Optical Networking: Recent Developments, Issues, and Trends

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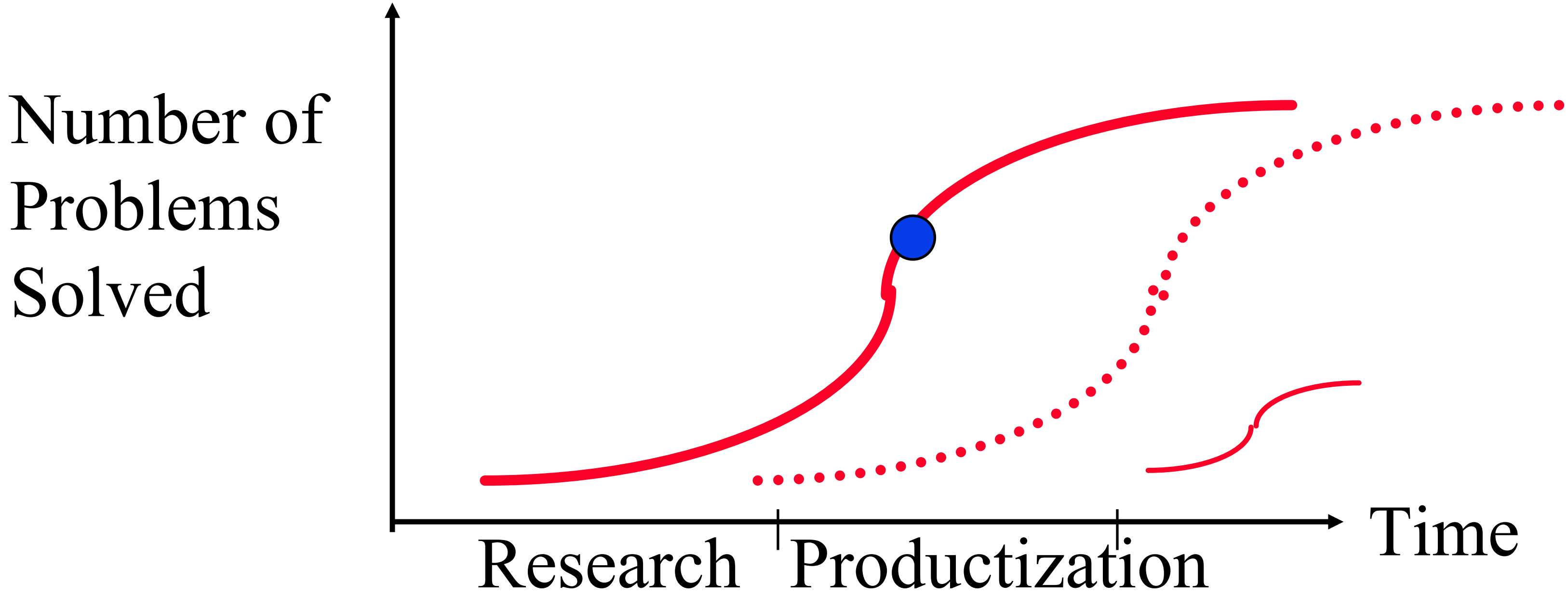
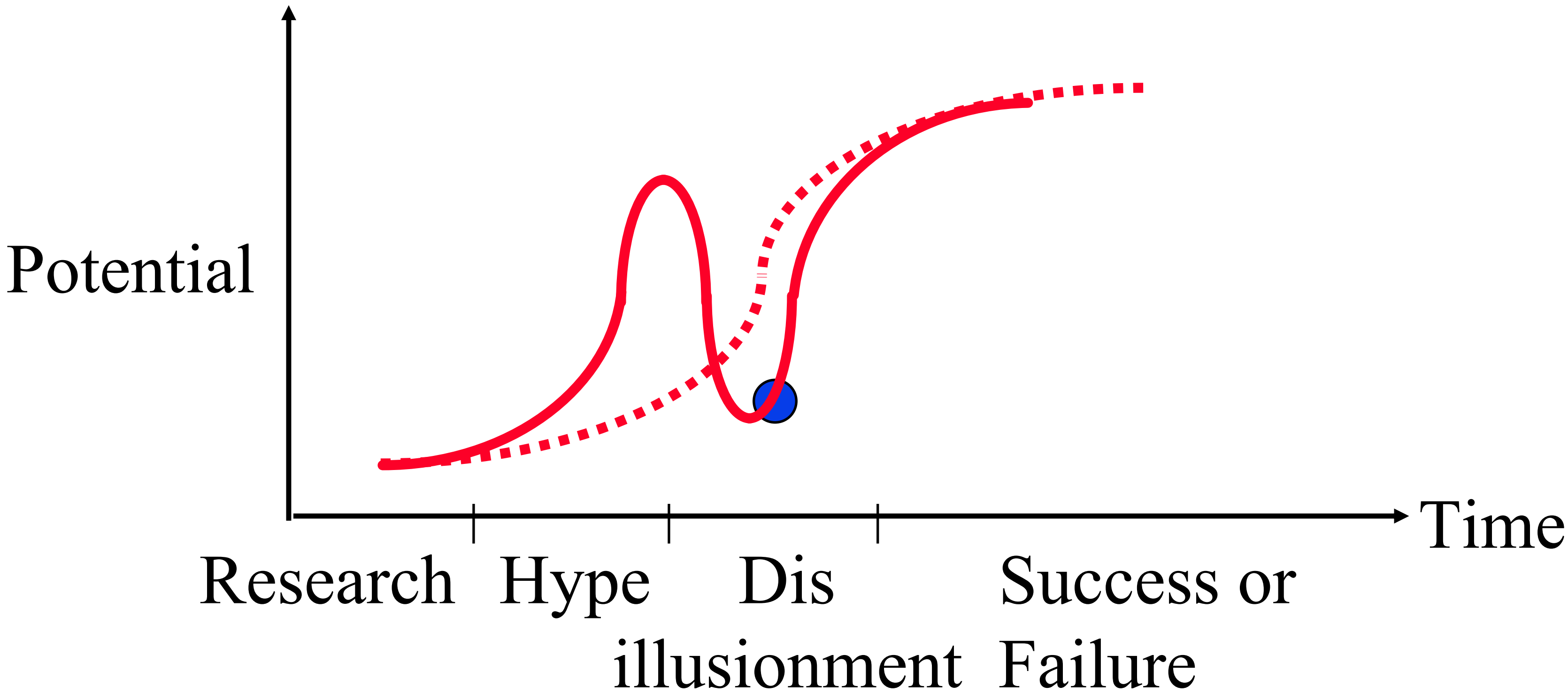
1. Trends in Networking
2. Core Network Issues: DWDM, OEO VS OOO
3. Metro Network Issues:
   Next Gen SONET vs Ethernet with RPR
4. Access Networks Issues: Passive optical networks
5. IP Control Plane: MPLS, GMPLS

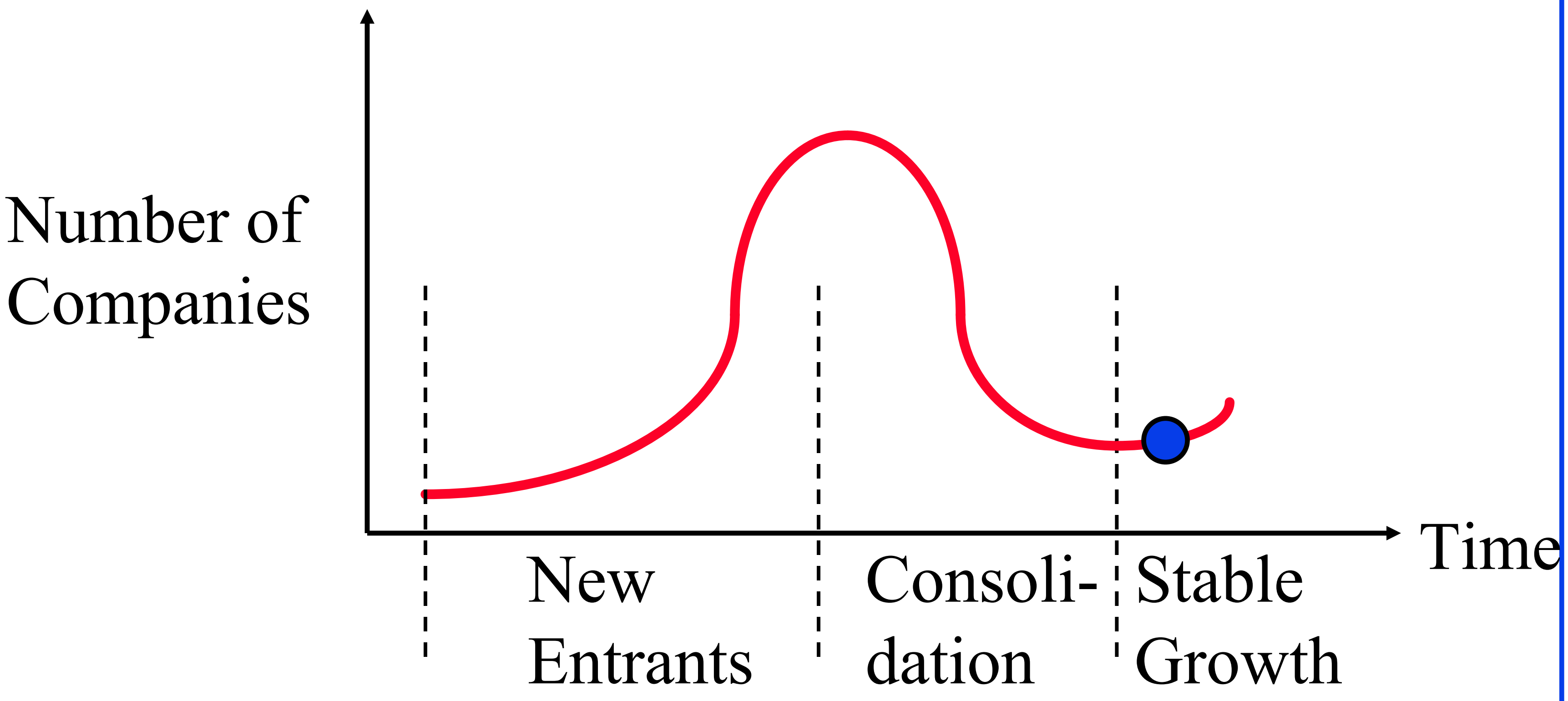
Life Cycles of Technologies



Hype Cycles of Technologies



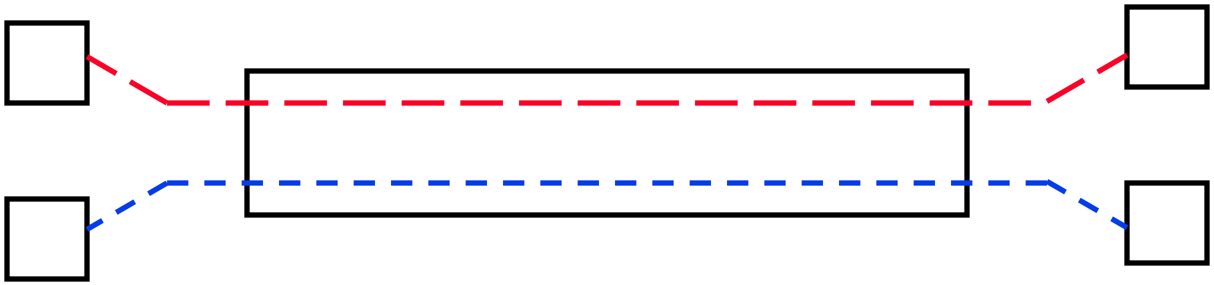
Industry Growth



Trend: Back to ILECs

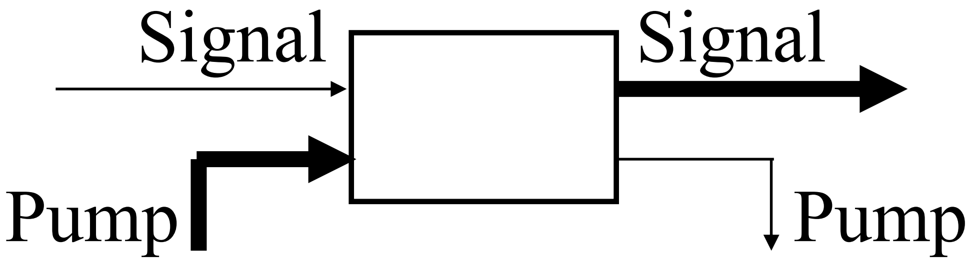
1. CLECs to ILECs
   ILEC: Slow, steady, predictable.
   CLEC: Aggressive, Need to build up fast
   New networks with newest technology
   No legacy issues
2. Back to Voice
   CLECs wanted to *start* with data
   ILECs want to *migrate* to data
   ⇒ Equipment that support voice circuits but allow packet based (hybrids) are more important than those that allow only packet based

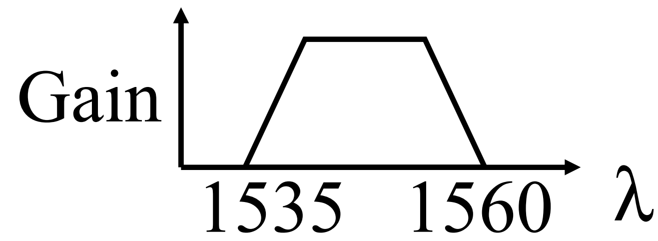
Sparse and Dense WDM



- 10Mbps Ethernet (10Base-F) uses 850 nm
- 100 Mbps Ethernet (100Base-FX) + FDDI use 1310 nm
- Some telecommunication lines use 1550 nm
- WDM: 850nm + 1310nm or 1310nm + 1550nm
- Dense ⇒ Closely spaced ≈ 0.1 - 2 nm separation
- Coarse = 2 to 25 nm = 4 to 12 λ's
- Wide = Different Wavebands

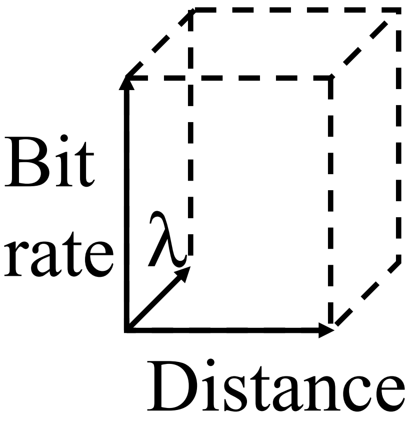
Optical Networking: Key Enabler





- 1980 AT&T installed Boston-Washington Fiber cable
- 1985 Poole at U of Southampton discovered EDFA
  Erbium-Doped Fiber Amplifiers (EDFAs)
- 1991 First commercial EDFA by Bell-Labs
- Up to 30 dB amplification
- Flat response in 1535-1560 nm
  Fiber loss is minimum in this region
  $\Rightarrow$ DWDM revolution

Recent DWDM Records

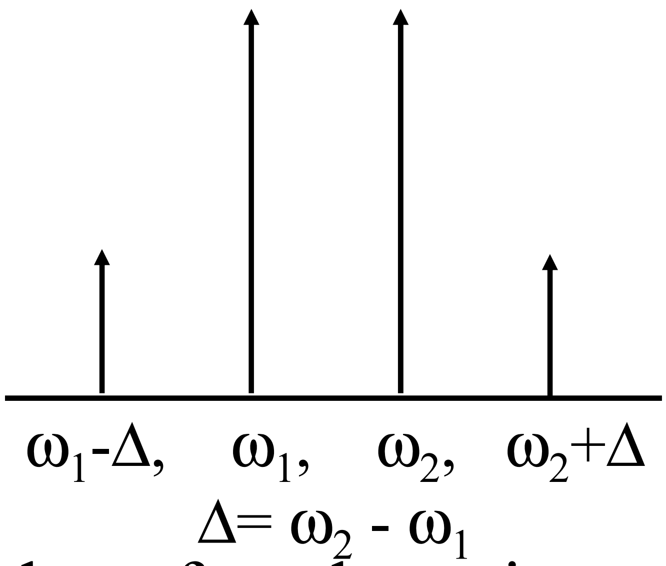


- 32λ× 5 Gbps to 9300 km (1998)
- 16λ× 10 Gbps to 6000 km (NTT'96)
- 160λ× 20 Gbps (NEC'00)
- 128λ× 40 Gbps to 300 km (Alcatel'00)
- 64λ× 40 Gbps to 4000 km (Lucent'02)
- 19λ× 160 Gbps (NTT'99)
- 7λ× 200 Gbps (NTT'97)
- 1λ×1200 Gbps to 70 km using TDM (NTT'00)
- 1022 Wavelengths on one fiber (Lucent'99)

Potential: 58 THz = 50 Tbps on 10,000 λ's

Ref: IEEE J. on Selected Topics in Quantum Electronics, 11/2000.

Four-Wave Mixing



- If two signals travel in the same phase for a long time, new signals are generated.

Core Optical Networks

- Higher Speed: 10 Gbps to 40 Gbps to 160 Gbps
- Longer Distances: 600 km to 6000 km
- More Wavelengths: 16 λ's to 160 λ's
- All-optical Switching: OOO vs OEO Switching

Optical Transport Products

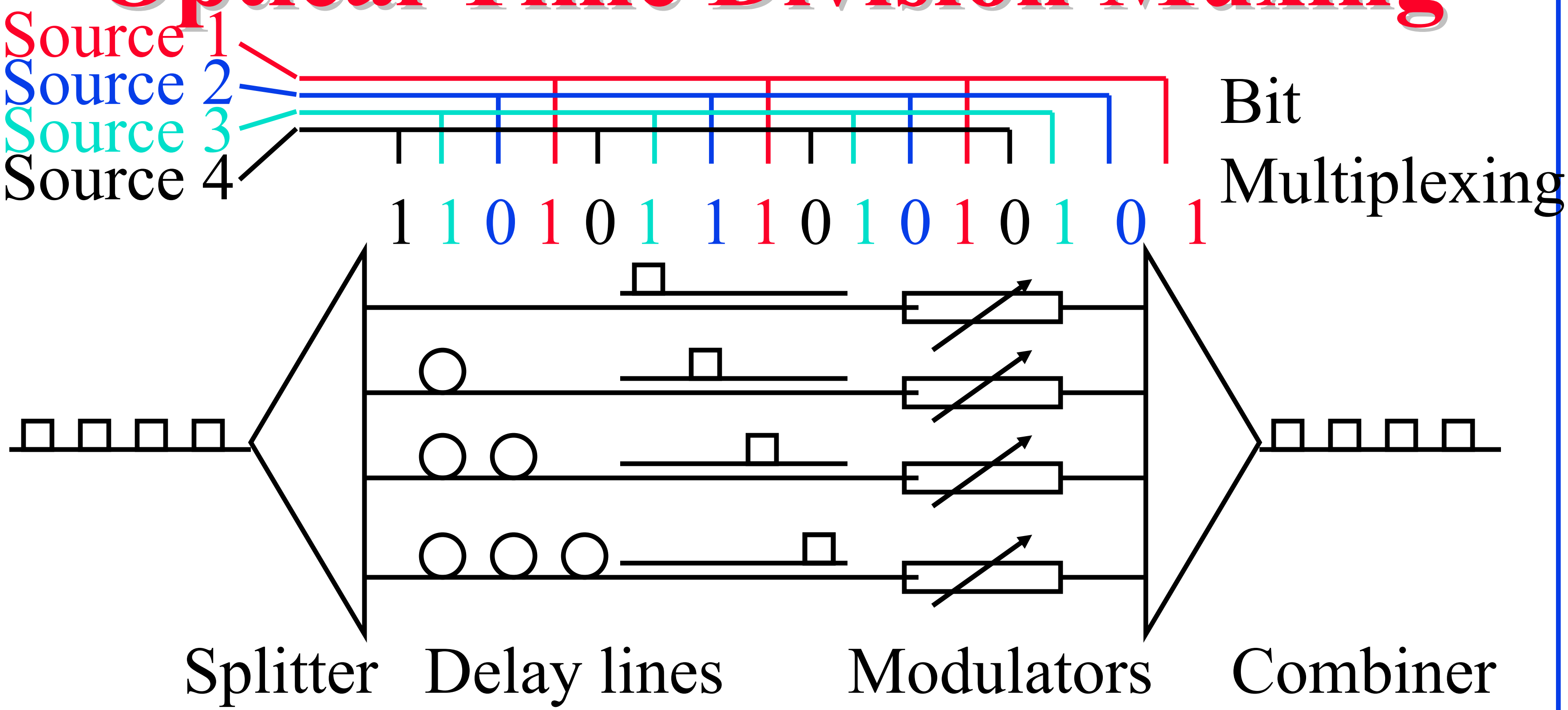
Product	λ's	Gb/s	km	Avail-ability
Siemens/Optisphere TransXpress √	80	40	250	2001
	160	10	250	2001
Alcatel 1640 OADM √	160	2.5	2300	2001
	80	10	330	2001
Corvis Optical Network Gateway √	160	2.5	3200	2000
	40	10	3200	2000
Ciena Multiwave CoreStream √	160	10	1600	2001
Nortel Optera LH4000 √	56	10	4000	2000
Optera LH 5000	104	40	1200	2002
Sycamore SN10000 X	160	10	800	2001
	40	10	4000	2001
Cisco ONS 15800 √	160	10	2000	2002

- Ref: "Ultra everything," Telephony, October 16, 2000
http://www.lightreading.com/document.asp?doc_id=19881

OEO vs OOO Switches

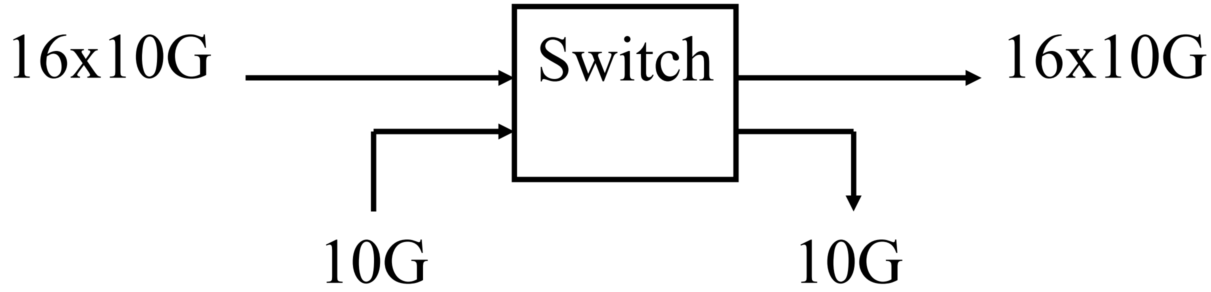
- OEO:
  - Requires knowing data rate and format, e.g., 10 Gbps SONET
  - Can multiplex lower rate signals
  - Cost/space/power increases linearly with data rate
- OOO:
  - Data rate and format independent
    ⇒ Data rate easily upgraded
  - Sub-wavelength mux/demux difficult
  - Cost/space/power relatively independent of rate
  - Can switch multiple ckts per port (waveband)
  - Issues: Wavelength conversion, monitoring

Optical Time Division Muxing



- 16 streams of 10 Gbps = 160 Gbps on one wavelength
- A laser produces short pulses.
  Pulse stream divided in to 16 substreams
  Each substream modulated by different source. Combined.

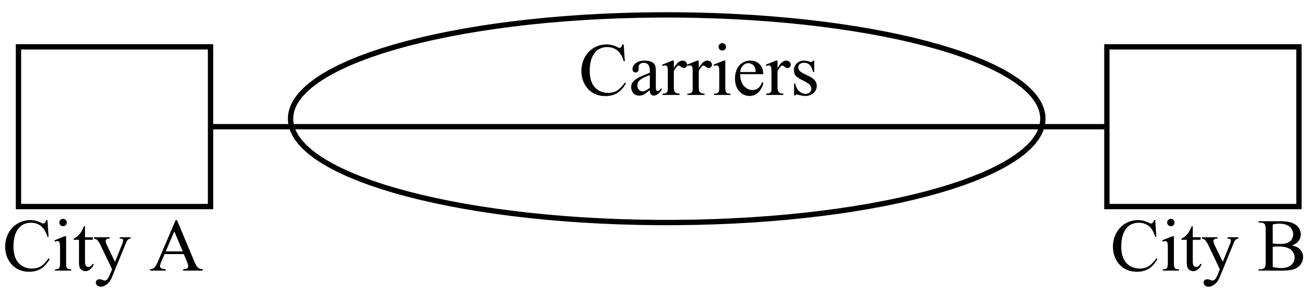
OTDM Switching



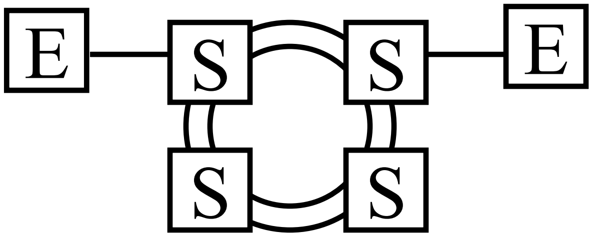
- A laser interacts with the stream every 16th bit
- Four-Wave Multiplexing (FWM) converts the bit to another wavelength
- The bit (wavelength) is filtered out
- Another bit is added in its place.
- Ref: **Siemens Claims 160-Gbit/s Milestone, Lightreading, November 28, 2003,** http://www.lightreading.com/document.asp?doc_id=44067

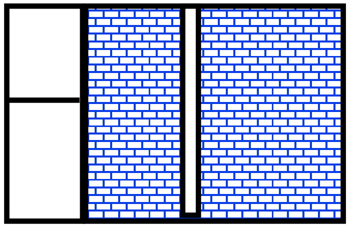
SONET

- Synchronous optical network
- Standard for digital optical transmission
- Developed originally by Bellcore to allow mid-span meet between carriers: MCI and AT&T. Standardized by ANSI and then by ITU
  $\Rightarrow$ Synchronous Digital Hierarchy (SDH)
- You can lease a SONET connection from carriers



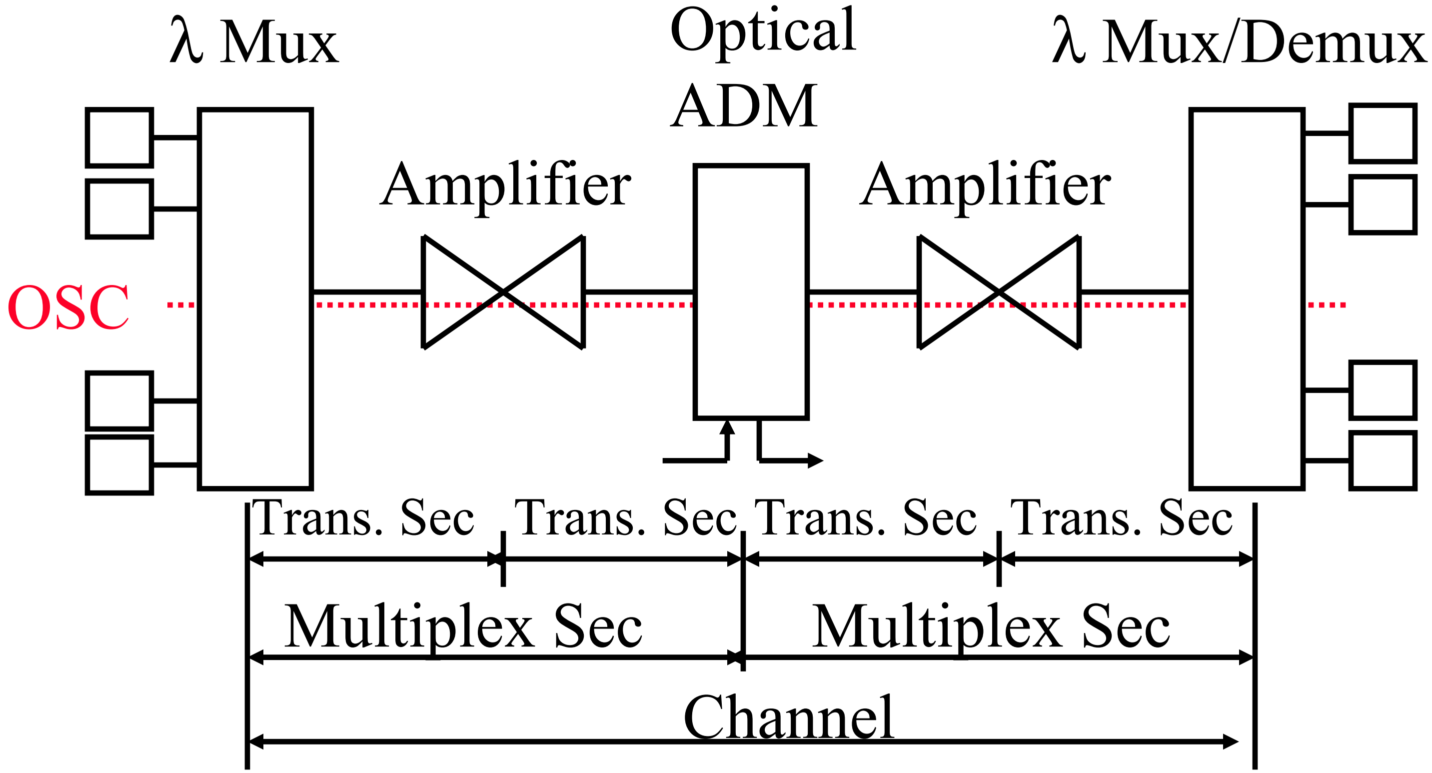
SONET Functions





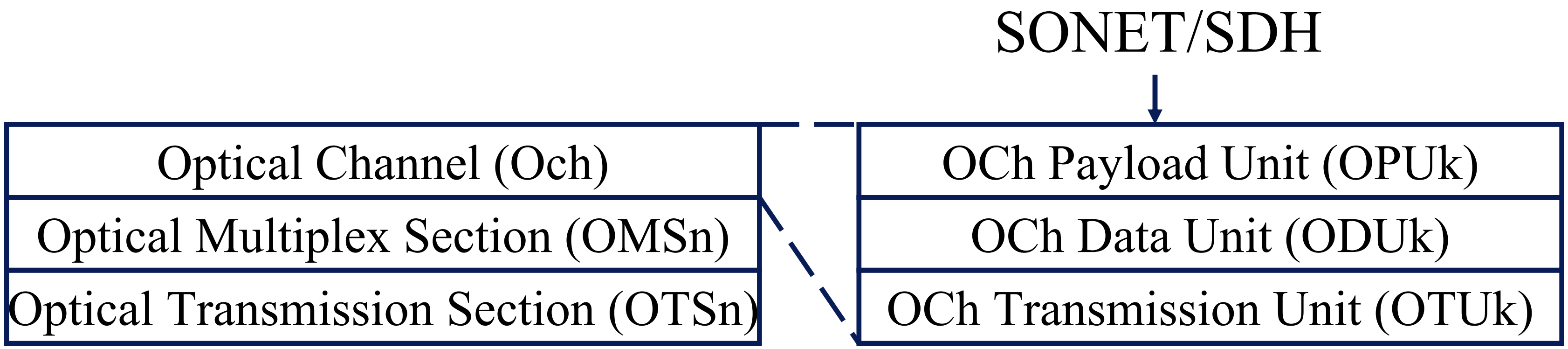
- Protection: Allows redundant Line or paths
- Fast Restoration: 50ms using rings
- Sophisticated OAM&P
- Ideal for Voice: No queues. Guaranteed delay
- Fixed Payload Rates: 51M, 155M, 622M, 2.4G, 9.5G
  Rates do not match data rates of 10M, 100M, 1G, 10G
- Static rates not suitable for bursty traffic
- One Payload per Stream
- High Cost

Optical Transport Network (OTN)



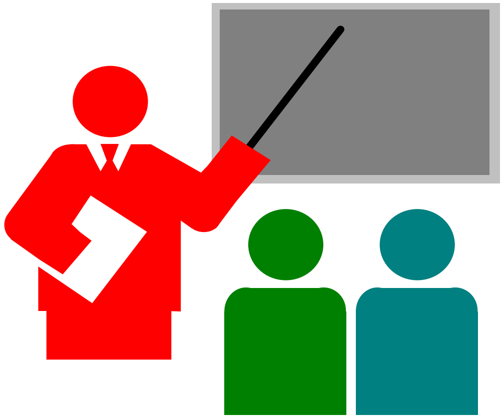
- G.709 Digital Wrapper designed for WDM networks
- OTN$n.k$ = n wavelengths at k^{th} rate, 2.5, 10, 40 Gbps plus one Optical Supervisory Channel (OSC)
- OTNnr.k = Reduced OTNn.k ⇒ Without OSC

OTN Layers and Frame Format



- **OTU1 Frame Format:** 4×4080 Octets/125 ms
  Forward Error Correction (FEC) increases distance by 2x to 4x.
  Frame Alignment (FA).

Summary



- DWDM systems use 1550 nm band due to EDFA
- O/O/O switches are bit rate and data format independent
- SONET/SDH have ring based protection
- OTN uses FEC digital wrapper and allows WDM

Metro Optical Networks

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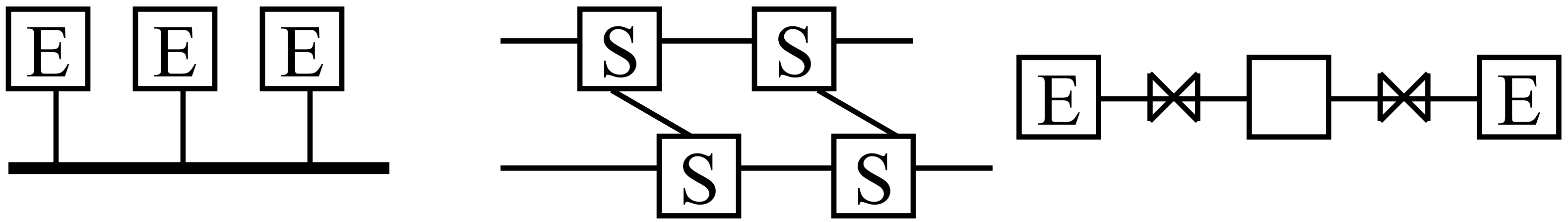
- Gigabit Ethernet
- 10 G Ethernet
- Resilient Packet Rings
- Next Generation SONET: VCAT, GFP, LCAS

LAN to WAN Convergence



- Past: Shared media in LANs. Point to point in WANs.
- Today: No media sharing in LANs
  - Datalink protocols limited to frame formats
  - No distance limitations due to MAC. Only Phy.
- 10 GbE over 40 km without repeaters
- Ethernet End-to-end.
- Ethernet carrier access service:$1000/mo 100Mbps

1 GbE: Key Design Decisions

- P802.3z ⇒ Update to 802.3
  Compatible with 802.3 frame format, services, management
- 1000 Mb vs. 800 Mb Vs 622 Mbps
  Single data rate
- **LAN** distances only
- No Full-duplex only ⇒ **Shared** Mode
  Allows both hub and switch based networks
  No one makes or uses GbE Hubs
- Same min and max frame size as 10/100 Mbps
  ⇒ Changes to **CSMA/CD** protocol
  Transmit longer if short packets

10 GbE: Key Design Decisions

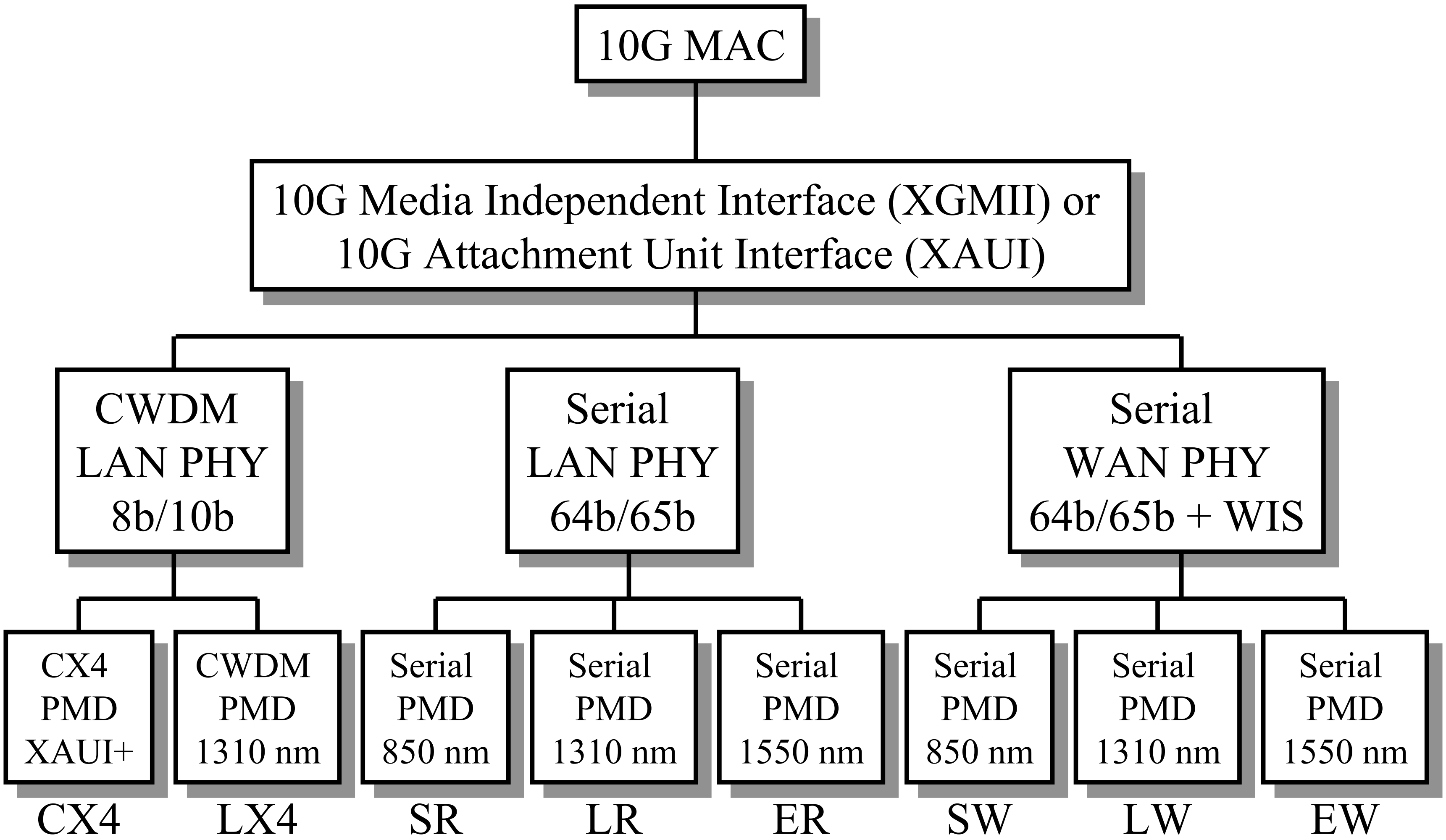
- P802.3ae ⇒ Update to 802.3
  Compatible with 802.3 frame format, services, management
- 10 Gbps vs. 9.5 Gbps. **Both** rates.
- LAN and **MAN** distances
- Full-duplex only ⇒ **No Shared** Mode
  Only switch based networks. No Hubs.
- Same min and max frame size as 10/100/1000 Mbps
  Point-to-point ⇒ **No CSMA/CD** protocol
- 10.000 Gbps at MAC interface
  ⇒ Flow Control between MAC and PHY
- Clock jitter: 20 or 100 ppm for 10GbE
  Incompatible with 4.6 ppm for SONET

10 GbE PMD Types

PMD	Description	MMF	SMF
10GBASE-R:			
10GBASE-SR	850nm Serial LAN	300 m	N/A
10GBASE-LR	1310nm Serial LAN	N/A	10 km
10GBASE-ER	1550nm Serial LAN	N/A	40 km
10GBASE-X:			
10GBASE-LX4	1310nm WWDM LAN	300 m	10 km
10GBASE-W:			
10GBASE-SW	850nm Serial WAN	300 m	N/A
10GBASE-LW	1310nm Serial WAN	N/A	10 km
10GBASE-EW	1550nm Serial WAN	N/A	40 km
10GBASE-LW4	1310nm WWDM WAN	300 m	10 km

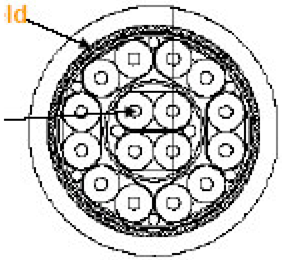
- S = Short Wave, L=Long Wave, E=Extra Long Wave
- R = Regular reach (64b/66b), W=WAN (64b/66b + SONET Encapsulation), X = 8b/10b ❑ 4 = 4 λ's

10GbE PHYs


10G MAC
10G Media Independent Interface (XGMII) or
10G Attachment Unit Interface (XAUI)
CWDM
LAN PHY
8b/10b
Serial
LAN PHY
64b/65b
Serial
WAN PHY
64b/65b + WIS
CX4
PMD
XAUI+
CWDM
PMD
1310 nm
Serial
PMD
850 nm
Serial
PMD
1310 nm
Serial
PMD
1550 nm
Serial
PMD
850 nm
Serial
PMD
1310 nm
Serial
PMD
1550 nm
CX4
LX4
SR
LR
ER
SW
LW
EW

10GBASE-CX4

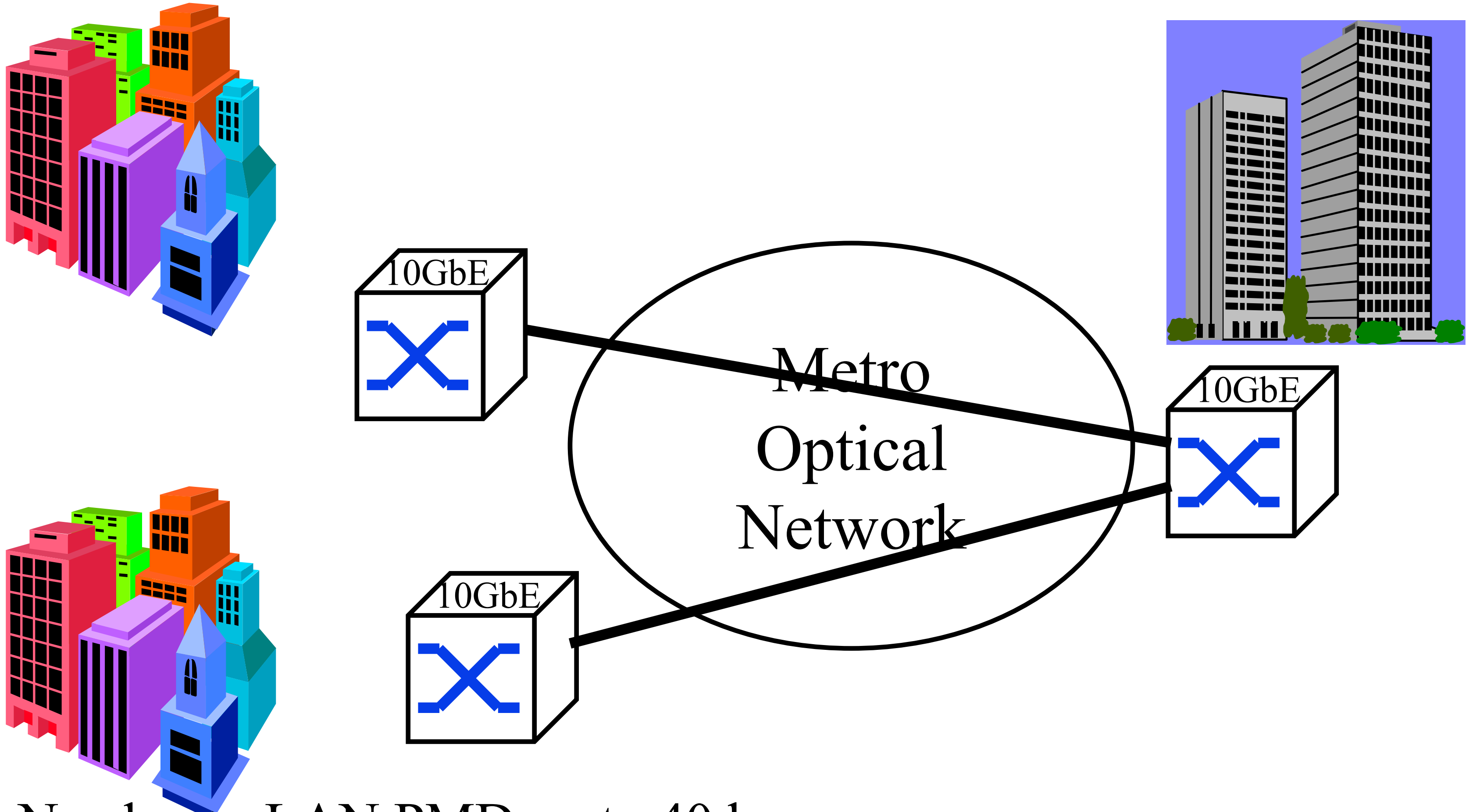
- Twinax cable with 8 pairs
- Based on Infiniband 4X copper phy. IB4X connectors.
- For data center applications (Not for horizontal wiring):
  - Switch-to-switch links
  - Switch-to-server links
  - External backplanes for stackables
- Standard: Start: Dec 2002 End: Dec 2003
- IEEE 802.3ak, http://www.ieee802.org/3/ak



10GBASE-T

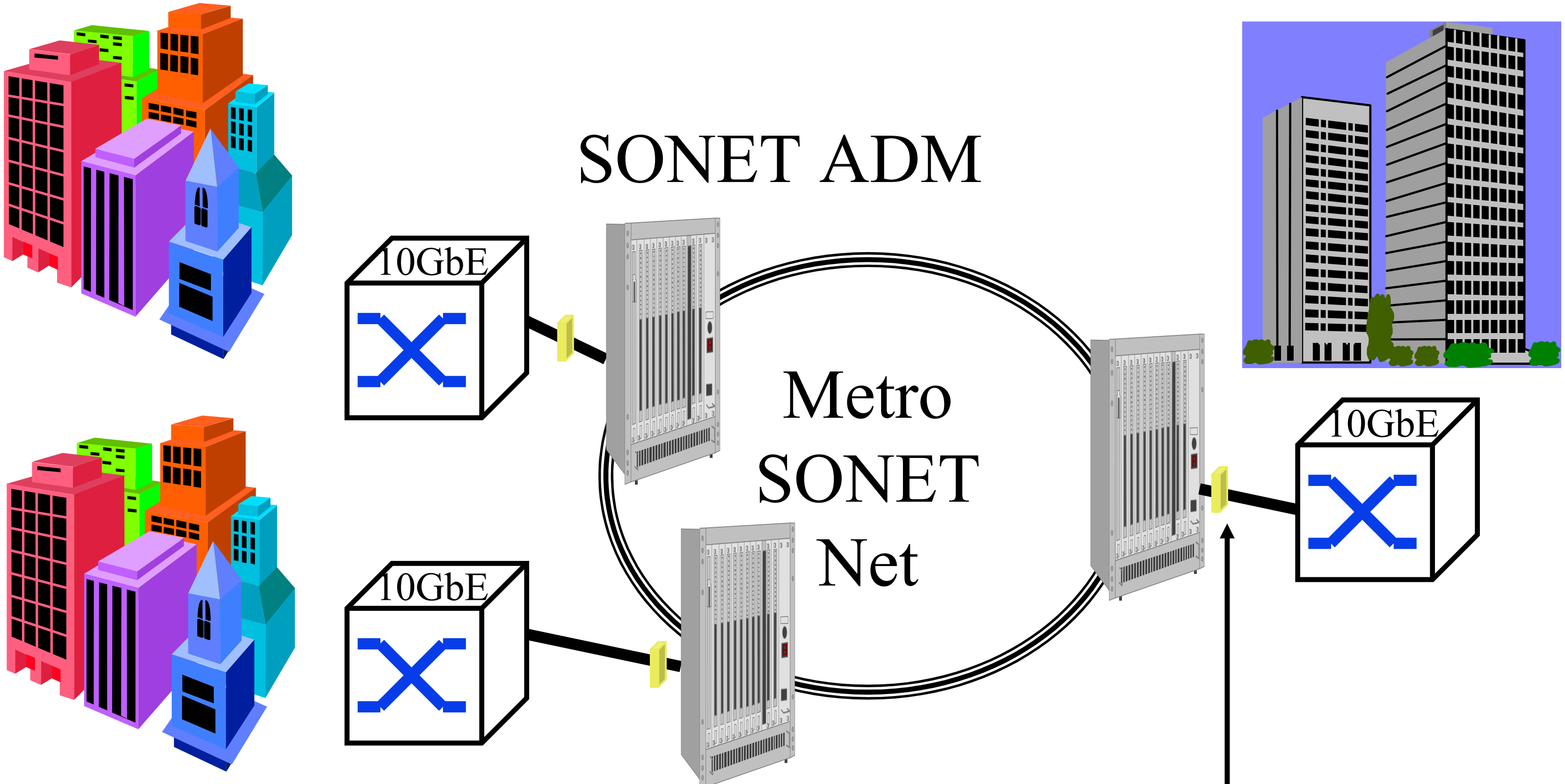
- New PHY for data center and horizontal wiring
- Compatible with existing 802.3ae MAC, XGMII, XAUI
- Standard: Start: Nov 2003 Finish: Jul 2006
- 100 m on Cat-7 and 55+ m on Cat-6
- Cost 0.6 of optical PHY. Greater reach than CX4
- 10-level coded PAM signaling with 3 bits/symbol
  833 MBaud/pair => 450 MHz bandwidth w FEXT cancellation
  (1GBASE-T uses 5-level PAM with 2 bits/symbol, 125 MBaud/pair, 80 MHz w/o FEXT)
- Full-duplex only. 1000BASE-T line code and FEC designed for half-duplex.
- http://www.ieee802.org/3/10GBT

10 GbE over Dark Fiber



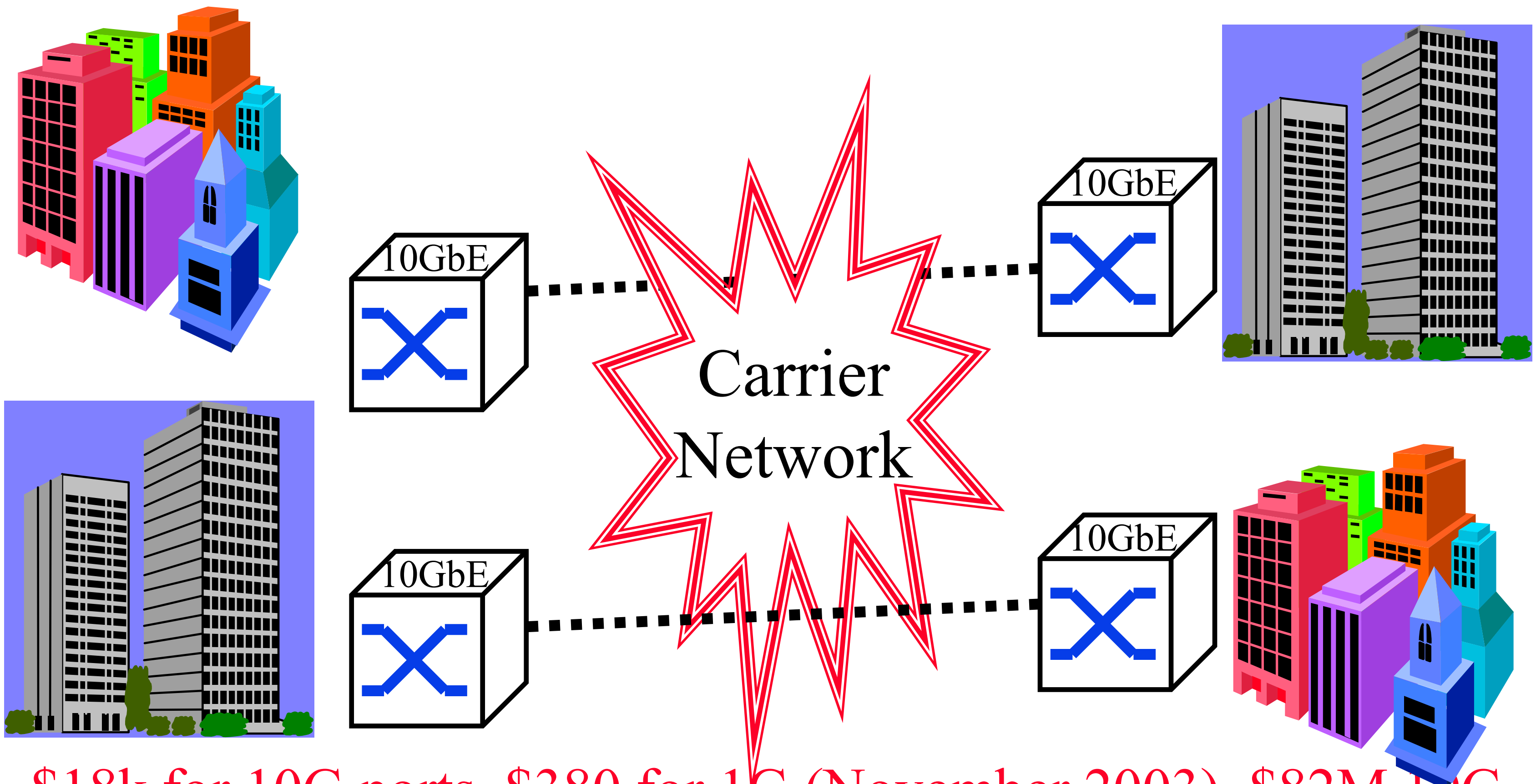
- Need only LAN PMD up to 40 km.
  No SONET overhead. No protection.

10 GbE over SONET/SDH



- Using WAN PMD.
  Legacy SONET. Protection via rings.
  ELTE = Ethernet Line Terminating Equipment

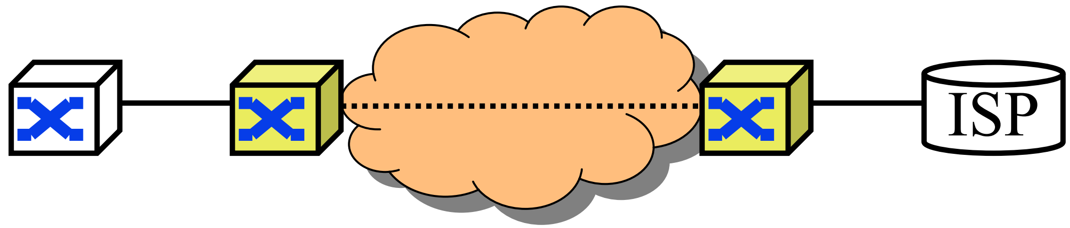
Metro Ethernet Services



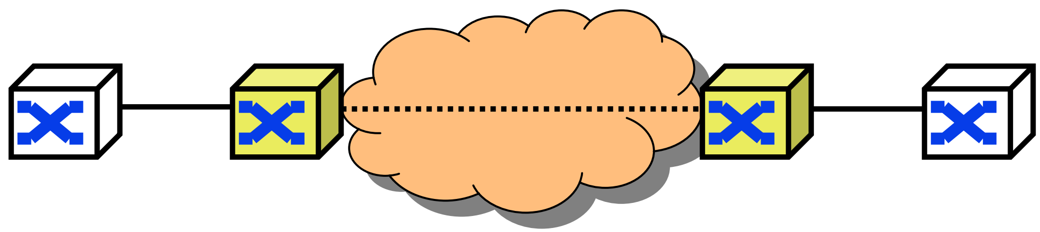
- $18k for 10G ports, $380 for 1G (November 2003). $82M 10G of $11.2B Ethernet.
- Transparent LAN service

Virtual Private LAN Services (VPLS)

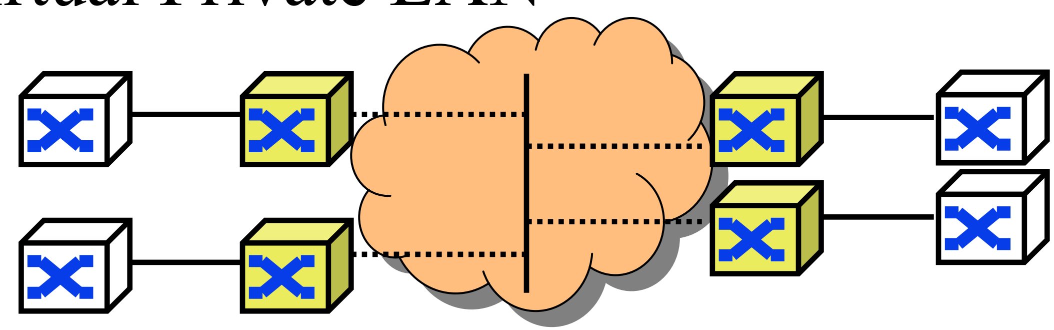
- Ethernet Internet Access



- Ethernet Virtual Private Line

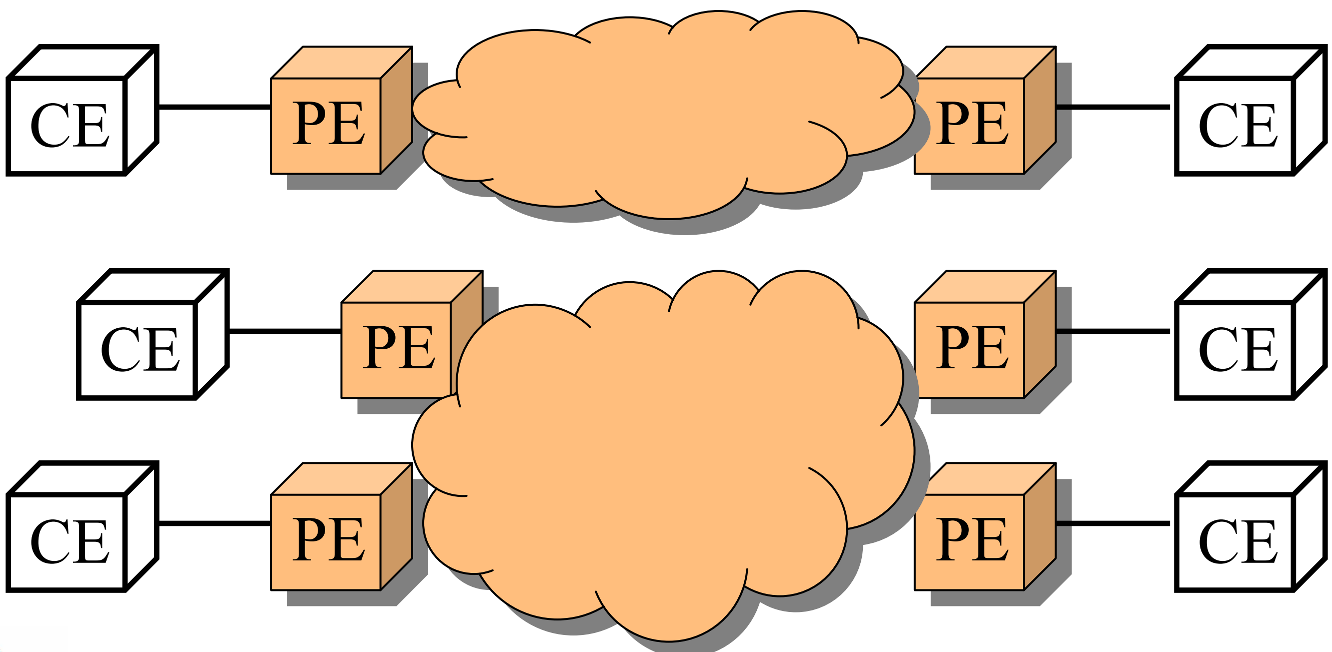


- Ethernet Virtual Private LAN



Metro Ethernet Services

- User-to-network Interface (UNI) = RJ45
- Ethernet Virtual Connection (EVC) = Flows
- Ethernet Line Service (ELS) = Point-to-point
- Ethernet LAN Service (E-LAN) = multipoint-to-multipoint



SONET vs Ethernet

Feature	SONET	Ethernet
Payload Rates	51M, 155M, 622M, 2.4G, 9.5G	10M, 100M, 1G, 10G
Payload Rate Granularity	Fixed	√Any
Bursty Payload	No	√Yes
Payload Count	One	√Multiple
Protection	√Ring	Mesh
OAM&P	√Yes	No
Synchronous Traffic	√Yes	No
Restoration	√50 ms	Minutes
Cost	High	√Low
Used in	Telecom	Enterprise

SONET vs Ethernet: Remedies

Feature	SONET	Ethernet	Remedy
Payload Rates	51M, 155M, 622M, 2.4G, 9.5G	10M, 100M, 1G, 10G	10GE at 9.5G
Payload Rate Granularity	Fixed	√Any	Virtual Concatenation
Bursty Payload	No	√Yes	Link Capacity Adjustment Scheme
Payload Count	One	√Multiple	Packet GFP
Protection	√Ring	Mesh	Resilient Packet Ring (RPR)
OAM&P	√Yes	No	In RPR
Synchronous Traffic	√Yes	No	MPLS + RPR
Restoration	√50 ms	Minutes	Rapid Spanning Tree
Cost	High	√Low	Converging
Used in	Telecom	Enterprise	

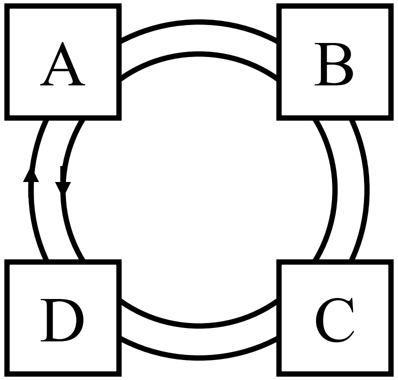
Enterprise vs Carrier Ethernet

Enterprise	Carrier
Distance: up to 2km	Up to 100 km
Scale:	
Few K MAC addresses	Millions of MAC Addresses
4096 VLANs	Millions of VLANs Q-in-Q
Protection: Spanning tree	Rapid spanning tree (Gives 1s, need 50ms)
Path determined by spanning tree	Traffic engineered path
Simple service	SLA
Priority ⇒ Aggregate QoS	Need per-flow QoS
No performance/Error monitoring (OAM)	Need performance/BER

Networking and Religion

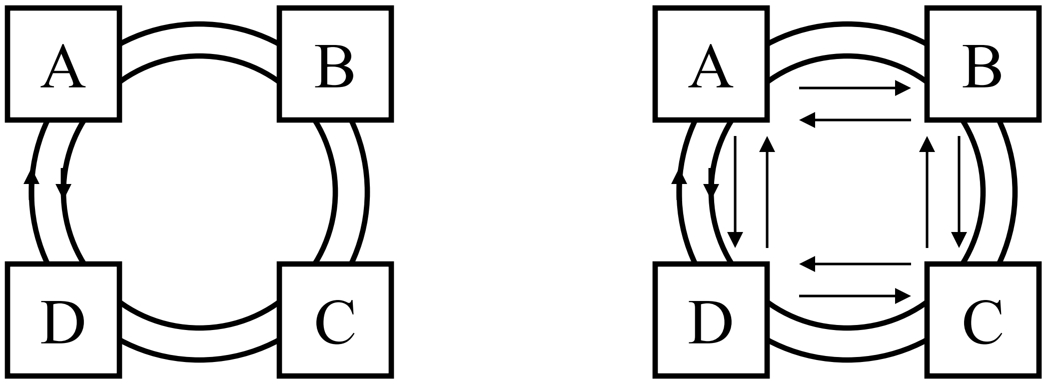
Both are based on a set of beliefs

RPR: Key Features



- Dual Ring topology
- Supports broadcast and multicast
- Packet based ⇒ Continuous bandwidth granularity
- Max 256 nodes per ring
- MAN distances: Several hundred kilometers.
- Gbps speeds: Up to 10 Gbps

RPR Features (Cont)



- Both rings are used (unlike SONET)
- Normal transmission on the shortest path
- Destination stripping ⇒ Spatial reuse
  Multicast packets are source stripped
- Several Classes of traffic: A0, A1, B-CIR, B-EIR, C
- Too many features and alternatives too soon (756 pages)

Networking: Failures vs Successes

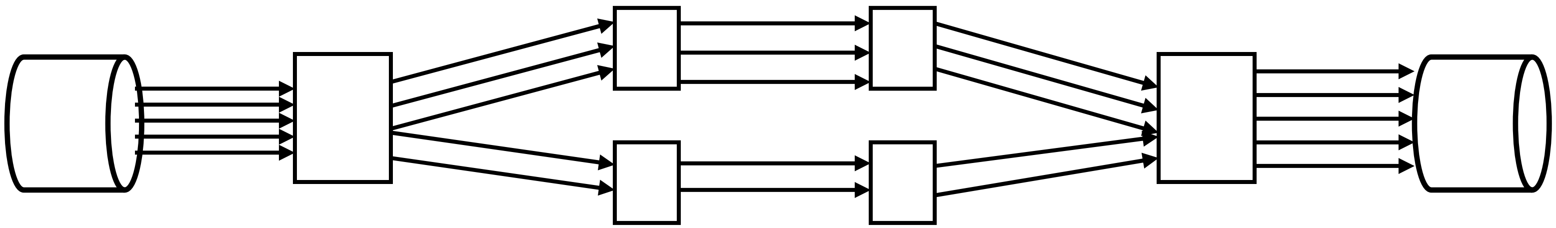
- 1980: Broadband (vs baseband)
- 1984: ISDN (vs Modems)
- 1986: MAP/TOP (vs Ethernet)
- 1988: OSI (vs TCP/IP)
- 1991: DQDB
- 1994: CMIP (vs SNMP)
- 1995: FDDI (vs Ethernet)
- 1996: 100BASE-VG or AnyLan (vs Ethernet)
- 1997: ATM to Desktop (vs Ethernet)
- 1998: Integrated Services (vs MPLS)
- 1999: Token Rings (vs Ethernet)

Requirements for Success

- Low Cost: Low startup cost ⇒ Evolution
- High Performance
- Killer Applications
- Timely completion
- Manageability
- Interoperability
- Coexistence with legacy LANs
  Existing infrastructure is more important than new technology

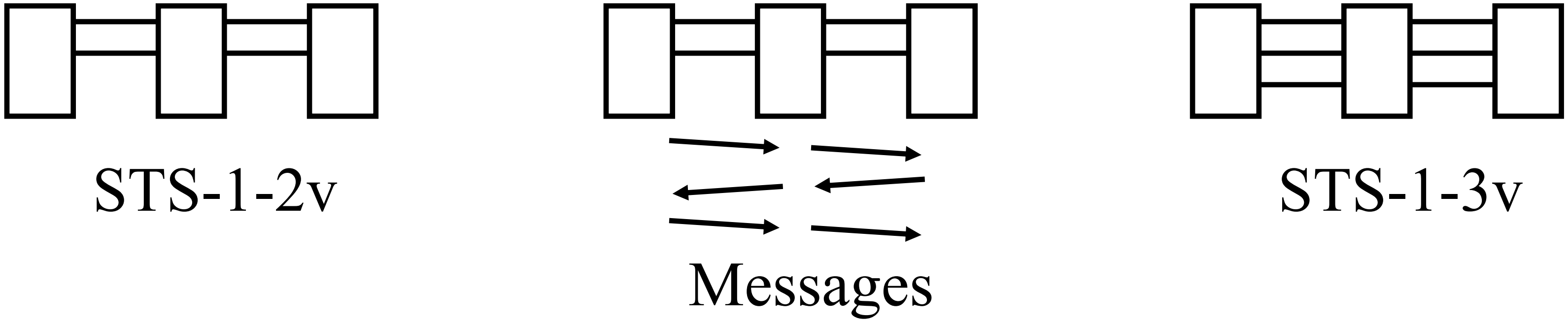
NAYNA Networks

SONET Virtual Concatenation



- VCAT: Bandwidth in increments of VT1.5 or STS-1
- For example: 10 Mbps Ethernet in 7 T1's = VT1.5-7v
  100 Mbps Ethernet in 2 OC-1 = STS-1-2v,
  1GE in 7 STS-3c = STS-3c-7v
- The concatenated channels can travel different paths
  ⇒ Need buffering at the ends to equalize delay
- All channels are administered together.
  Common processing only at end-points.

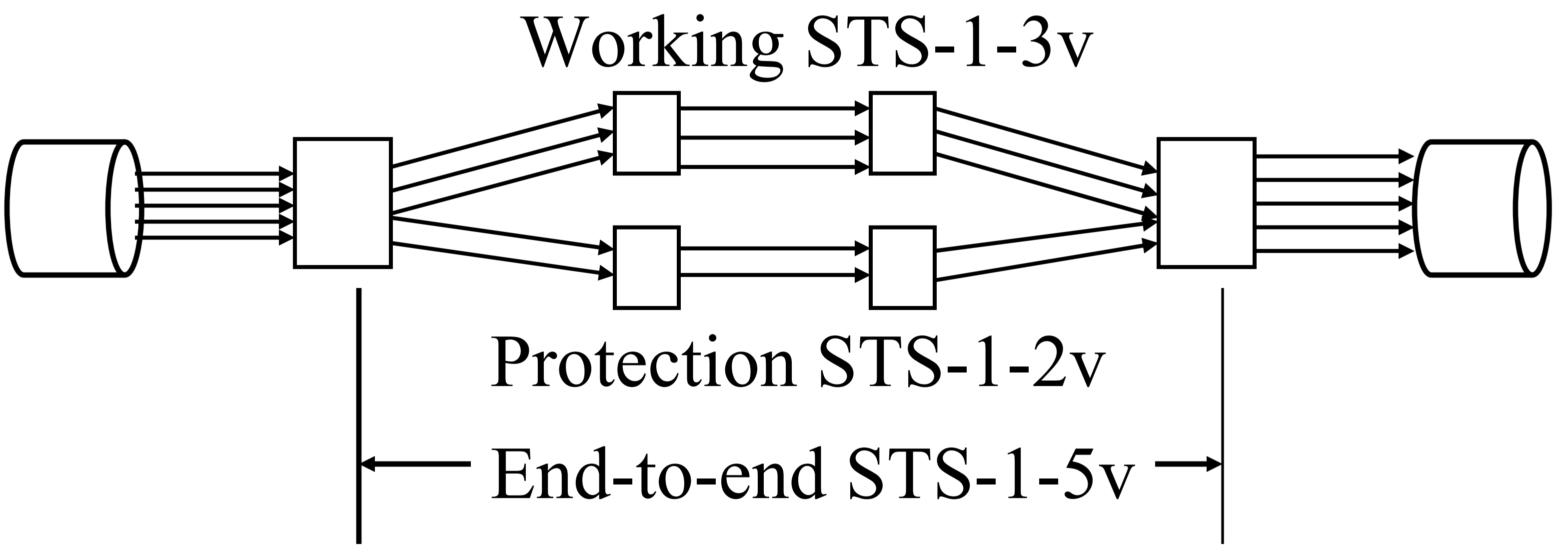
SONET LCAS



- Link Capacity Adjustment Scheme for Virtual Concatenation
- Allows hitless addition or deletion of channels from virtually concatenated SONET/SDH connections
- Control messages are exchanged between end-points to accomplish the change

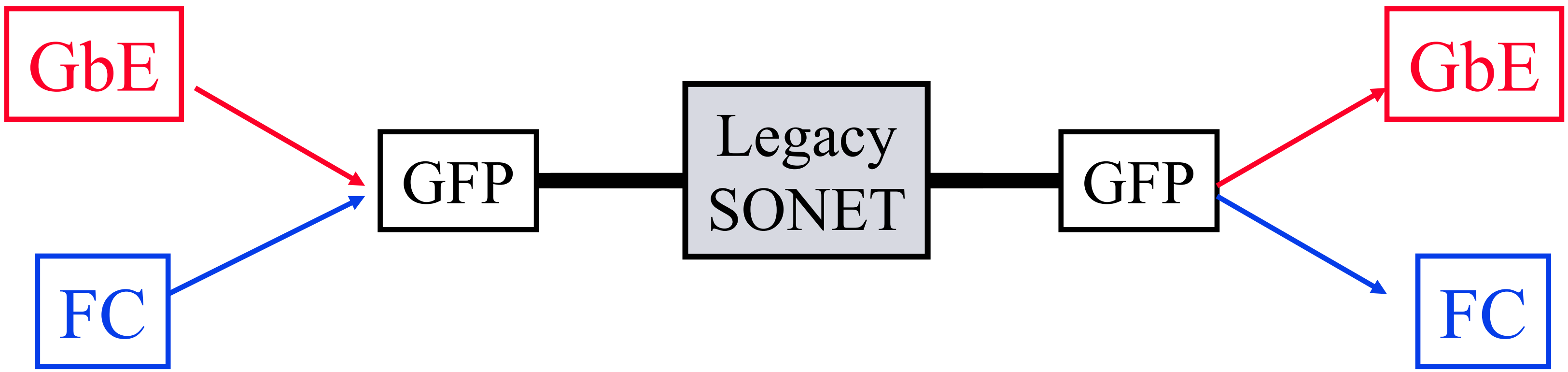
LCAS (Cont)

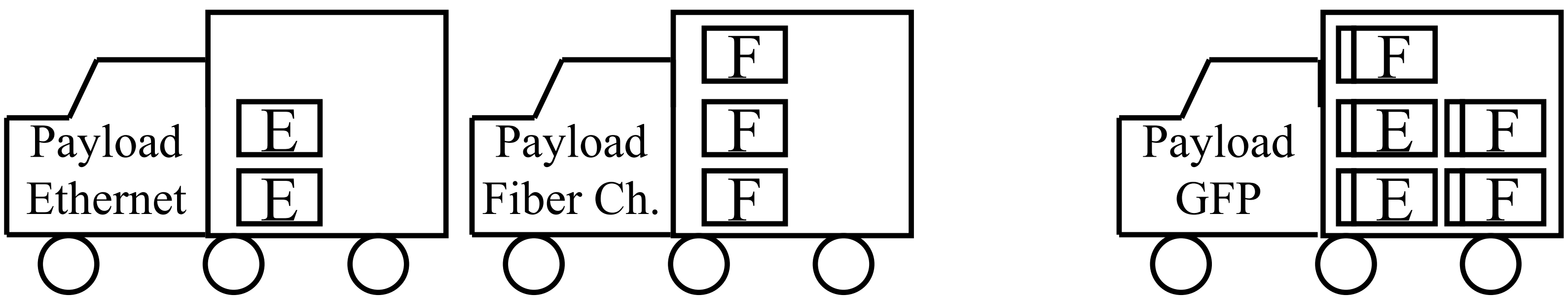
- Provides enhanced reliability. If some channels fail, the remaining channels can be recombined to produce a lower speed stream



Generic Framing Procedure (GFP)

- Allows multiple payload types to be aggregated in one SONET path and delivered separately at destination

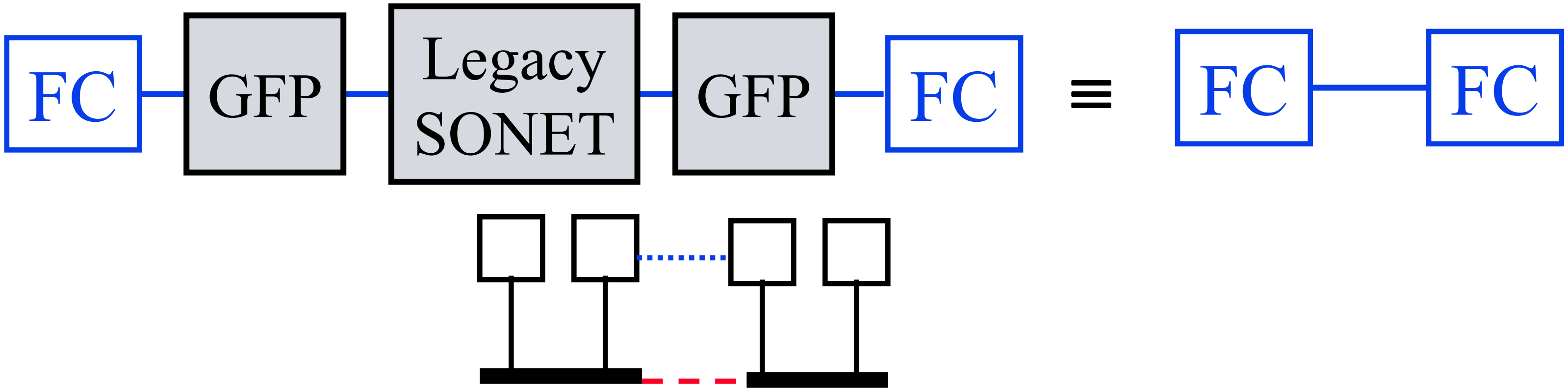




Legacy SONET/SDH NextGen SONET/SDH

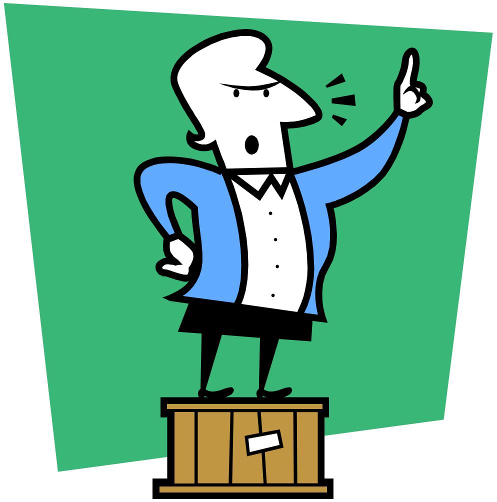
Transparent GFP

- Allows LAN/SAN PHY extension over SONET links Control codes carried as if it were a dark fiber.



- Problem: 8b/10b results in 1.25 Gb stream for 1 GbE
- Solution: Compress 80 PHY bits to 65 bits
  ⇒ 1.02 Gbps SONET payload per GbE

Summary



- 10 GbE does not support CSMA/CD.
  Two speeds: 10,000 Mbps and 9,584.640 Mbps
- RPR to provide carrier grade reliability

Summary (Cont)

- Virtual concatenation allows a carrier to use any arbitrary number of STS-1's or T1's for a given connection. These STS-1's can take different paths.
- LCAS allows the number of STS-1's to be dynamically changed
- Frame-based GFP allows multiple packet types to share a connection
- Transparent GFP allows 8b/10 coded LANs/SANs to use PHY layer connectivity at lower bandwidth.

Optical Access Networks

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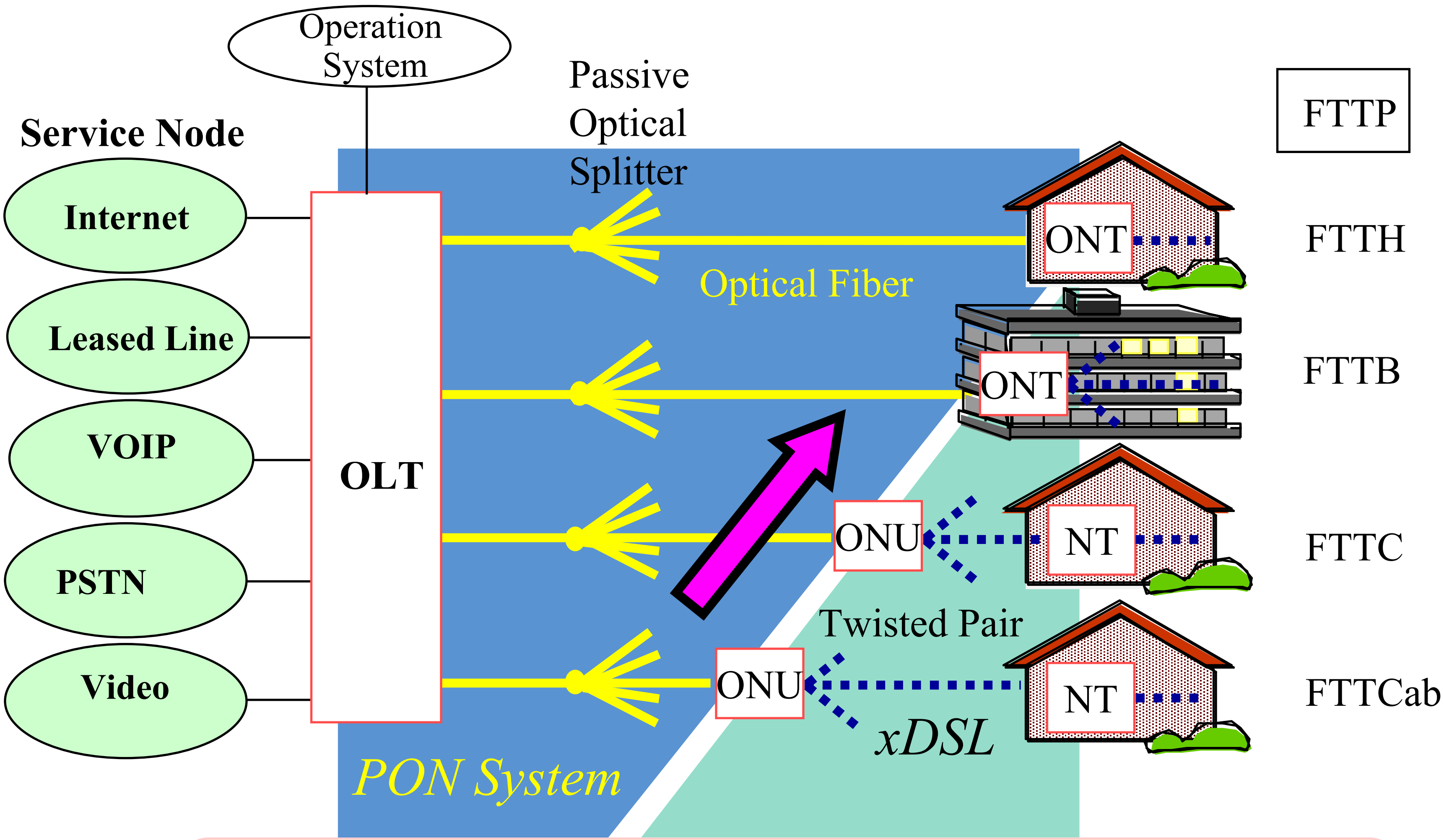
- Fiber to the x (FTTx)
- Passive Optical Networks: What? How? Where? Why?
- Recent Developments

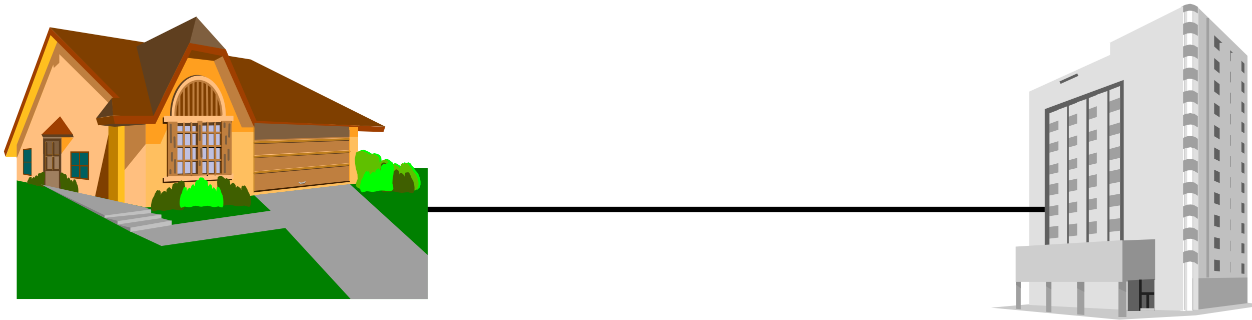
Access: Fiber To The X (FTTx)



FTTH :Fiber To The Home
FTTB :Fiber To The Building
FTTC:Fiber To The Curb
FTTCab :Fiber To The Cabinet

NAYNA Networks

Ethernet in the First Mile



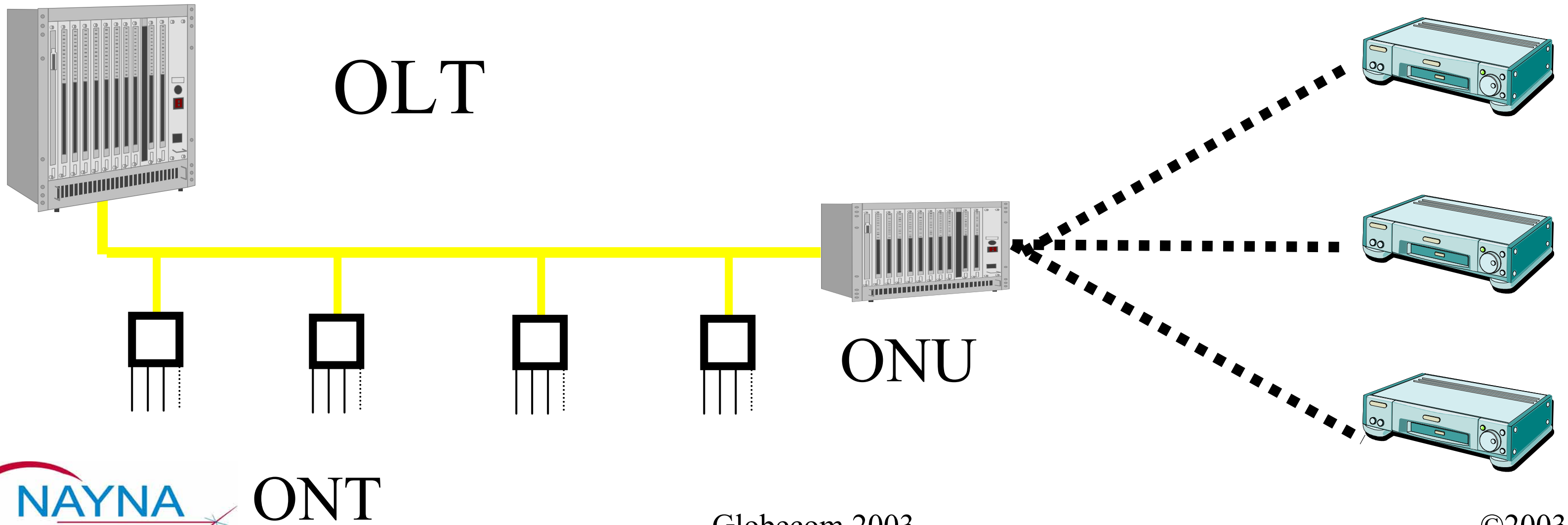
- IEEE 802.3 Study Group started November 2000
- Originally called Ethernet in the Last Mile
- EFM Goals: Media: Phone wire, Fiber
  Speed: 125 kbps to 1 Gbps
  - Distance: 1500 ft, 18000 ft, 1 km - 40 km
  - Both point-to-point and point-to-multipoint
- EPON = point-to-multipoint fiber
- Ref: http://www.ieee802.org/3/efm/public/index.htm

EFM PHYs

2BASE-TL	Baseband PHY based on SHDSL, L ⇒ 2.7km
10PASS-TS	Duplex on a single voice UTP pair using VDSL QAM or DMT, S⇒0.7km. Pass⇒Voice+Data -O = Central Office, -R = CPE
100BASE-LX10	Duplex Fiber PHY w 10km 1310nm laser
100BASE-BX10-D	Bidirectional 1550nm downstream laser
100BASE-BX10-U	Bidirectional 1310nm upstream laser
1000BASE-LX10	Extended (10km) 1310nm long-wavelength laser
1000BASE-BX10-D	Bidirectional 1490nm downstream laser
1000BASE-BX10-U	Bidirectional 1310nm upstream laser
1000BASE-PX10-D	PON 1490nm downstream laser 10 km
1000BASE-PX10-U	PON 1310nm upstream laser 10 km
1000BASE-PX20-D	PON 1490nm downstream laser 20 km
1000BASE-PX20-U	PON 1310nm upstream laser 20 km

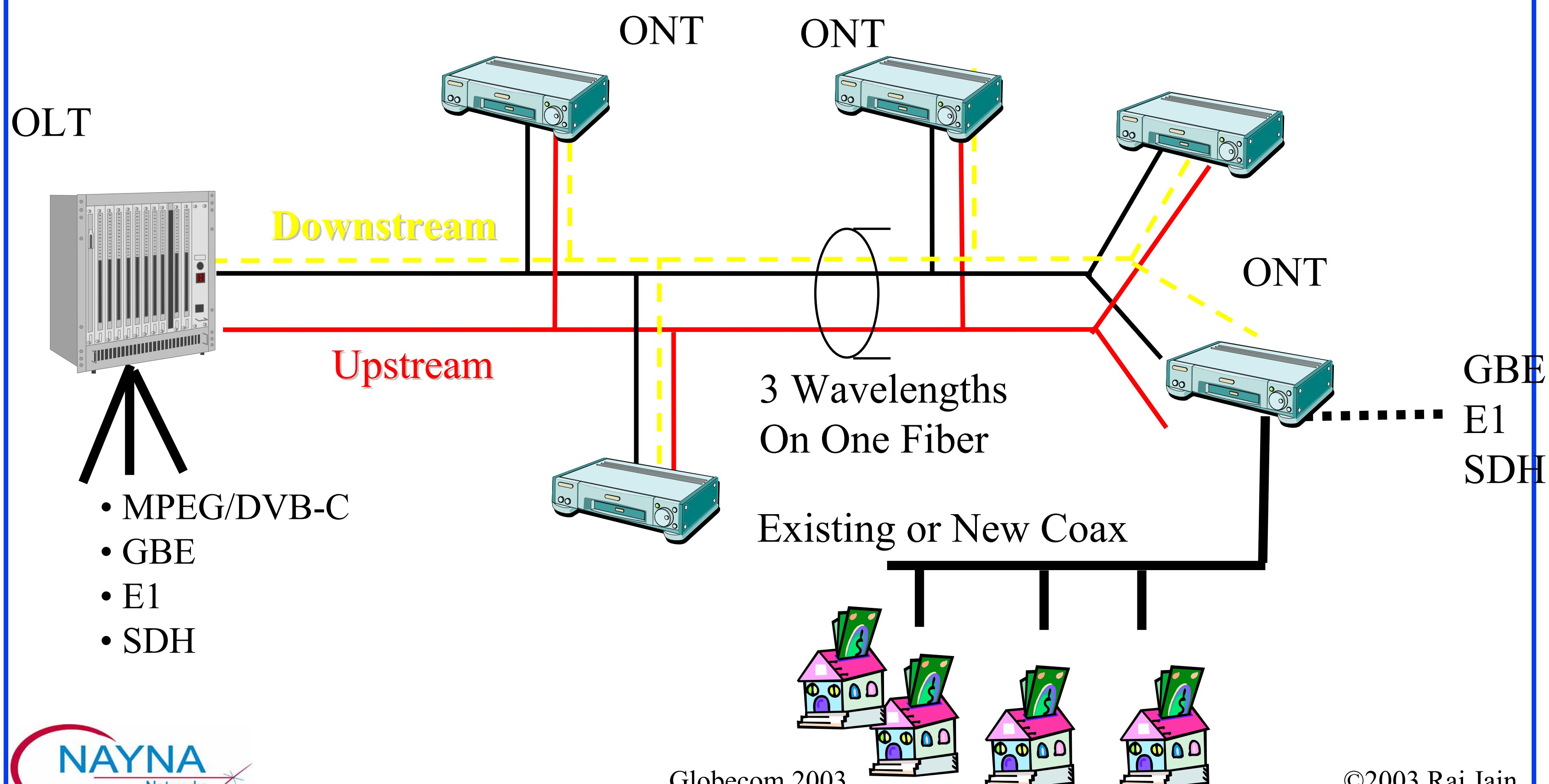
Passive Optical Networks

- A single fiber is used to support multiple customers
- No active equipment in the path ⇒ Highly reliable
- Both upstream and downstream traffic on ONE fiber (1490nm down, 1310nm up). OLT assigned time slots upstream.
- Optical Line Terminal (OLT) in central office
- Optical Network Terminal (ONT) on customer premises
  Optical Network Unit (ONU) at intermediate points w xDSL

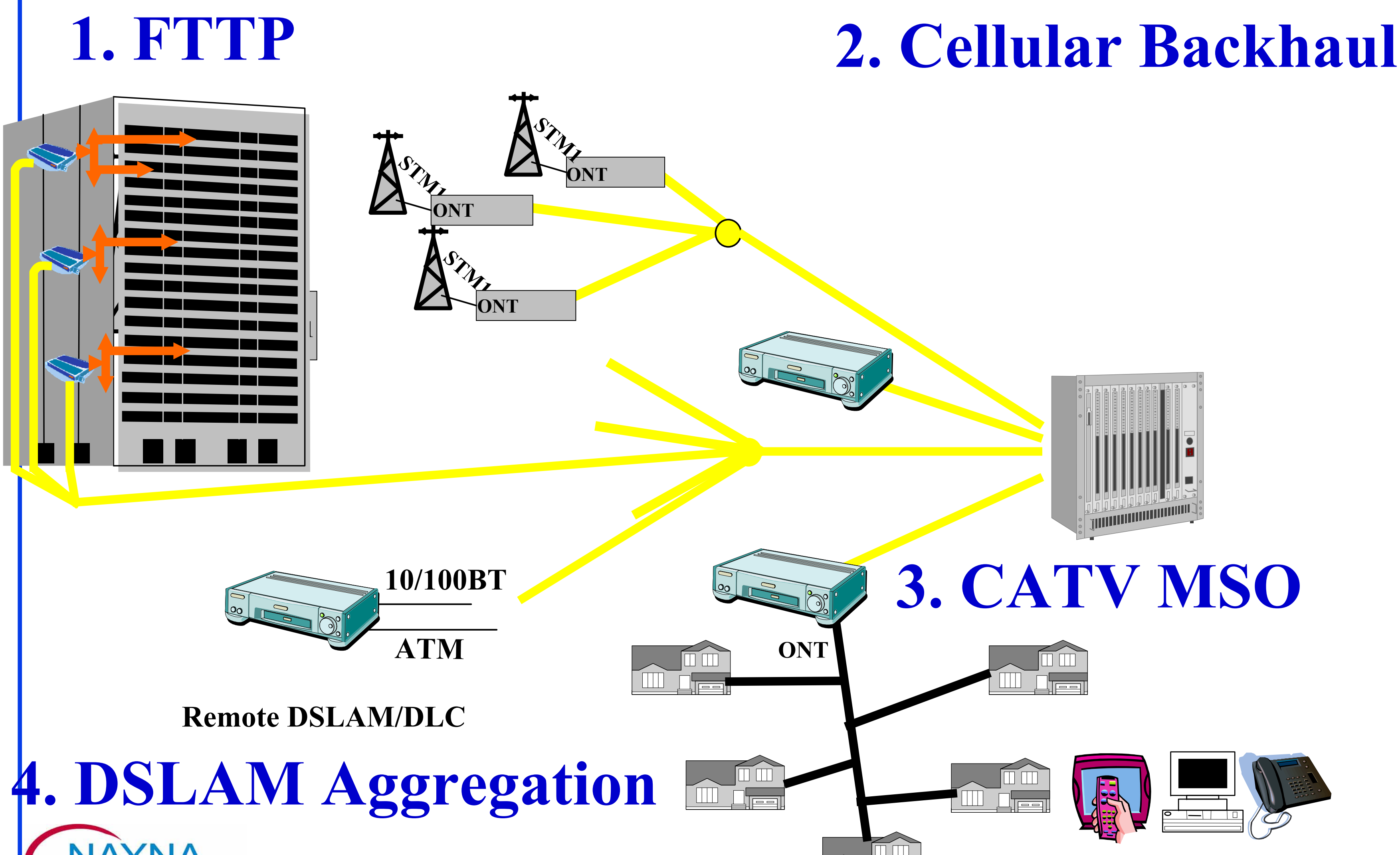


Broadcast Video Over PON

- Analog or Digital Video on 1550 nm



PON Applications



Why PONs?

- **Reduced OpEx**: Passive network
  - High reliability $\Rightarrow$ Reduced truck rolls
  - Reduced power expenses
  - Shorter installation times
- **Reduced CapEx**:
  - 16 -128 customers per fiber
  - 1 Fiber +1+N transceivers vs N Fibers + 2N transceivers
- **Increased Revenue Opportunities**: Multi-service: Data, E1/T1, Voice, Video
- **Scalable**:
  - CO Equipment Shared $\Rightarrow$ New customers can be added easily
  - Bandwidth is Shared $\Rightarrow$ Customer bandwidth can be changed

Types of PONs

- **APON**: Initial name for ATM based PON spec. Designed by Full Service Access Network (FSAN) group
- **BPON**: Broadband PON standard specified in ITU G.983.1 thru G.893.7 = APON renamed
  - 155 or 622 Mbps downstream, 155 upstream
- **EPON**: Ethernet based PON draft being designed by IEEE 802.3ah.
  - 1000 Mbps down and 1000 Mbps up.
- **GPON**: Gigabit PON standard specified in ITU G.984.1 and G.984.2
  - 1244 and 2488 Mbps Down, 155/622/1244/2488 up

PON Developments

- GPON recommendations G.984.x are out.
  EPON draft is progressing fast.
- FCC removed fibers from unbundling
- SBC, Verizon, Bellsouth issued an RFP in USA
  - Carriers in Japan and Europe are seriously investigating FTTH
  - Most big telecom vendors in US were caught off-guard with no PON equipment
- Most action in Access than in Core or Metro
- Venture Financing for PON is up
  - Several PON companies received funding this year
- Over 800 Communities in USA are investigating fibers to home using PONs
- Fiber-to-the-Home Installations Expected to Reach Approximately One Million by 2004 [FTTH Council]

Conclusion: 2004 will be the year of PON

Summary

1. 2004 will be the year of PONs
2. PONs reduce OpEx and CapEx for carriers and increase carrier revenue opportunities with value-added services
3. Multi-service support in next-generation EPON products is a key differentiator.
4. EPON products need to offer quad-play: Data, voice, video, and TDM to be effective

IP Over DWDM

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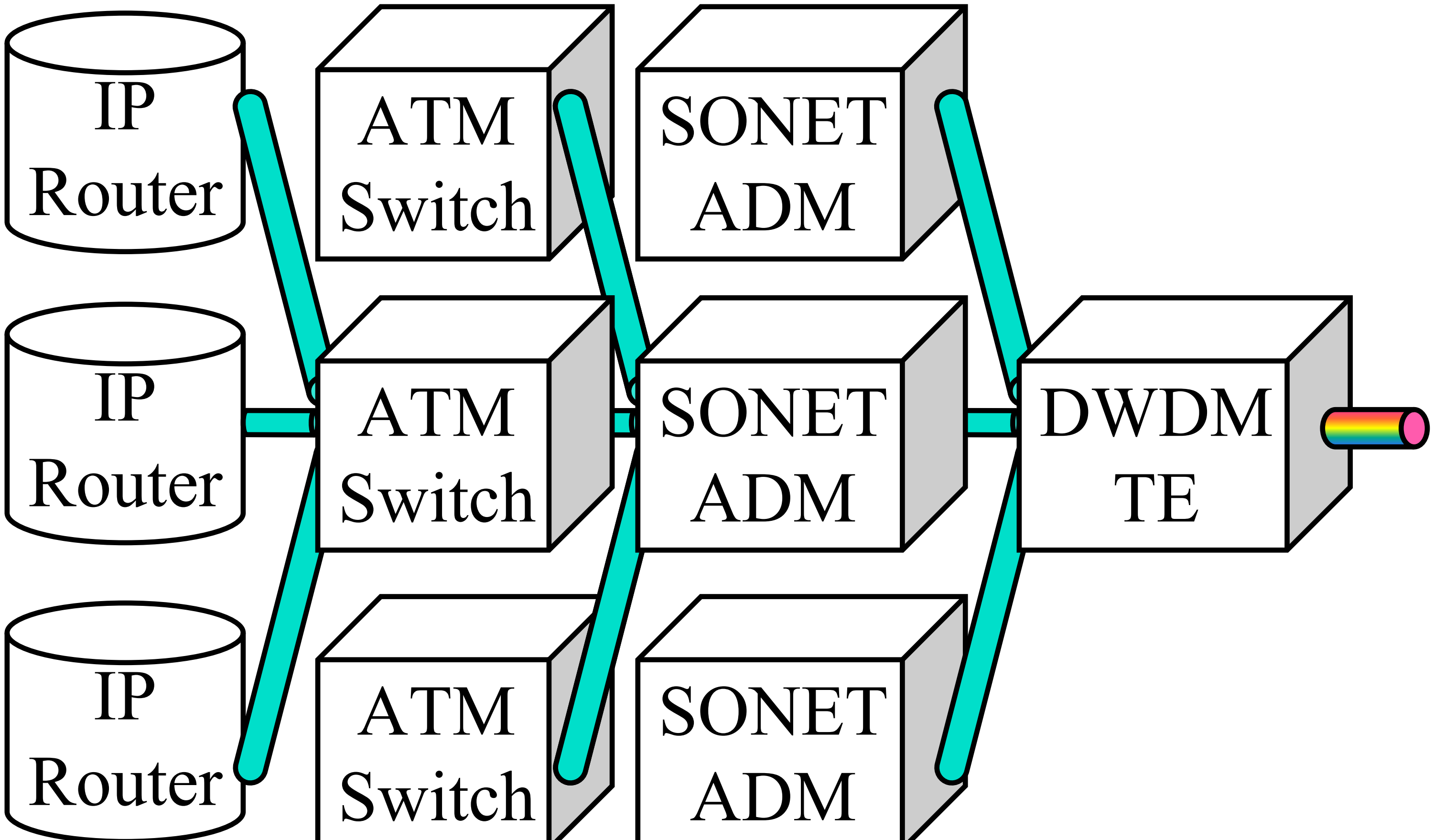
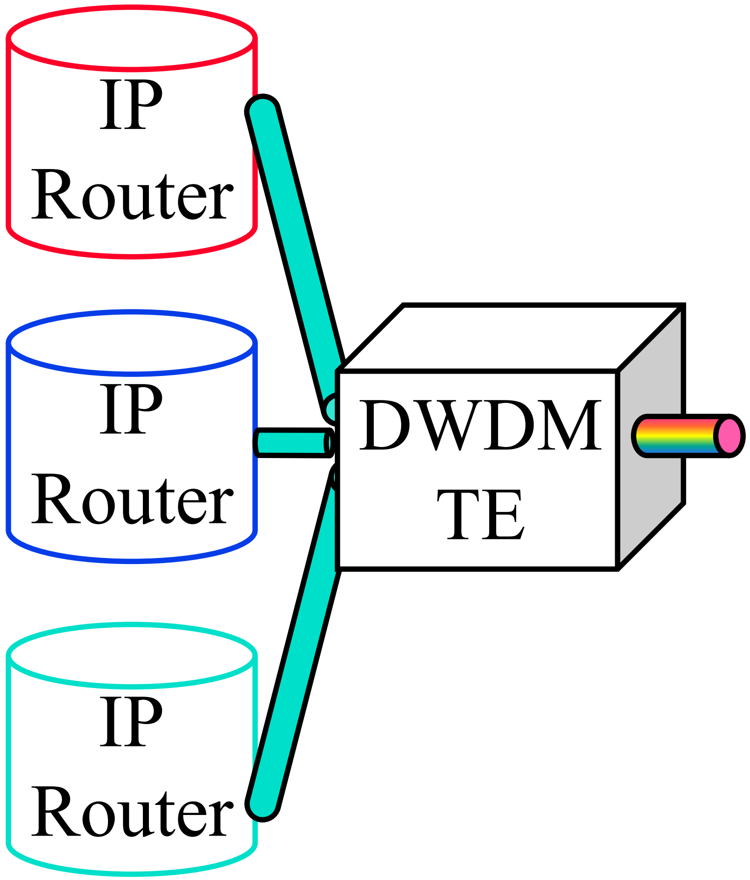
- IP over DWDM
- UNI
- ASTN/ASON
- MPLS, MPλS, GMPLS

IP over DWDM (Past)

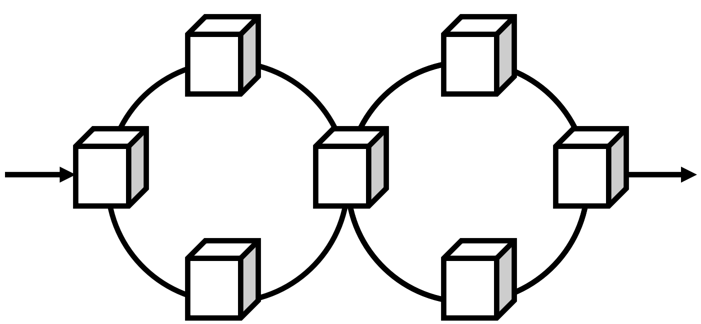


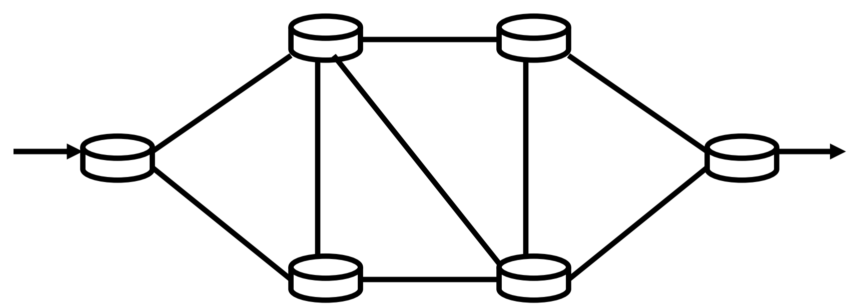
IP over DWDM (Future)



Telecom vs Data Networks

	Telecom Networks	Data Networks
Topology Discovery	Manual	Automatic
Path Determination	Manual	Automatic
Circuit Provisioning	Manual	No Circuits
Transport & Control Planes	Separate	Mixed
User and Provider Trust	No	Yes
Protection	Static using Rings	No Protection



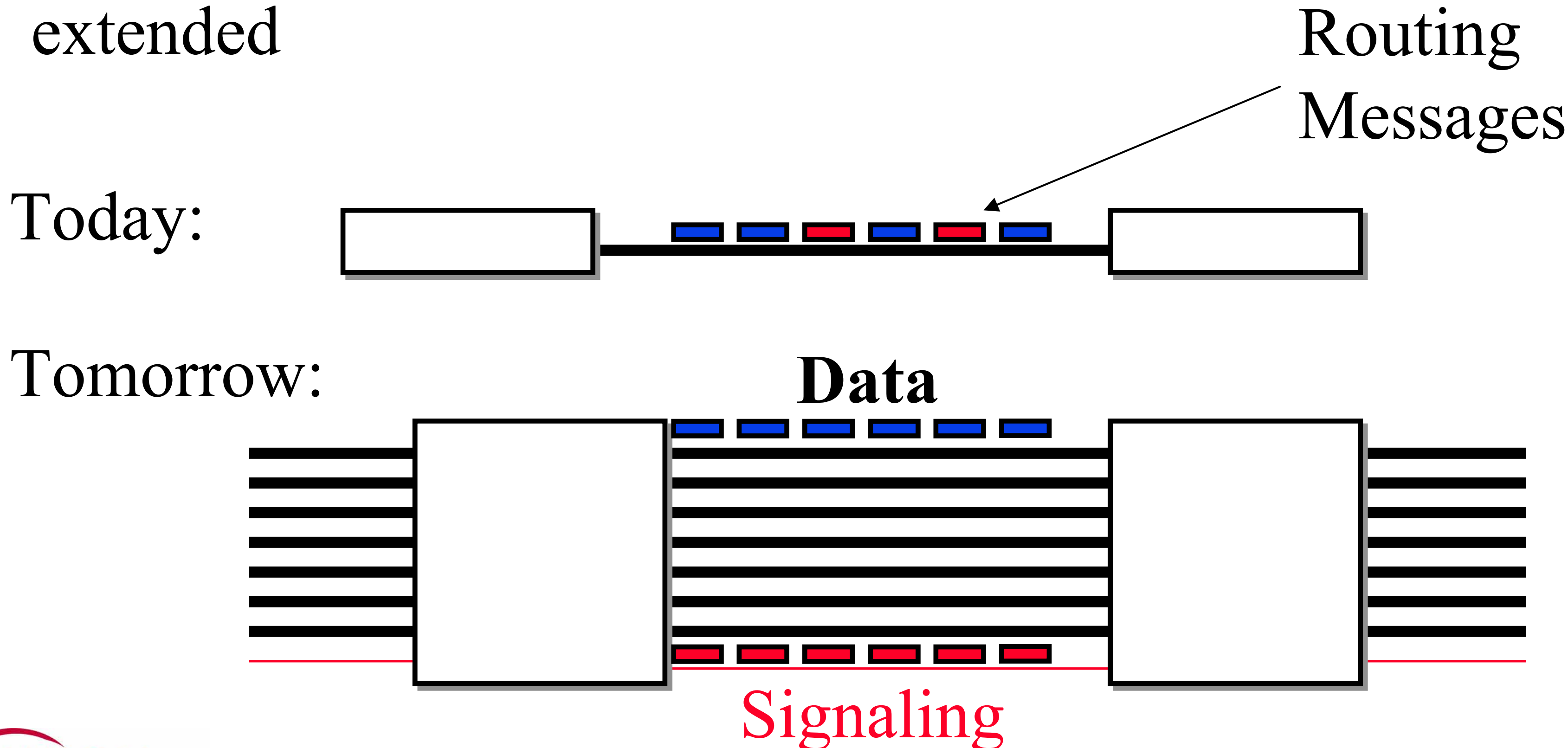


IP over DWDM Issues

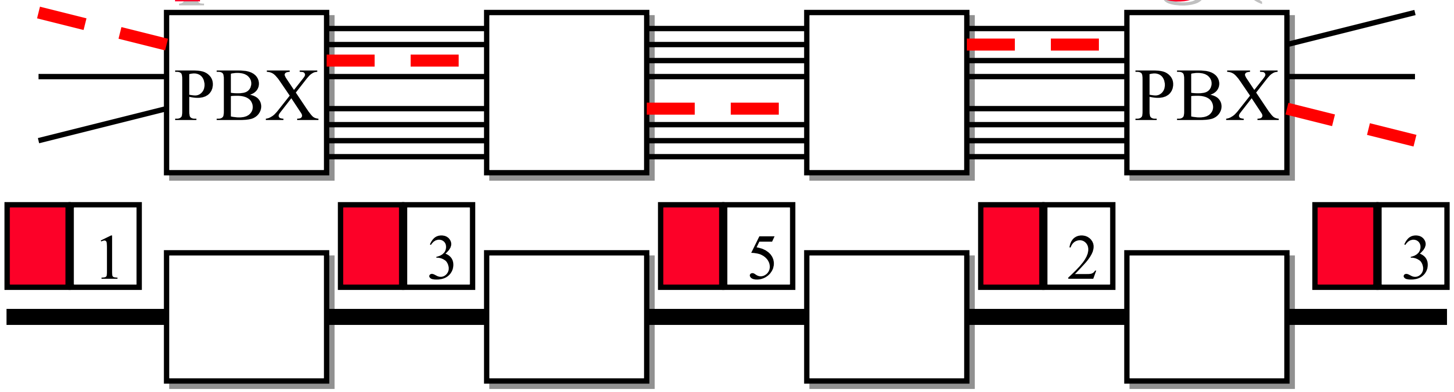
1. Data and Control plane separation
2. Circuits
3. Signaling
4. Addressing
5. Protection and Restoration

Control and Data Plane Separation

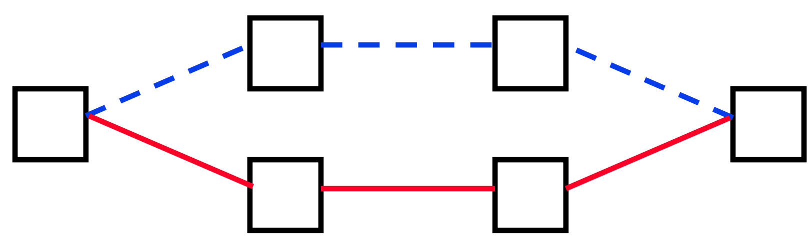
- Separate control and data channels
- IP routing protocols (OSPF and IS-IS) are being extended



Multiprotocol Label Switching (MPLS)

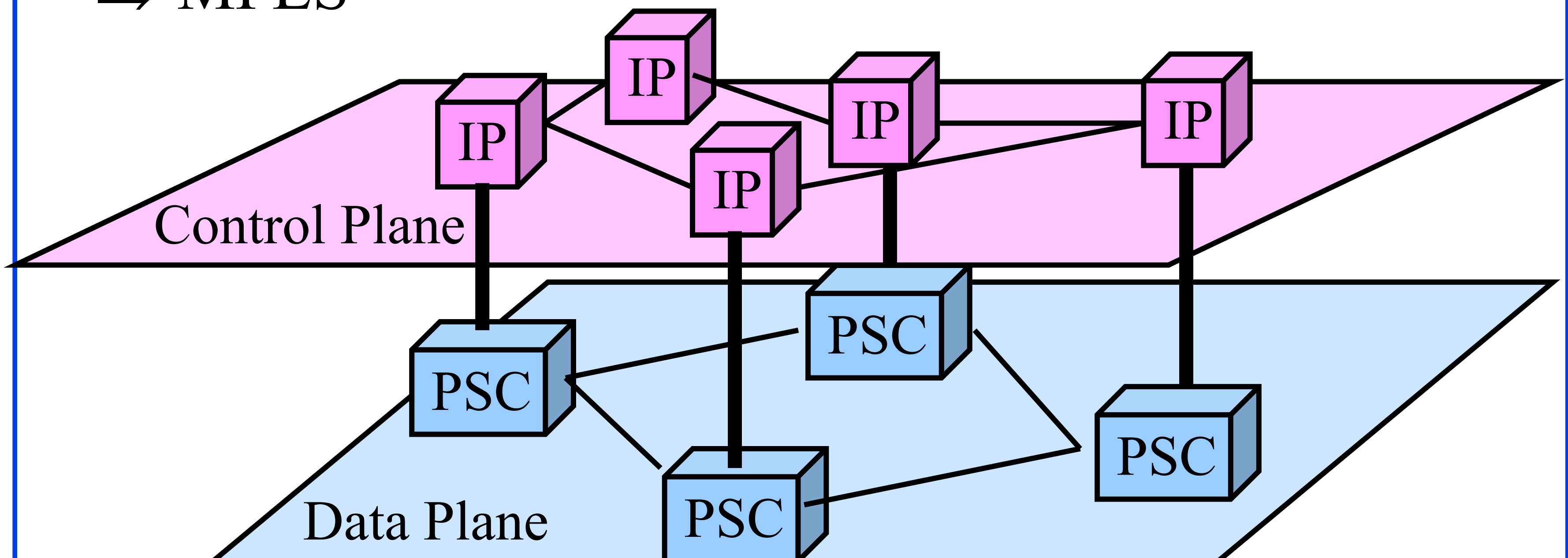


- Allows virtual circuits in IP Networks (May 1996)
- Each packet has a virtual circuit number called ‘label’
- Label determines the packet’s queuing and forwarding
- Circuits are called Label Switched Paths (LSPs)
- LSP’s have to be set up before use
- Allows traffic engineering



IP-Based Control Plane

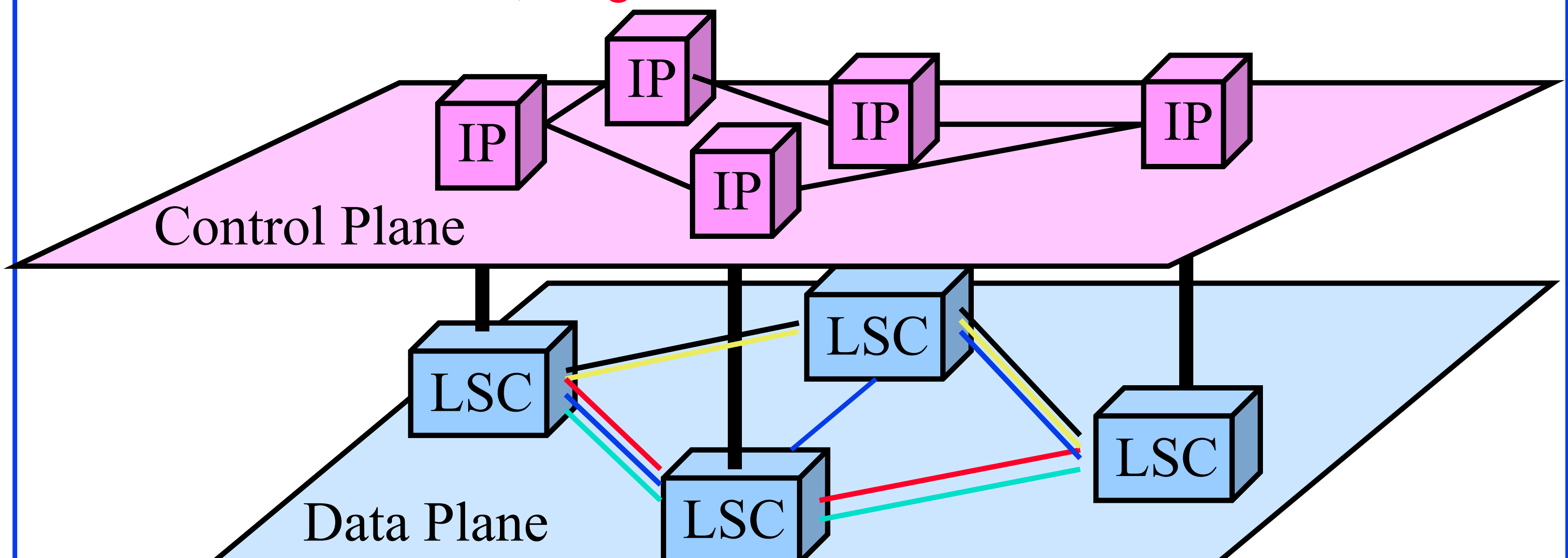
- Control is by IP packets (electronic).
  Data can be any kind of packets (IPX, ATM cells).
  ⇒ MPLS



PSC = Packet Switch Capable Nodes

MPλS

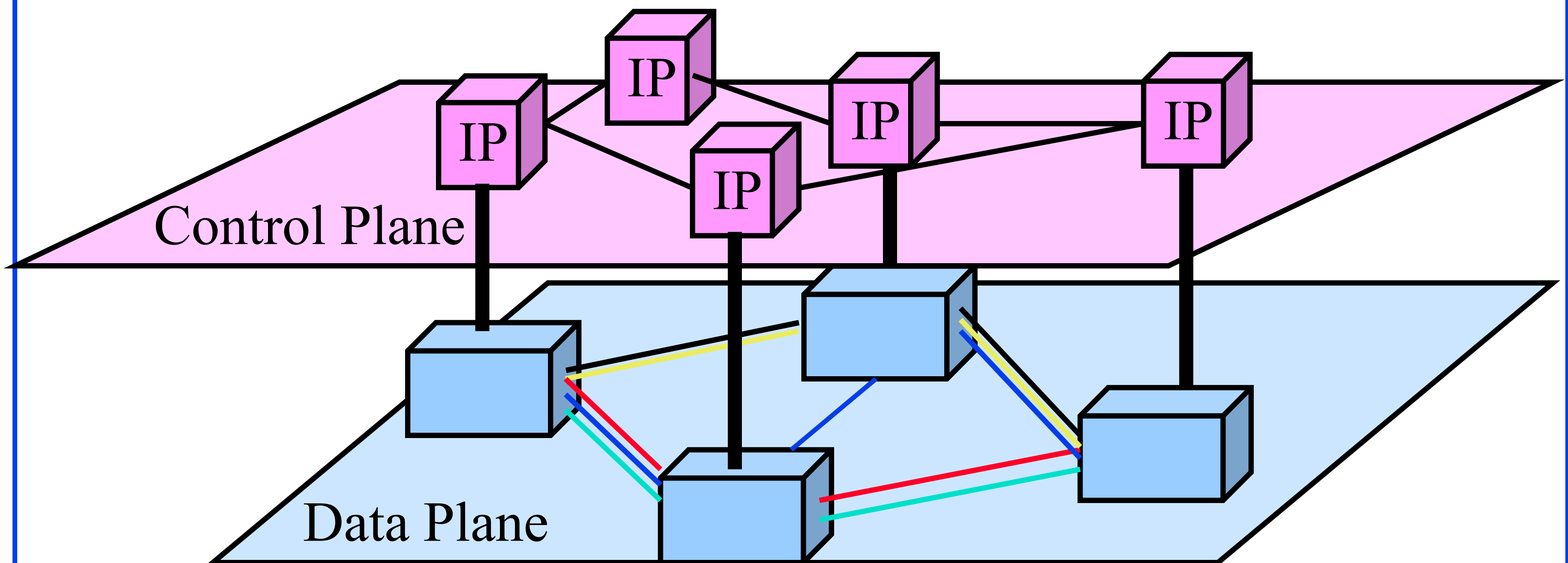
- Control is by IP packets (electronic).
  Data plane consists of wavelength circuits
  ⇒ Multiprotocol Lambda Switching (October 1999)
- Ref: Hassan and Jain, "High-Performance TCP/IP" Prentice Hall 2003.



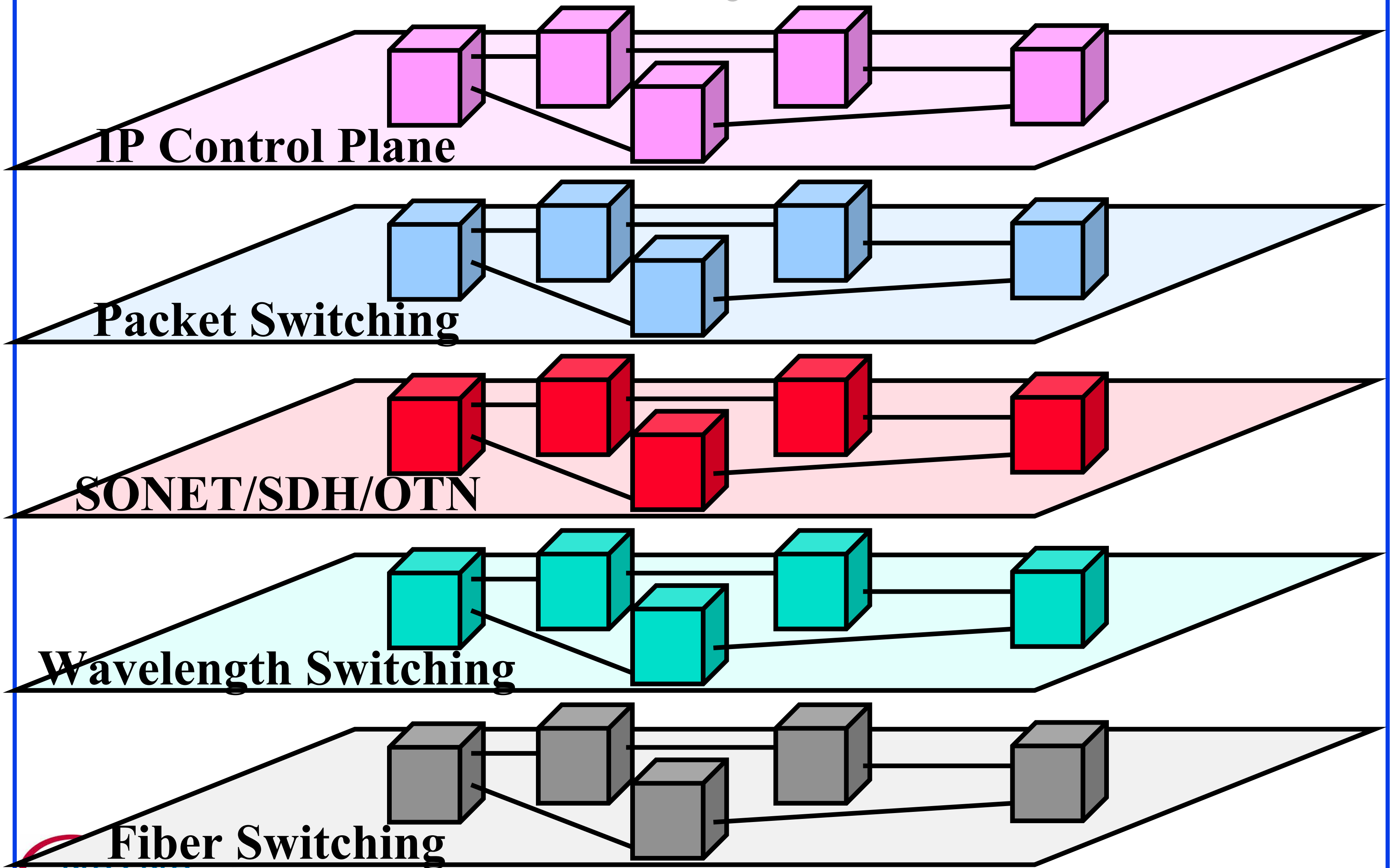
LSC = Lambda Switch Capable Nodes
= Optical Cross Connects = OXC

GMPLS

- Data Plane = Wavelengths, Fibers, SONET Frames, Packets (October 2000)
- Two separate routes: Data route and control route

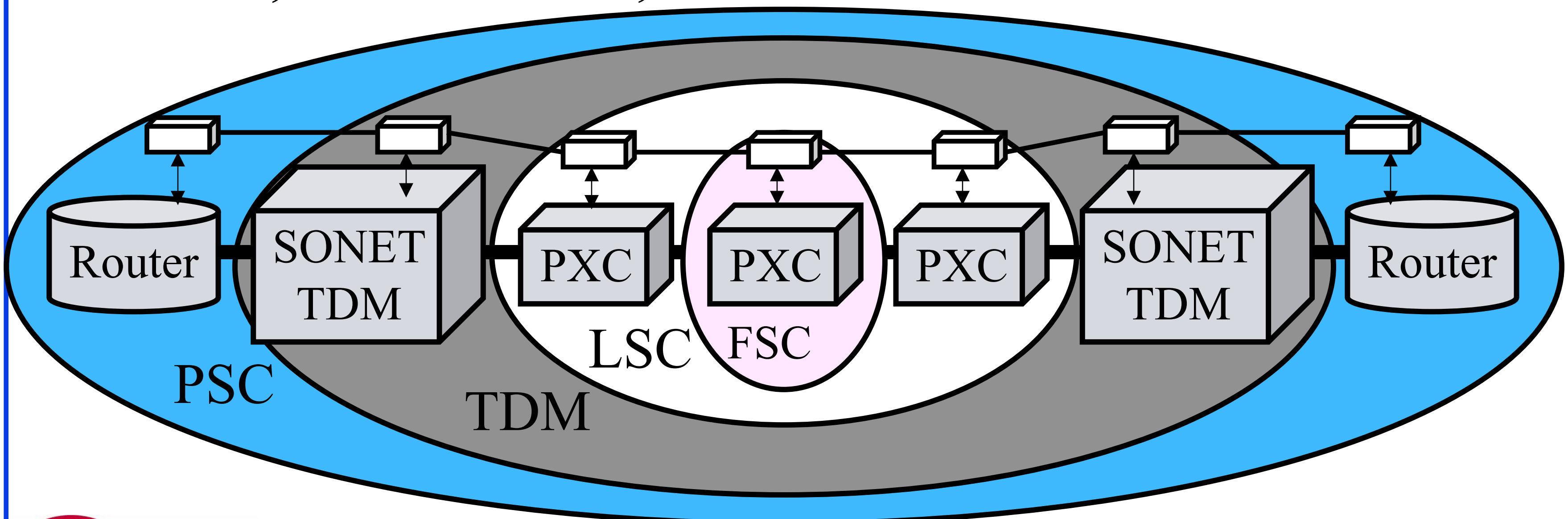


GMPLS: Layered View



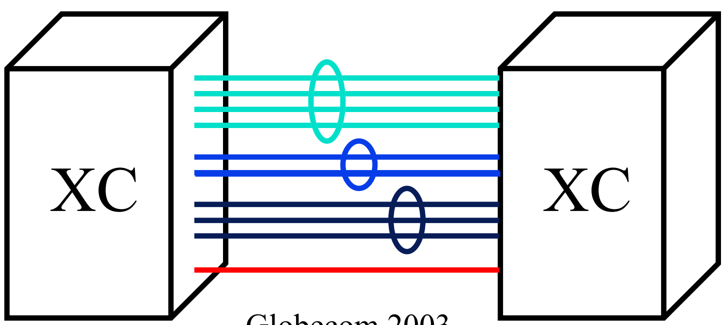
GMPLS: Hierarchical View

- Packets over SONET over Wavelengths over Fibers
- Packet switching regions, TDM regions, Wavelength switching regions, fiber switching regions
- Allows data plane connections between SONET ADMs, PXCs. FSCs, in addition to routers



MPLS vs GMPLS

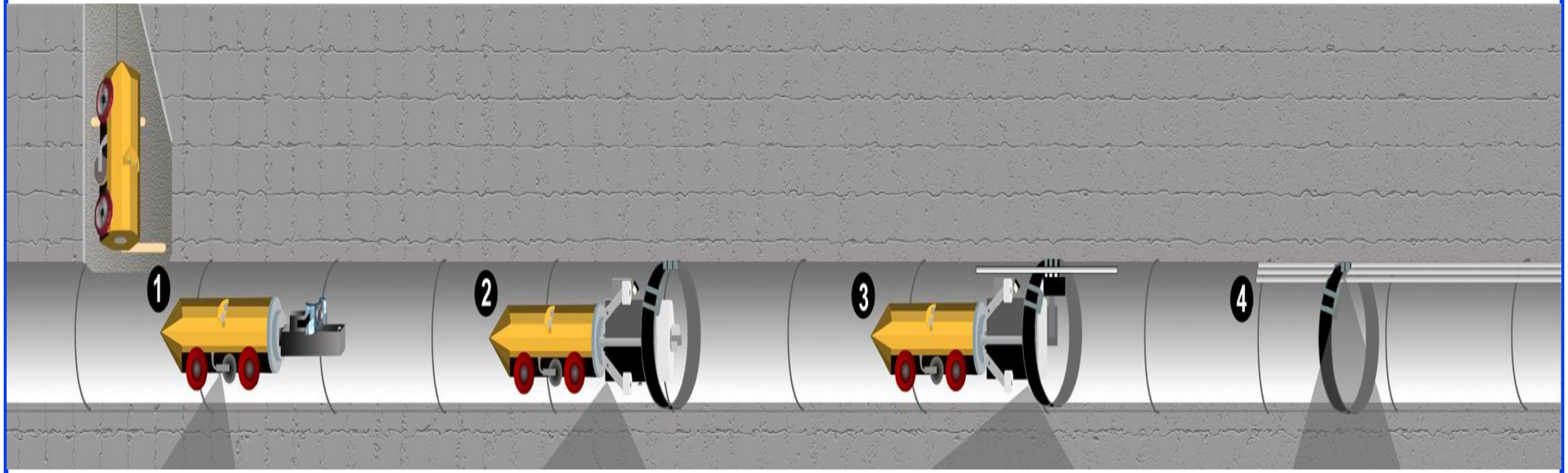
Issue	MPLS	GMPLS
Data & Control Plane	Same channel	Separate
Types of Nodes and labels	Packet Switching	PSC, TDM, LSC, FSC, …
Bandwidth	Continuous	Discrete: OC-n, λ's, ..
# of Parallel Links	Small	100-1000's
Port IP Address	One per port	Unnumbered
Fault Detection	In-band	Out-of-band or In-Band



Fiber Access Thru Sewer Tubes (FAST)

- Right of ways is difficult in dense urban areas
- Sewer Network: Completely connected system of pipes connecting every home and office
- Municipal Governments find it easier and more profitable to let you use sewer than dig street
- Installed in Zurich, Omaha, Albuquerque, Indianapolis, Vienna, Ft Worth, Scottsdale, ...
- Corrosion resistant inner ducts containing up to 216 fibers are mounted within sewer pipe using a robot called Sewer Access Module (SAM)
- Ref: http://www.citynettelecom.com, NFOEC 2001, pp. 331

FAST Installation



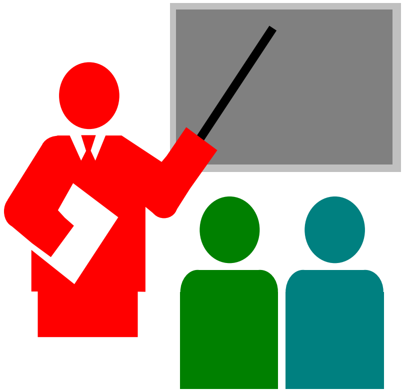
1. Robots map the pipe
2. Install rings
3. Install ducts
4. Thread fibers

Fast Restoration: Broken sewer pipes replaced with minimal disruption

Summary

1. High speed routers
   ⇒ IP directly over DWDM
2. Separation of control and data plane
   ⇒ IP-Based control plane
3. Transport Plane = Packets ⇒ MPLS
   Transport Plane = Wavelengths
   ⇒ MPλS
   Transport Plane = λ, SONET, Packets
   ⇒ GMPLS
4. UNI allows users to setup paths on demand

Summary: Key Points



1. ILEC vs CLECs ⇒ Evolution vs Revolution
2. Core market is stagnant
   ⇒ No OOO Switching and Long Haul Transport
3. Metro Ethernet ⇒ Ethernet Service vs Transport
   ⇒ Next-Gen SONET vs Ethernet with RPR
4. PONs provide a scalable, upgradeable, cost effective solution.
5. IP over DWDM: MPλS, GMPLS, PWE3

Standards Organizations

- IETF: www.ietf.org
  - Multiprotocol Label Switching (MPLS)
  - IP over Optical (IPO)
  - Traffic Engineering (TE)
  - Common Control and Management Plane (CCAMP)
- Optical Internetworking Forum (OIF): www.oiforum.com
- ANSI T1X1.5: http://www.t1.org/t1x1/_x15-hm.htm
- ITU, www.itu.ch, Study Group 15 Question 14 and Question 12
- Optical Domain Service Interface (ODSI) - Completed December 2000

References

- Detailed references in http://www.cis.ohio-state.edu/~jain/refs/opt_refs.htm
- Recommended books on optical networking, http://www.cis.ohio-state.edu/~jain/refs/opt_book.htm
- Optical Networking and DWDM, http://www.cis.ohio-state.edu/~jain/cis788-99/dwdm/index.html
- IP over Optical: A summary of issues, (internet draft) http://www.cis.ohio-state.edu/~jain/ietf/issues.html
- Lightreading, http://www.lightreading.com