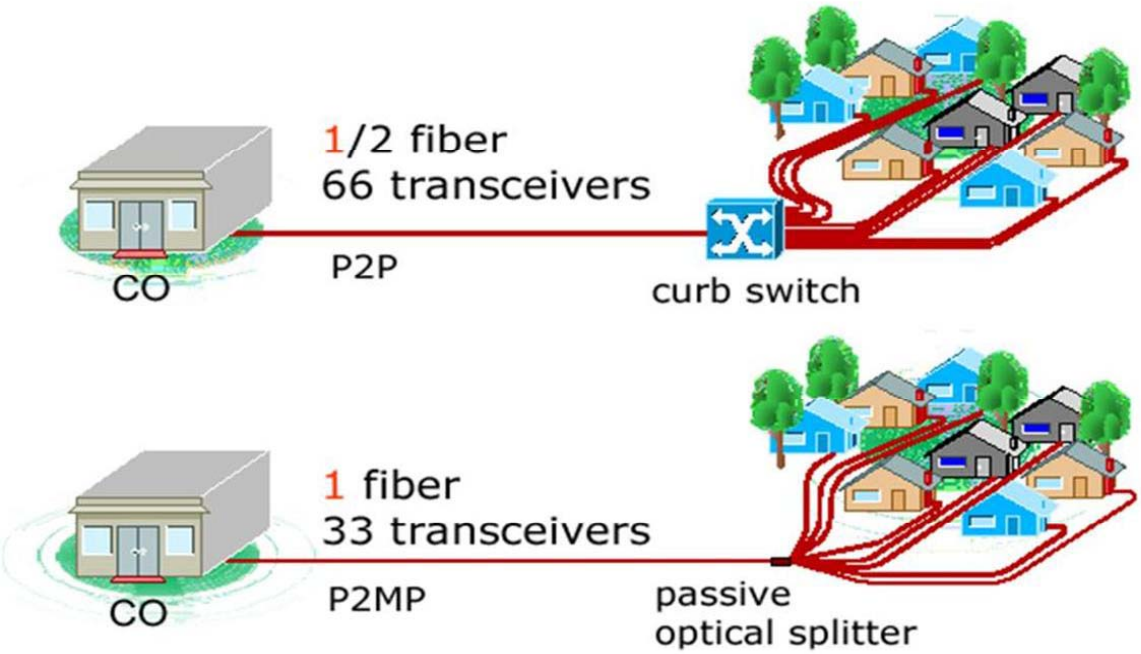
HFC

Downstream

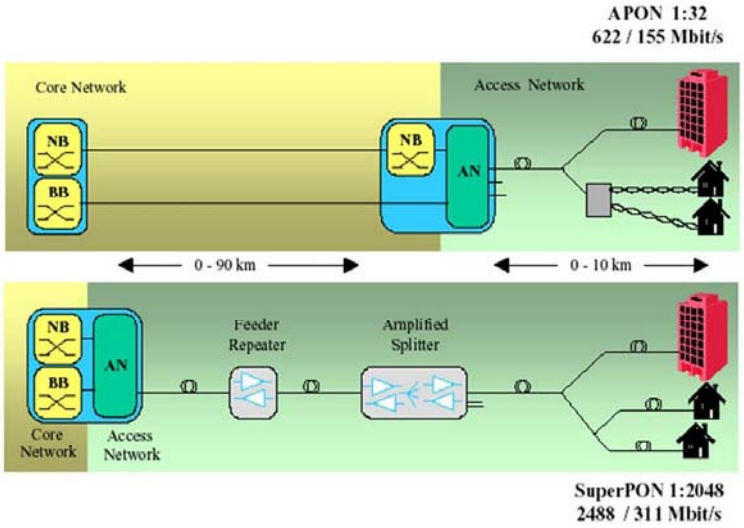


Upstream

Passive Optical Network (PON)



ATM Passive Optical Network (APON)



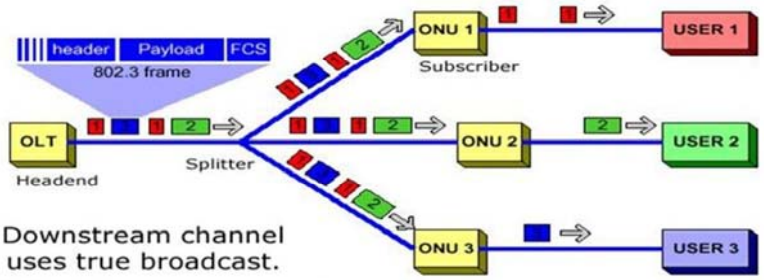
– ITU-T Recommendation **G.982** (1996), *Optical access networks to support services up to the ISDN primary rate or equivalent bit rates.*
– ITU-T Recommendation **G.983.1** (2005), *Broadband optical access systems based on Passive Optical Networks (PON).*
– ITU-T Recommendation **G.984.1** (2003), *Gigabit-capable Passive Optical Network (G-PON): General characteristics.*

Ethernet Passive Optical Network (EPON)

IEEE std.802.3z
Gigabit Ethernet

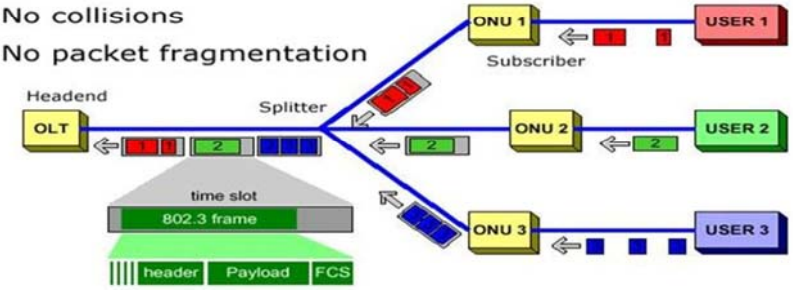
IEEE std.802.3ae
10Gigabit Ethernet

IEEE std.802.3ah
Ethernet PON

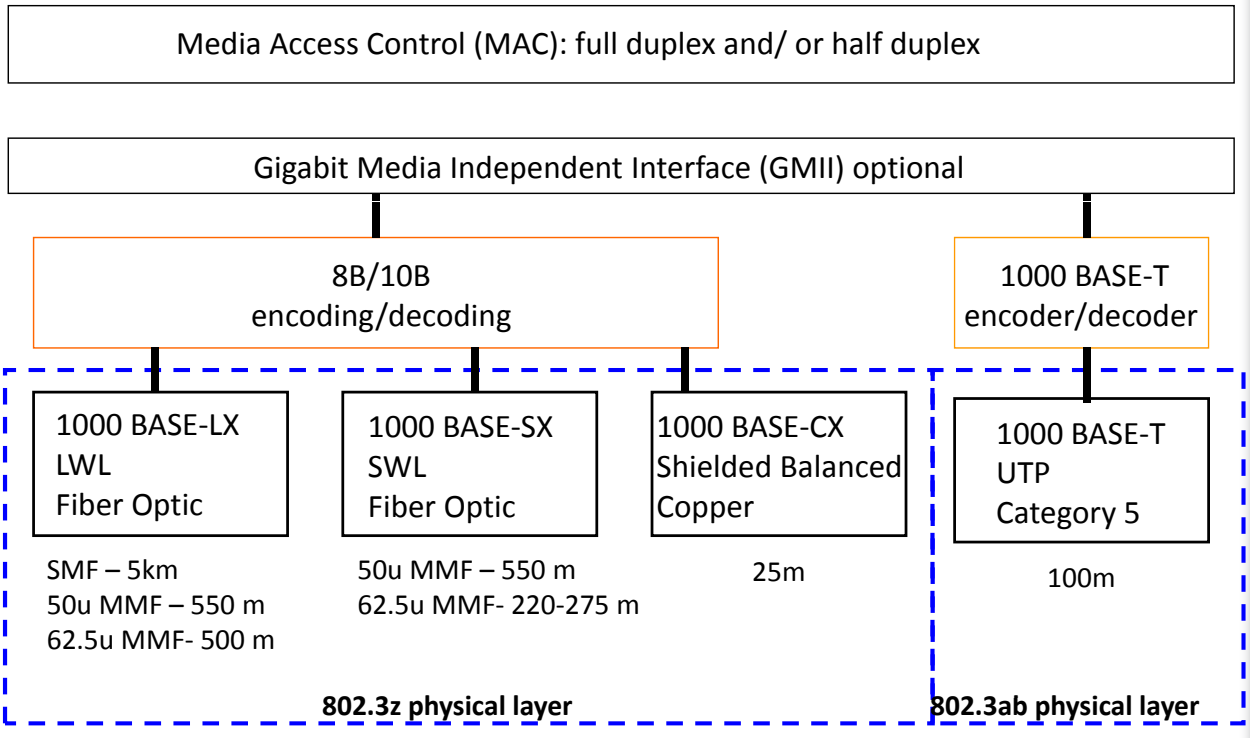


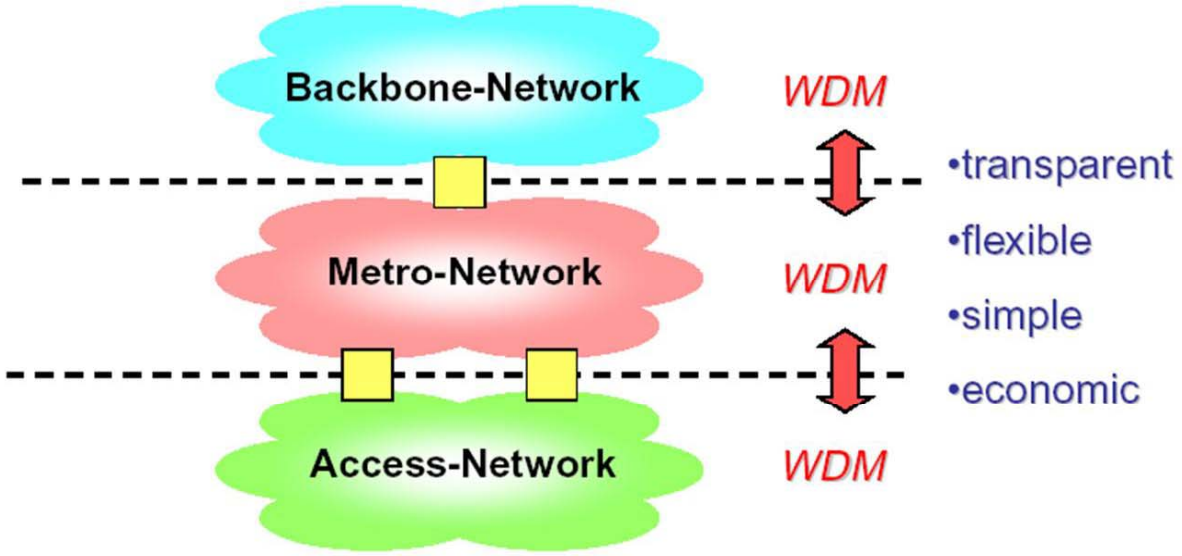
- Downstream channel uses true broadcast.
- 802.3 Frames extracted by MAC addresses.

- Upstream time slicing
- No collisions
- No packet fragmentation

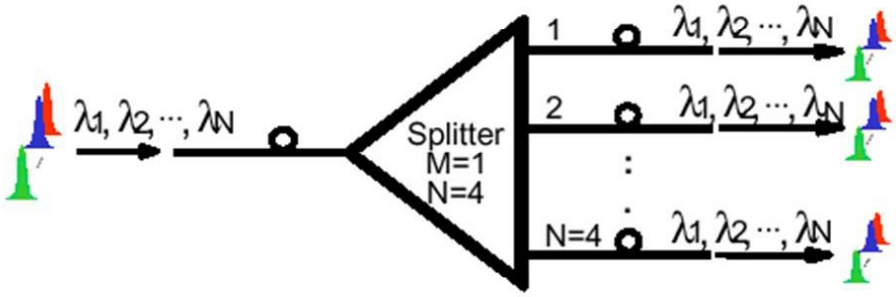


"Ethernet Upper Layers"





Broadcast & Select Networks based on:



Wavelength routing Networks based on: