Optical Networking: Recent Developments, Issues, and Trends

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Future

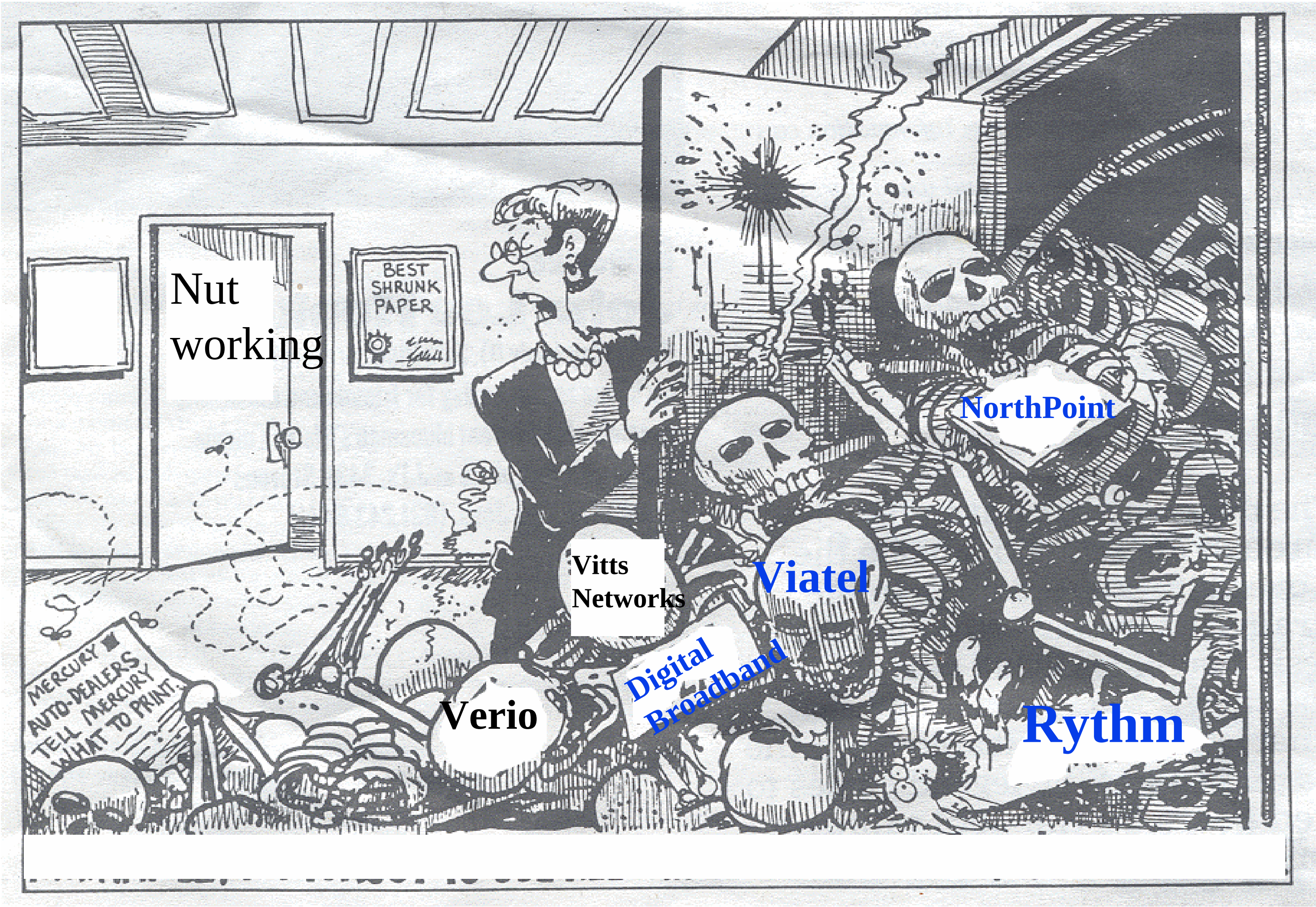
All I want you to tell me is what will be the networking technology in the year 2002.

1. Trends in Networking
2. SONET, SDH, OTN
3. Gigabit and 10 G Ethernet, RPR, Next Gen SONET
4. IP over DWDM, GMPLS, ASON

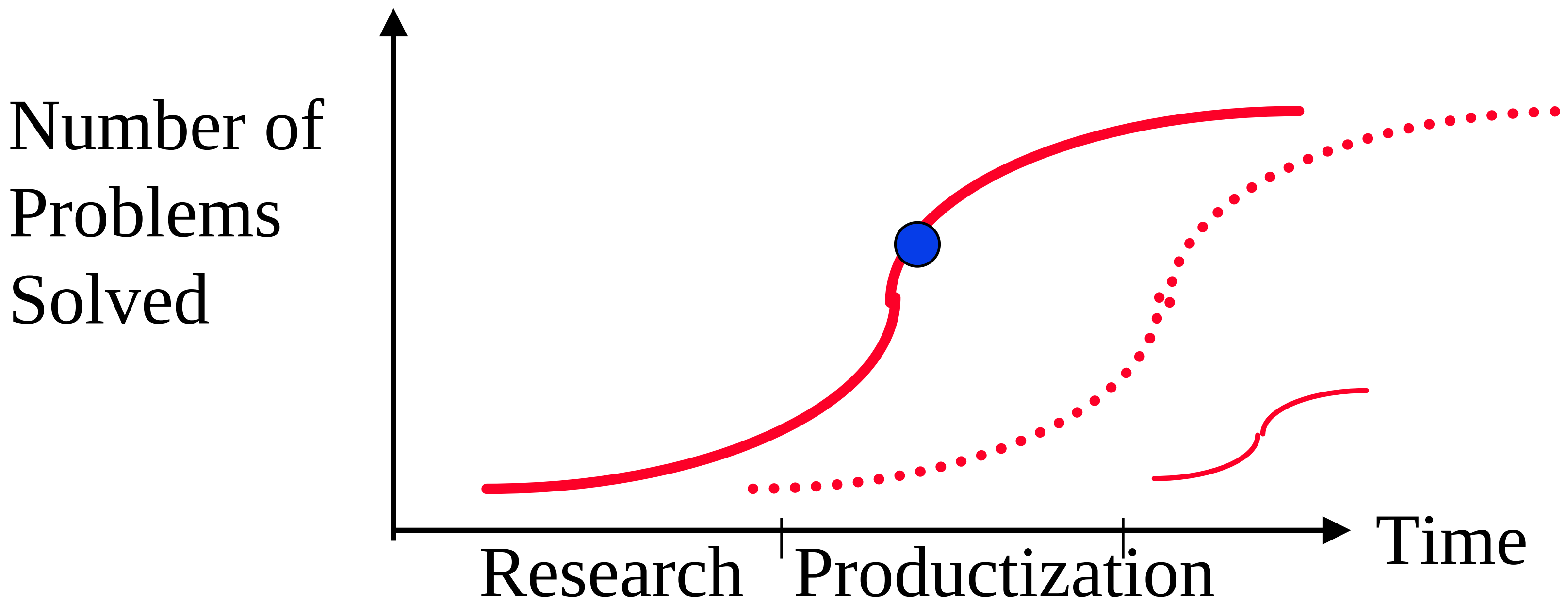
Networking Trends

- Life Cycles of Technologies
- Traffic and Capacity growth
- Ethernet Everywhere

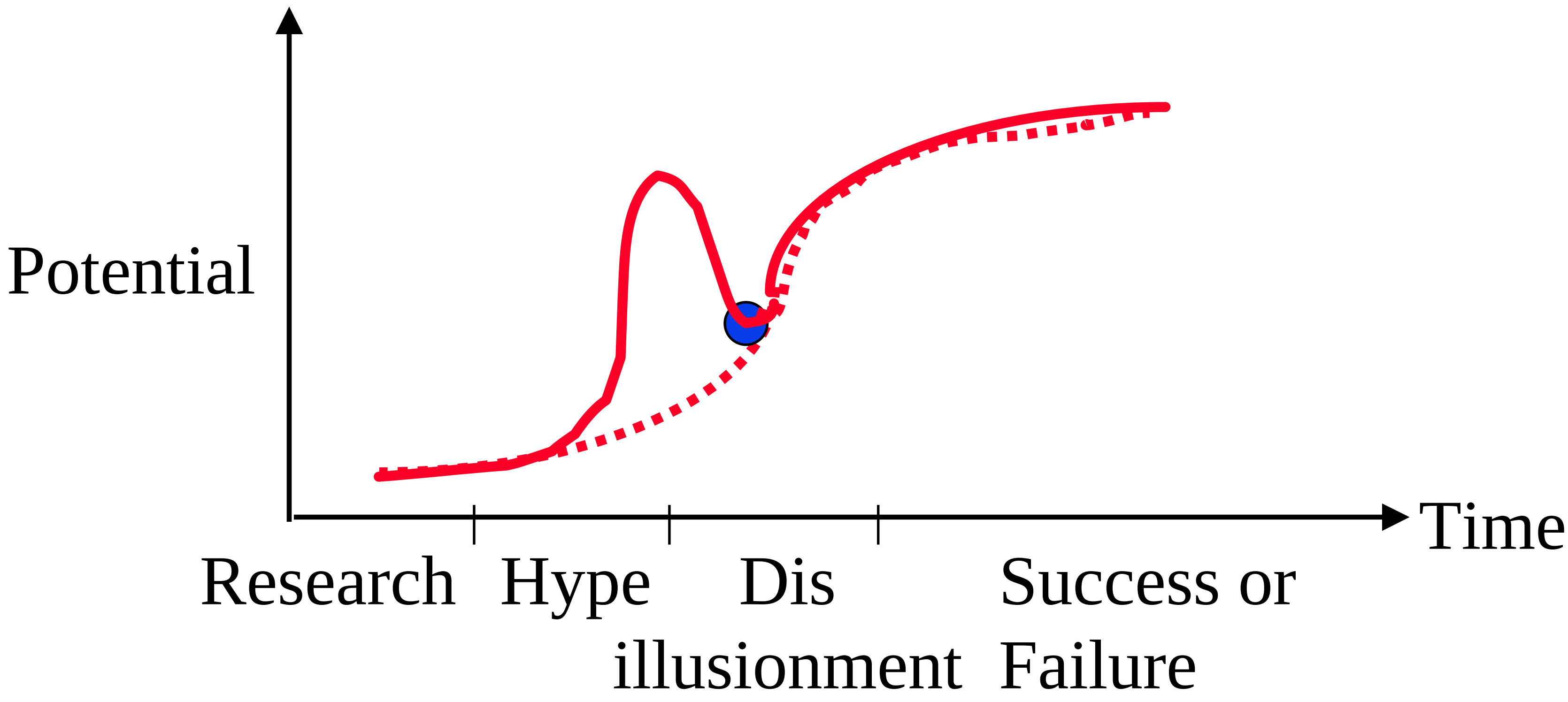
Competitive Local Exchange Carriers ...



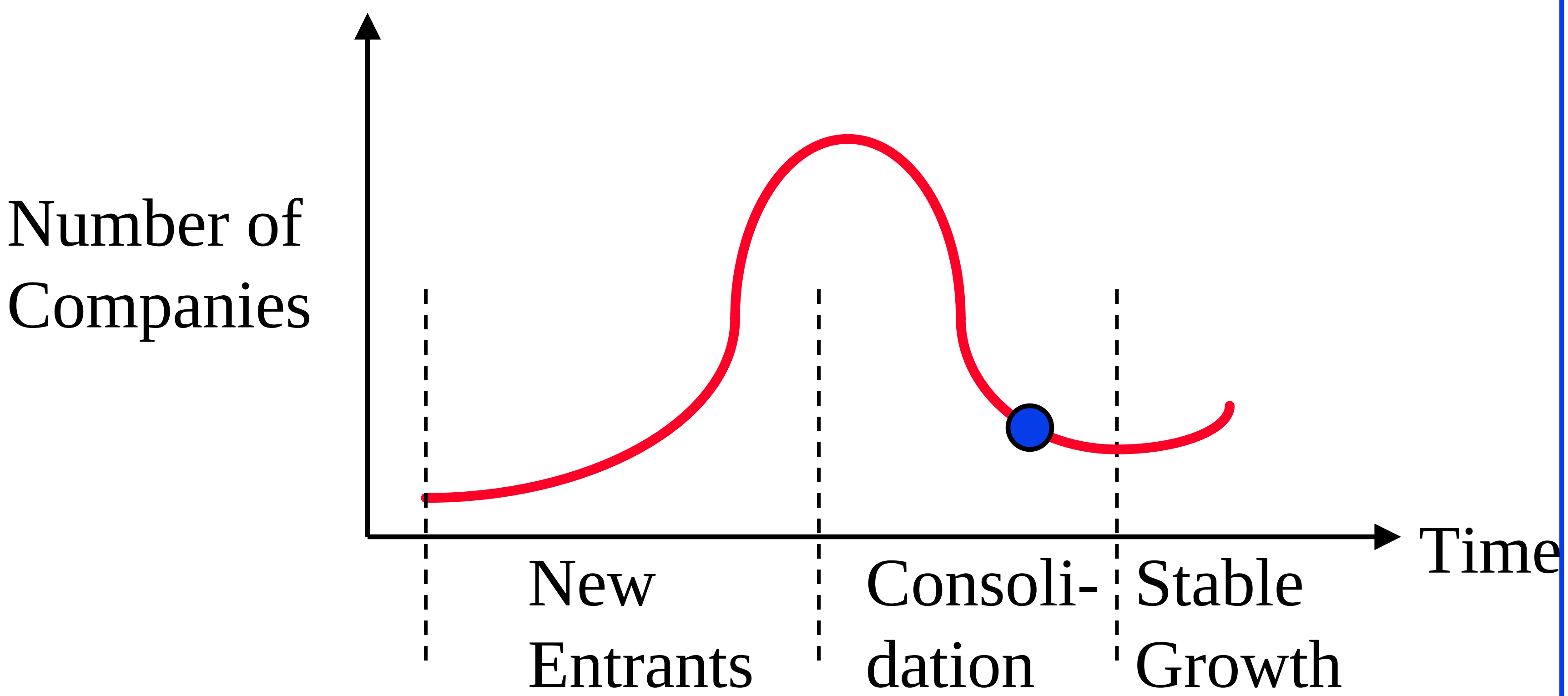
Life Cycles of Technologies



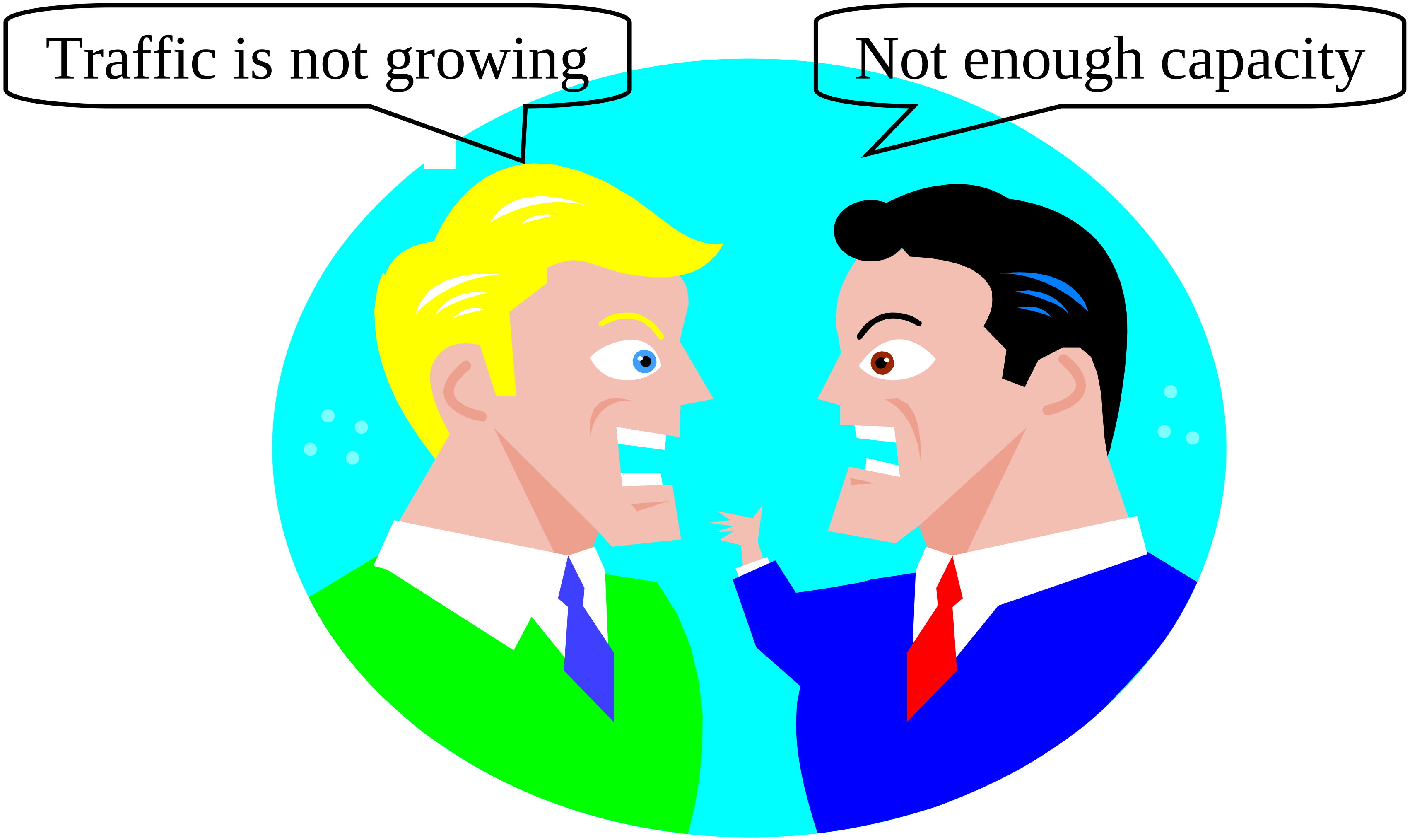
Hype Cycles of Technologies



Industry Growth



Glut-sters vs Gap-sters



Traffic vs Capacity Growth

Expensive Bandwidth	Cheap Bandwidth
❑ Sharing	❑ No sharing
❑ Multicast	❑ Unicast
❑ Virtual Private Networks	❑ Private Networks
❑ Need QoS	❑ QoS less of an issue
❑ Likely in WANs	❑ Possible in LANs

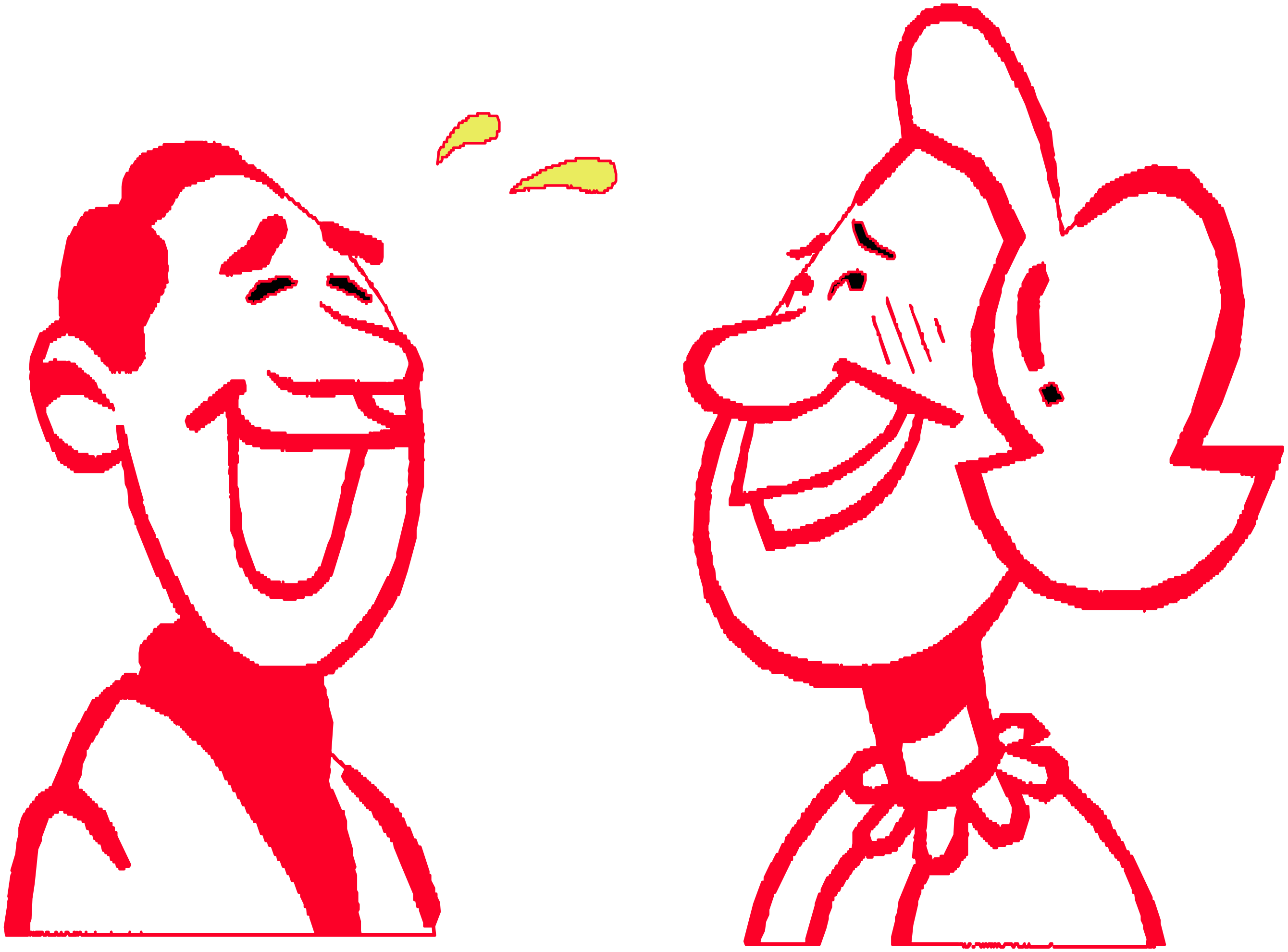
Predictions

"And of all variations of multimedia, the one that will drive ATM is personal computers videoconferencing - interactive, two-way, real-time, integrated digital voice, video and data. Ethernet will remain as a legacy LAN." - Robert Metcalfe, Inventor of Ethernet

Trend: Ethernet Everywhere

- Ethernet in Enterprise Backbone
  - Ethernet vs ATM (Past)
- Ethernet in Metro: Ethernet vs SONET
  - 10 G Ethernet
  - Survivability, Restoration ⇒ Ring Topology
- Ethernet in Access: EFM
- Ethernet in homes: Power over Ethernet

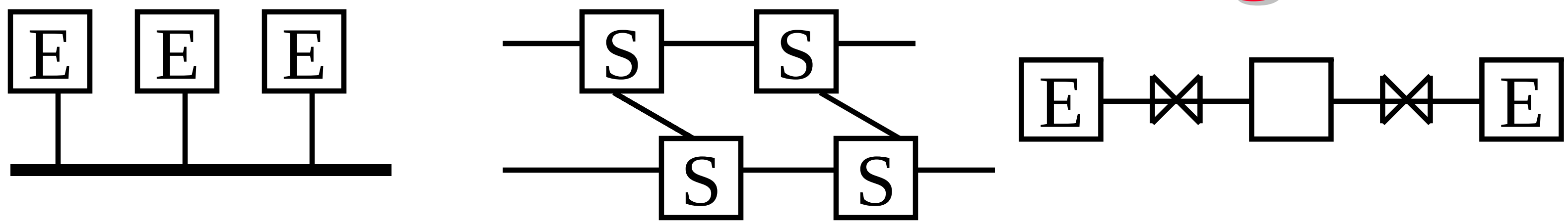
Before



RSVP V1 RFC came out in September 1997

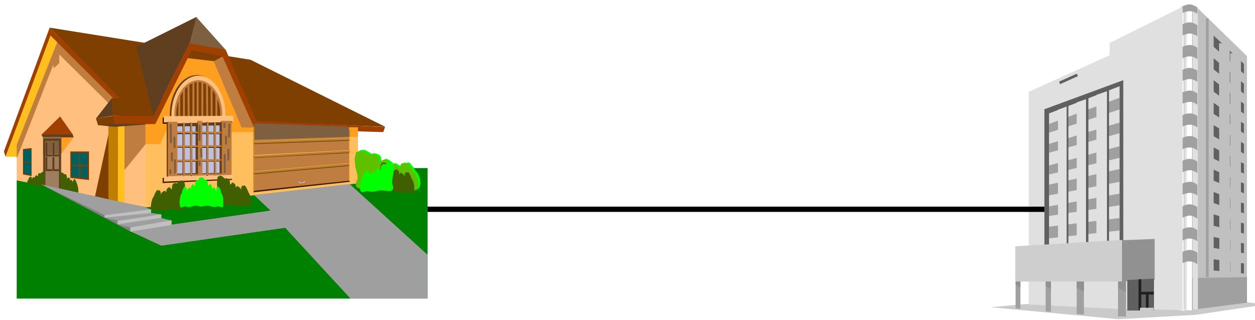
After

Trend: LAN - WAN Convergence



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

Ethernet in the First Mile

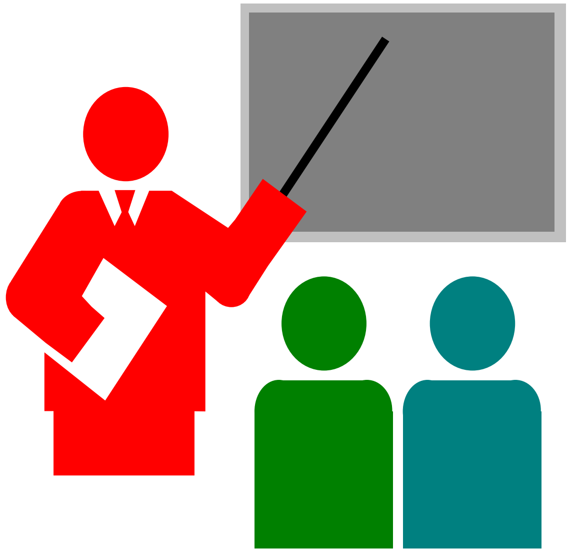


- IEEE 802.3 Study Group started November 2000
- Originally called Ethernet in the Last Mile
- Current Technologies: ISDN, xDSL, Cable Modem, Satellite, Wireless, PON
- EFM Goals: Media: Phone wire, Fiber, Air
  - Speed: 125 kbps to 1 Gbps
  - Distance: 1500 ft, 18000 ft, 1 km - 40 km
- Ref: http://www.ieee802.org/3/efm/public/index.htm

Power over Ethernet

- IEEE 802.3af group approved 30 January 2000 Power over MDI (Media Dependent Interface)
- Applications: Web Cams, PDAs, Intercoms, Ethernet Telephones, Wireless LAN Access points, Fire Alarms, Remote Monitoring, Remote entry
- Power over TP to a single Ethernet device: 10BASE-T, 100BASE-TX, 1000BASE-T (TBD)
- Interoperate with legacy RJ-45 Ethernet devices
- Standard Expected: November 2002
- Ref: http://grouper.ieee.org/groups/802/3/power_study/public/nov99/802.3af_PAR.pdf

Summary



- Traffic > Capacity
  $\Rightarrow$ Need QoS, traffic engineering in WANs
- Ethernet everywhere
  $\Rightarrow$ Rings, many rates, longer distances, Power

DWDM, SONET, SDH, OTN

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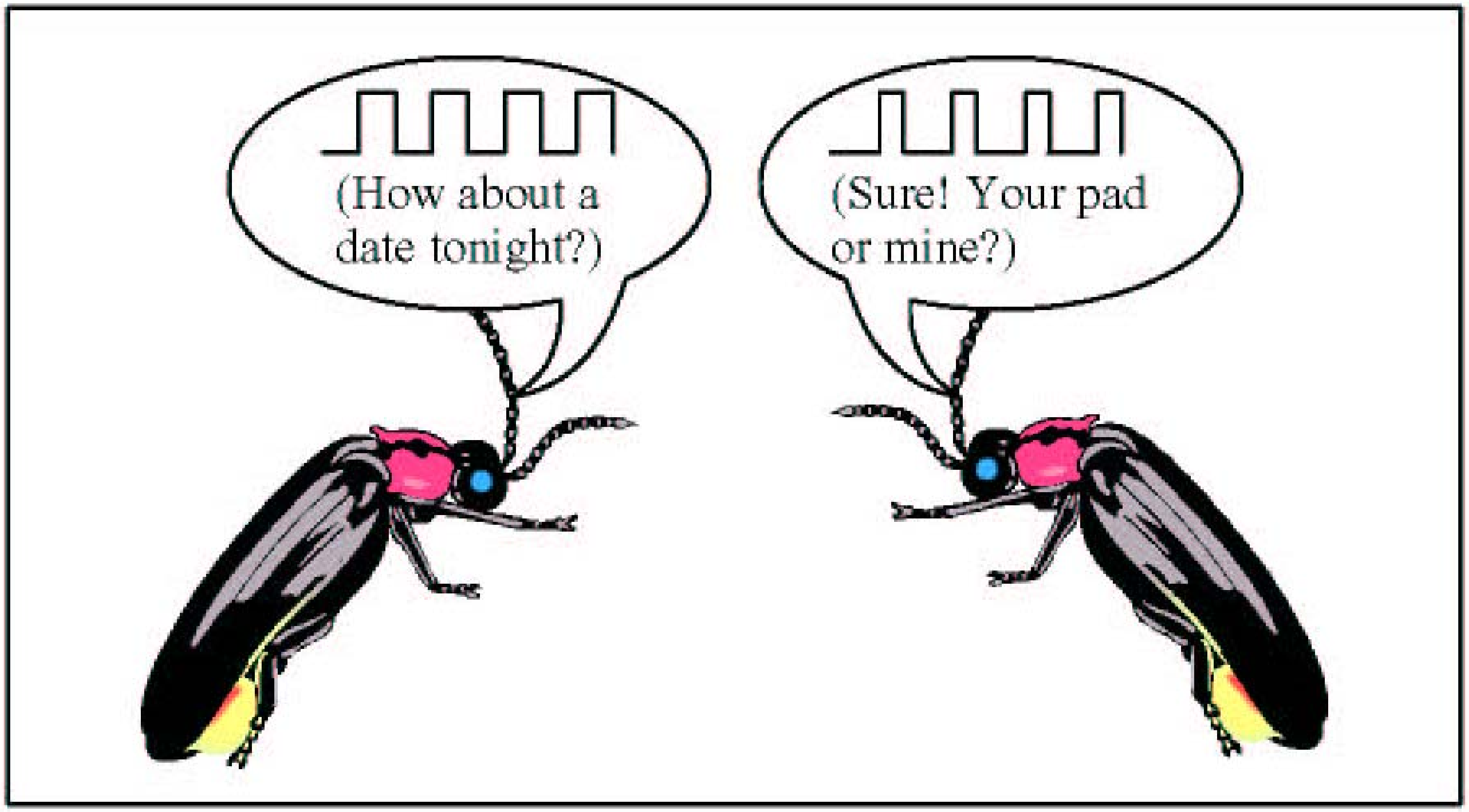
- DWDM
- OEO VS OOO
- SONET
- SDH
- OTN

Optical Communication…History

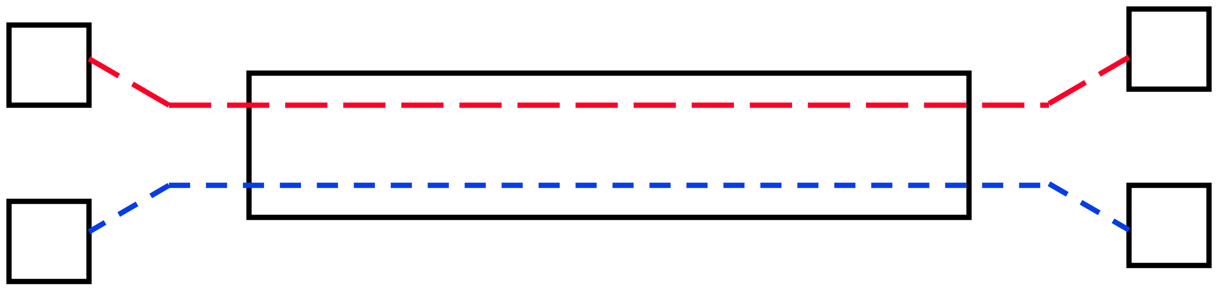


Fireflies use pulse-width modulation.

Photonic Sensing

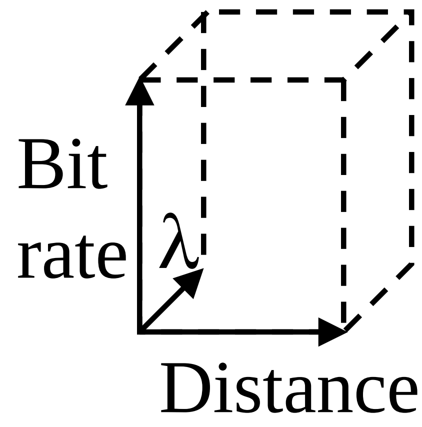
Brittle Stars use optical crystals for photonic sensing.
- USA Today, August 24, 2001

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

Recent DWDM Records

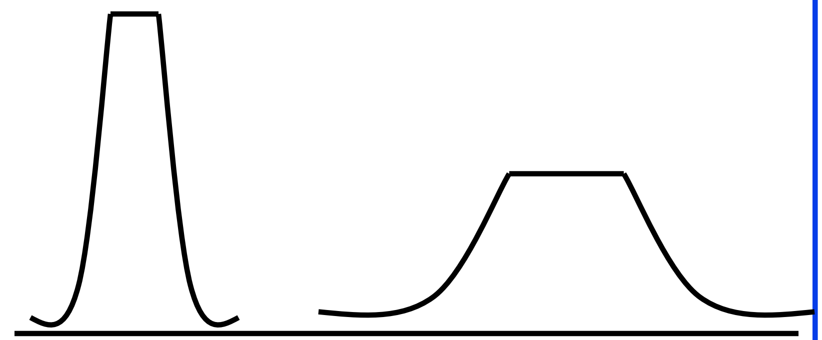


- 32λ× 5 Gbps to 9300 km (1998)
- 16λ× 10 Gbps to 6000 km (NTT'96)
- 160λ× 20 Gbps (NEC'00)
- 128λ× 40 Gbps to 300 km (Alcatel'00)
- 64λ× 40 Gbps to 4000 km (Lucent'02)
- 19λ× 160 Gbps (NTT'99)
- 7λ× 200 Gbps (NTT'97)
- 1λ×1200 Gbps to 70 km using TDM (NTT'00)
- 1022 Wavelengths on one fiber (Lucent'99)

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

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

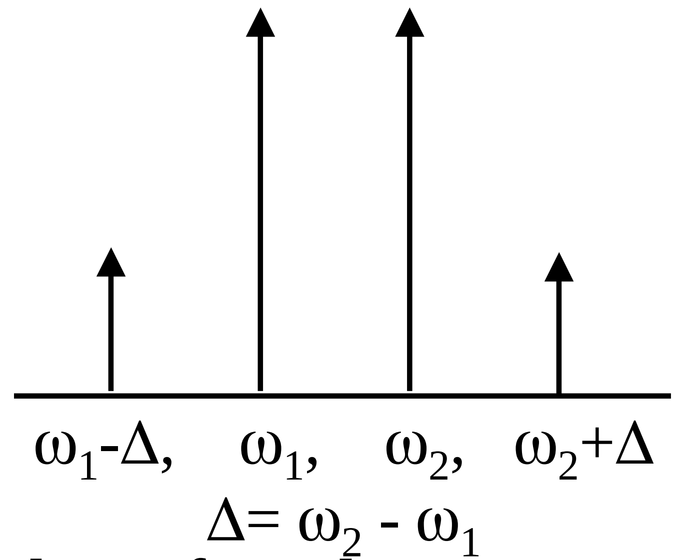
Attenuation and Dispersion



- Pulses become shorter and wider as they travel through the fiber

Hot Interconnect 2002

Four-Wave Mixing



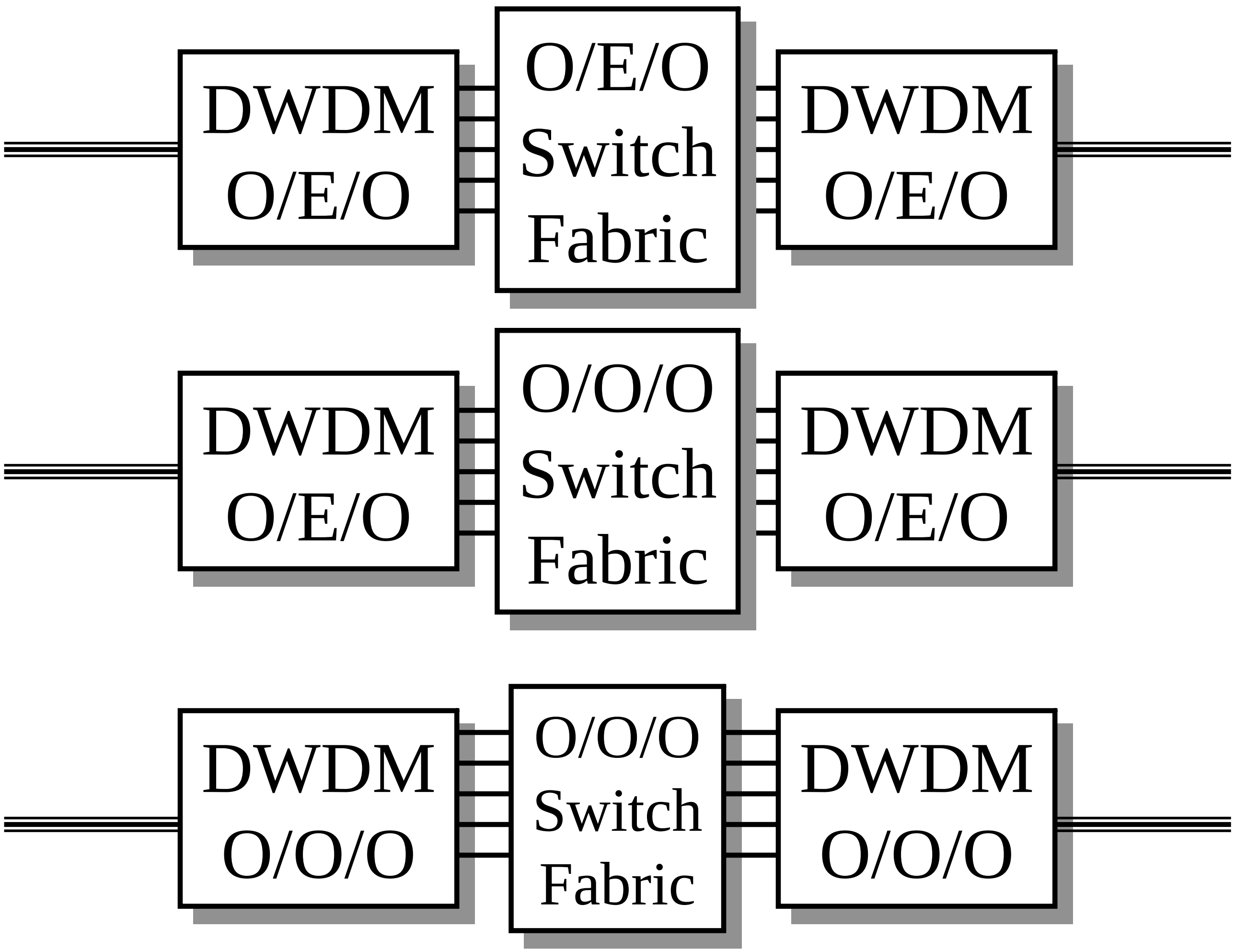
- If two signals travel in the same phase for a long time, new signals are generated.

Recent Products Announcements

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	160	10	800	2001
	40	10	4000	2001
Cisco ONS 15800	160	10	2000	2002

- Ref: "Ultra everything," Telephony, October 16, 2000

Optical Crossconnect Architectures



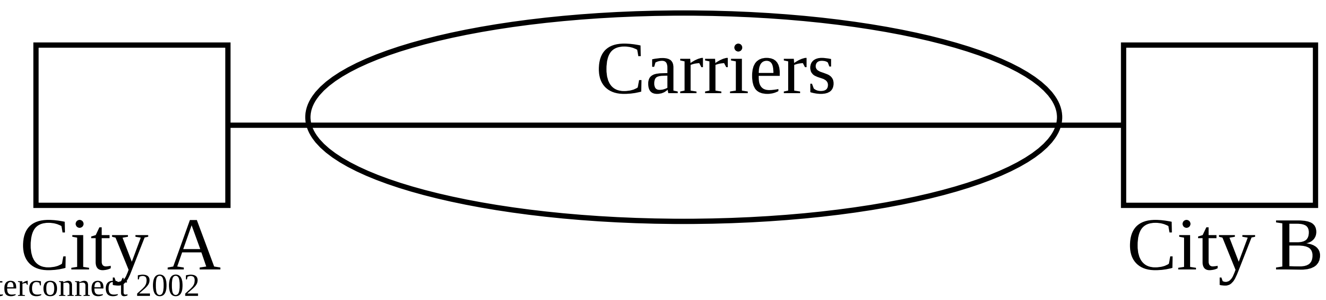
OEO vs OOO Switches

- 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
    $\Rightarrow$ 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

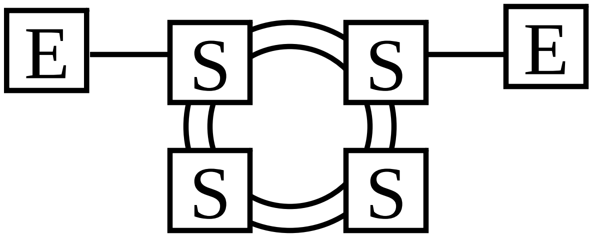
SONET

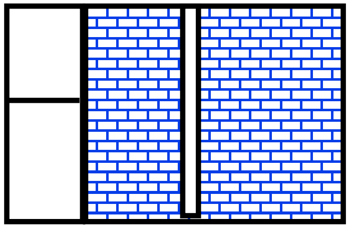
- Synchronous optical network
- Standard for digital optical transmission (bit pipe)
- Developed originally by Bellcore to allow mid-span meet between carriers: MCI and AT&T. Standardized by ANSI and then by ITU

  $\Rightarrow$ Synchronous Digital Hierarchy (SDH)
- You can lease a SONET connection from carriers



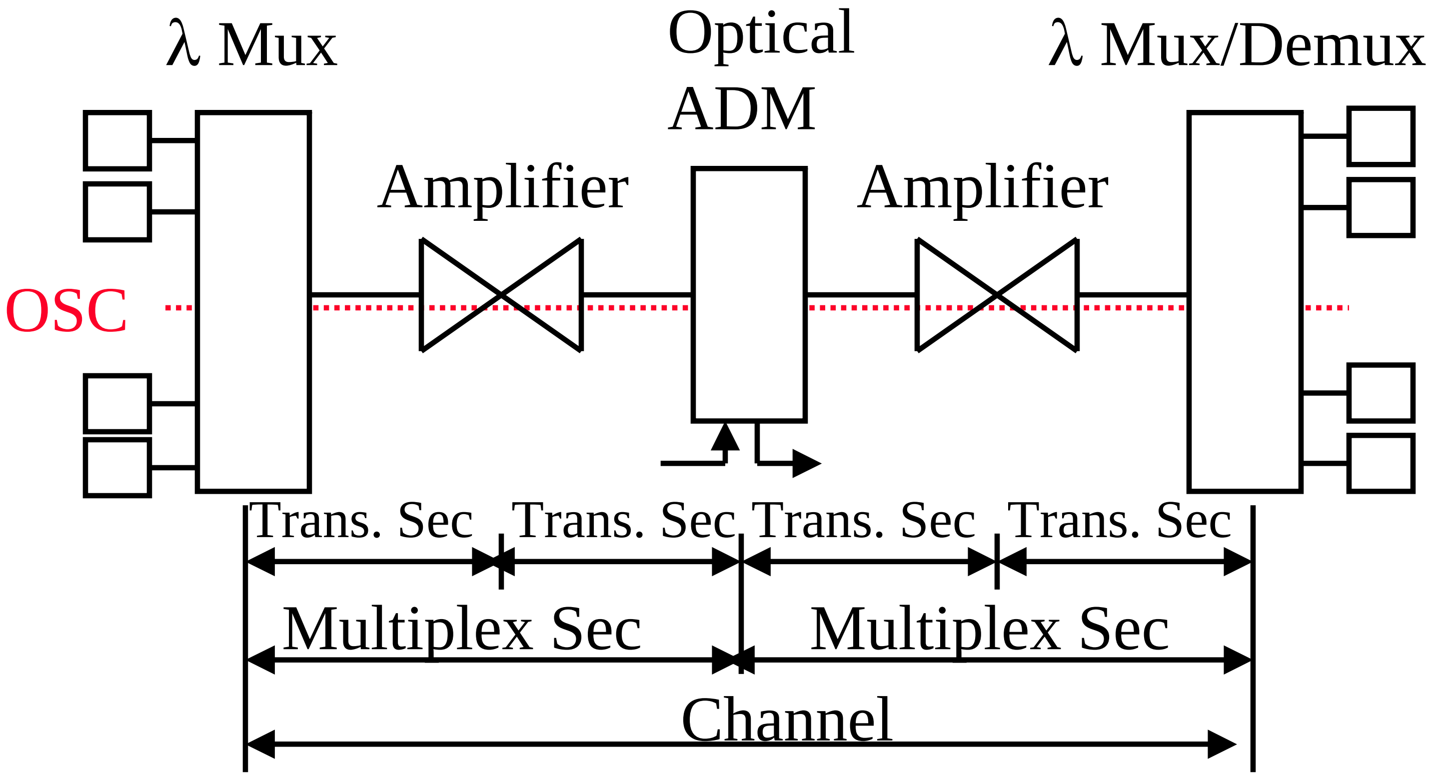
SONET Functions





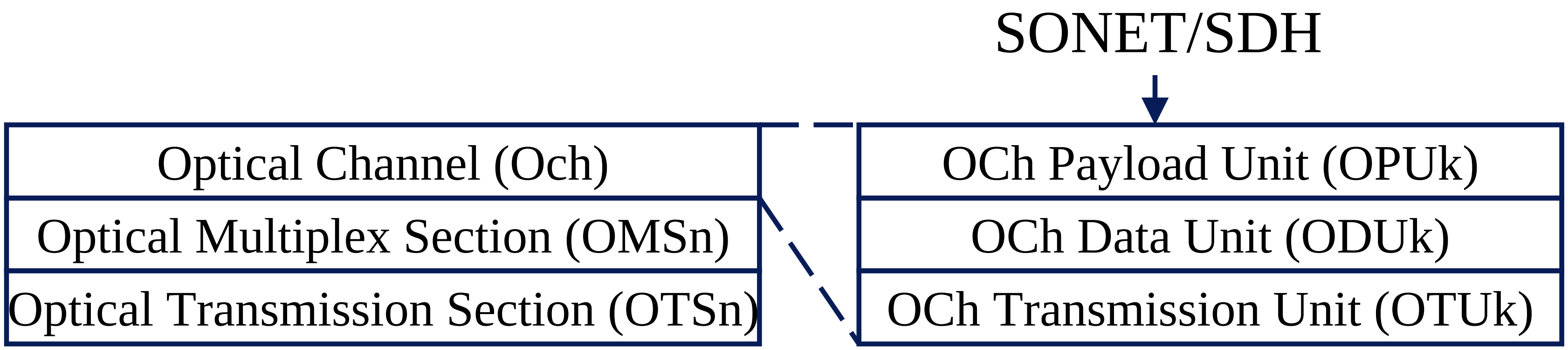
- Protection: Allows redundant Line or paths
- Fast Restoration: 50ms using rings
- Sophisticated OAM&P
- Ideal for Voice: No queues. Guaranteed delay
- Fixed Payload Rates: 51M, 155M, 622M, 2.4G, 9.5G
  Rates do not match data rates of 10M, 100M, 1G, 10G
- Static rates not suitable for bursty traffic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

Optical Transport Network (OTN)



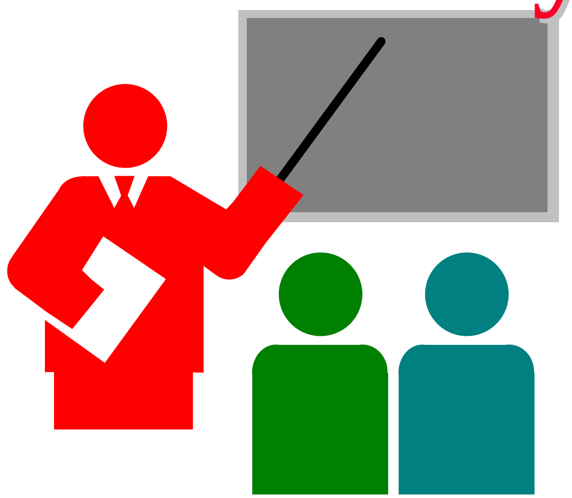
- G.709 Digital Wrapper designed for WDM networks
- OTN*n*.*k* = *n* wavelengths at *k*th rate, 2.5, 10, 40 Gbps plus one Optical Supervisory Channel (OSC)
- OTNnr.k = Reduced OTNn.k ⇒ Without OSC

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
- STS-n = OC-n = n X 51. Mbps line rate
  STM-n = STS-3n is used in Europe
- SONET/SDH have ring based protection
- OTN uses FEC digital wrapper and allows WDM

1G/10G Ethernet, RPR, Next Gen SONET

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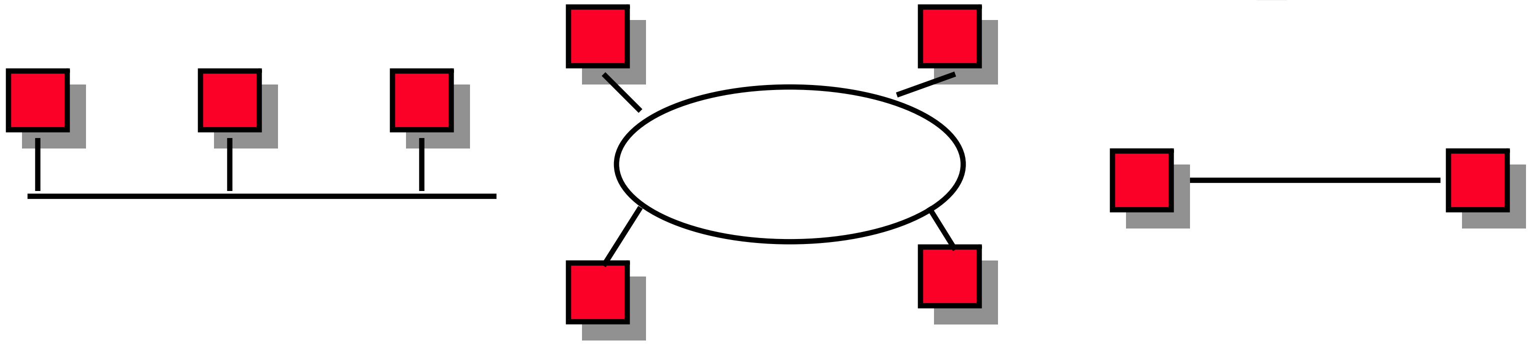
- Distance Bandwidth Principle
- Gigabit Ethernet
- 10 G Ethernet
- Resilient Packet Rings
- Next Generation SONET: VCAT, GFP, LCAS

The Magic Word α

Distance-B/W Principle



- Efficiency = Max throughput/Media bandwidth
- Efficiency is a non-increasing function of α
  α = Propagation delay /Transmission time
  = (Distance/Speed of light)/(Transmission size/Bits/sec)
  = Distance×Bits/sec/(Speed of light)(Transmission size)
- Bit rate-distance-transmission size tradeoff.
- 100 Mb/s ⇒ Change distance or frame size

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
  Both hub and switch based networks
- Same min and max frame size as 10/100 Mbps
  ⇒ Changes to CSMA/CD protocol
  Transmit longer if short packets

1000Base-X

- 1000Base-LX: 1300-nm laser transceivers
  - 2 to 550 m on 62.5-μm or 50-μm multimode, 2 to 5000 m on 10-μm single-mode
- 1000Base-SX: 850-nm laser transceivers
  - 2 to 275 m on 62.5-μm, 2 to 550 m on 50-μm. Both multimode.
- 1000Base-CX: Short-haul copper jumpers
  - 25 m 2-pair shielded twinax cable in a single room or rack.

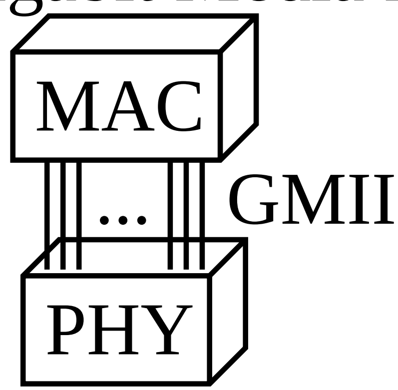
    Uses **8b/10b** coding ⇒ 1.25 GBaud/s line rate
- *1000Base-ZX: Long haul lasers to 70 km (not Std)*

1000Base-T

- 100 m on 4-pair Cat-5 UTP
  ⇒ Network diameter of 200 m
- Applications: Server farms, High-performance workgroup, Network computers
- Supports CSMA/CD (Half-duplex):
  Carrier Extension, Frame Bursting
- 250 Mbps/pair full-duplex DSP based PHY
  ⇒ Requires new 5-level (PAM-5) signaling
  with 4-D 8-state Trellis code FEC
- FEC coded symbols.
  Octet data to 4 quinary (5-level) symbols and back,
  e.g., 001001010 = {0, -2, 0, -1}

1000BASE-T (Cont)

- Inside PHY, before coding, the data is scrambled using $x^{33}+x^{20}+1$ in one direction and $x^{33}+x^{13}+1$ self-synchronizing scrambler in the other direction
- Automatically detects and corrects pair-swapping, incorrect polarity, differential delay variations across pairs
- Autonegotiation ⇒ Compatibility with 100Base-T
- Complies with Gigabit Media Independent Interface
- 802.3ab-1999



10 GbE: Key Design Decisions

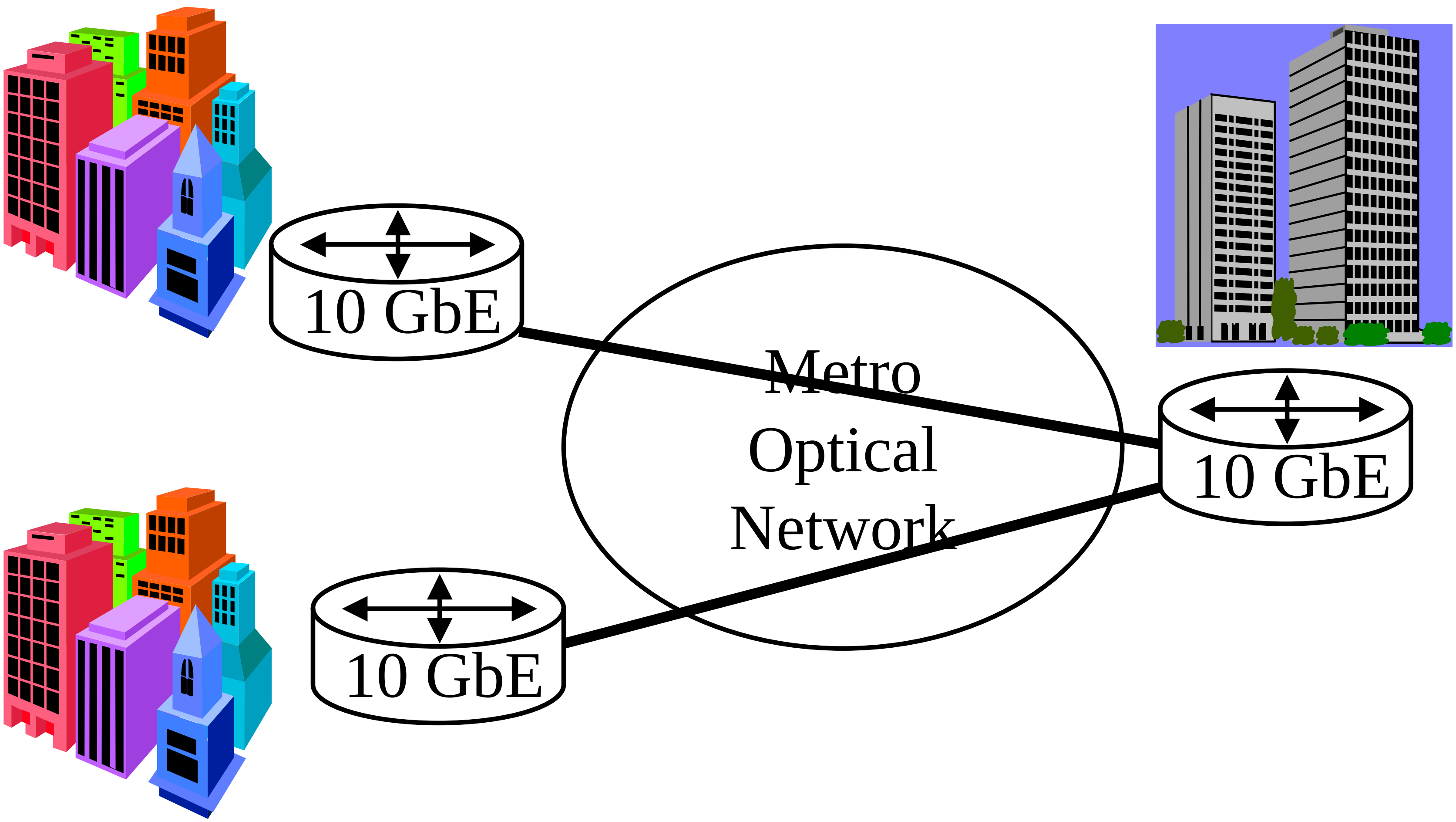
- P802.3ae ⇒ Update to 802.3
  Compatible with 802.3 frame format, services, management
- 10 Gbps vs. 9.5 Gbps. **Both** rates.
- LAN and MAN distances
- Full-duplex only ⇒ No Shared Mode
  Only switch based networks. No Hubs.
- Same min and max frame size as 10/100/1000 Mbps
  Point-to-point ⇒ No CSMA/CD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

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

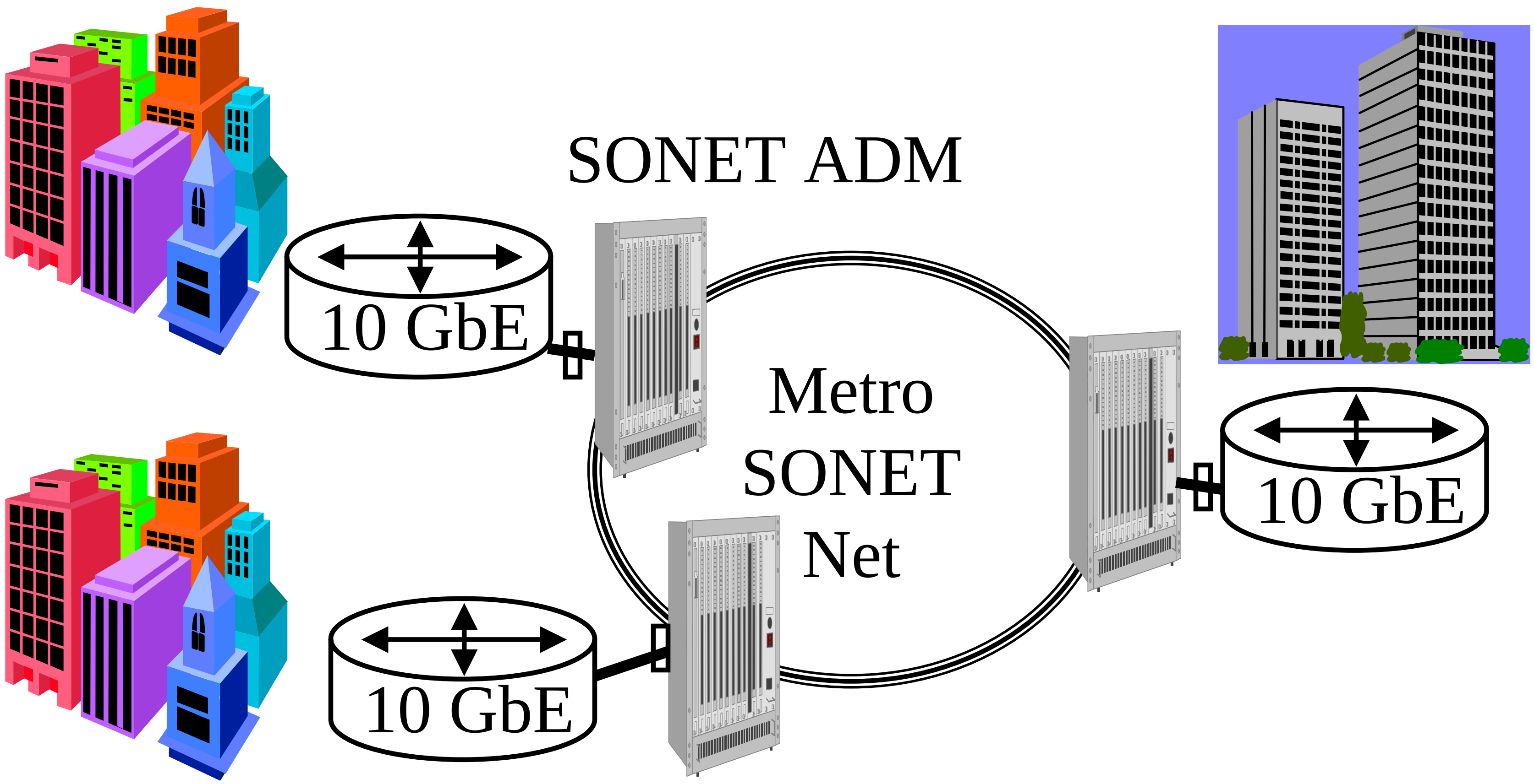
- S = Short Wave, L=Long Wave, E=Extra Long Wave
- R = Regular reach (64b/66b), W=WAN (64b/66b + SONET Encapsulation), X = 8b/10b
- 4 = 4 λ's

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

Future Possibilities

- 40 Gbps
- 100 Gbps:
  - 16λ×6.25 Gbps
  - 8λ × 12.5 Gbps
  - 4λ × 12.5 using PAM-5
- 160 Gbps
- 1 Tbps:
  - 12 fibers with 16λ × 6.25 Gbps
  - 12 fibers with 8λ × 12.5 Gbps
- 70% of 802.3ae members voted to start 40G in 2002

Ethernet vs SONET

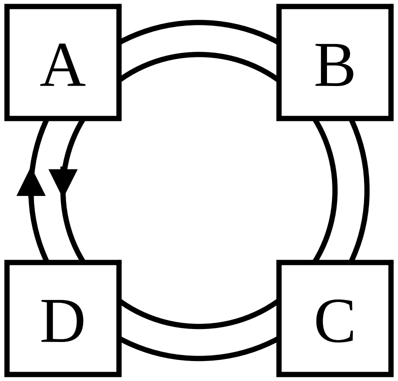
Feature	SONET	Ethernet
Payload Rates	51M, 155M, 622M, 2.4G, 9.5G	10M, 100M, 1G, 10G
Payload Rate Granularity	Fixed	√Any
Bursty Payload	No	√Yes
Payload Count	One	√Multiple
Protection	√Ring	Mesh
OAM&P	√Yes	No
Synchronous Traffic	√Yes	No
Restoration	√50 ms	Minutes
Cost	High	√Low
Used in	Telecom	Enterprise

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	

Networking and Religion

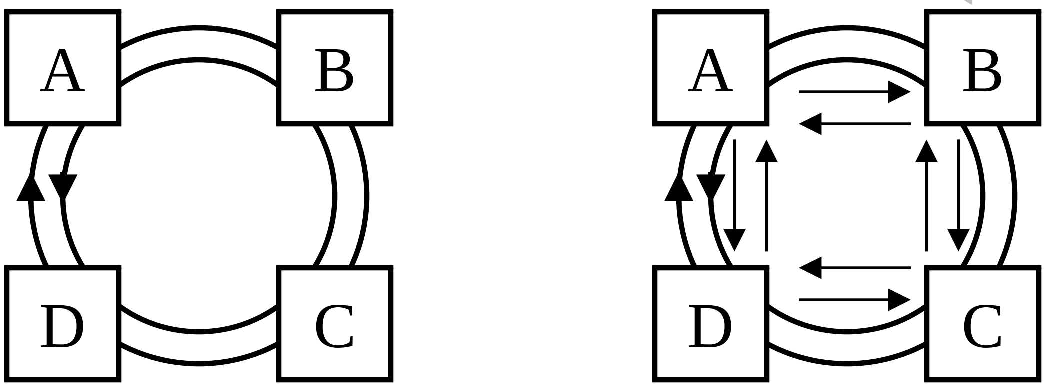
Both are based on a set of beliefs

RPR: Key Features



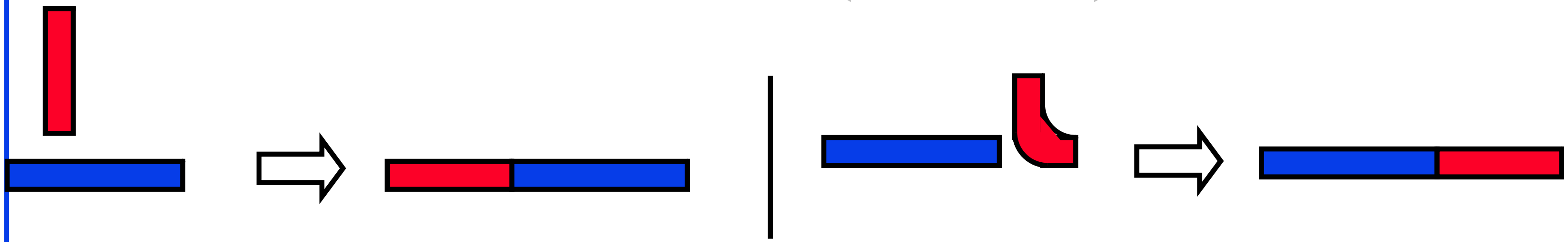
- Dual Ring topology
- Supports broadcast and multicast
- Packet based ⇒ Continuous bandwidth granularity
- Max 256 nodes per ring
- MAN distances: Several hundred kilometers.
- Gbps speeds: Up to 10 Gbps

RPR Features (Cont)



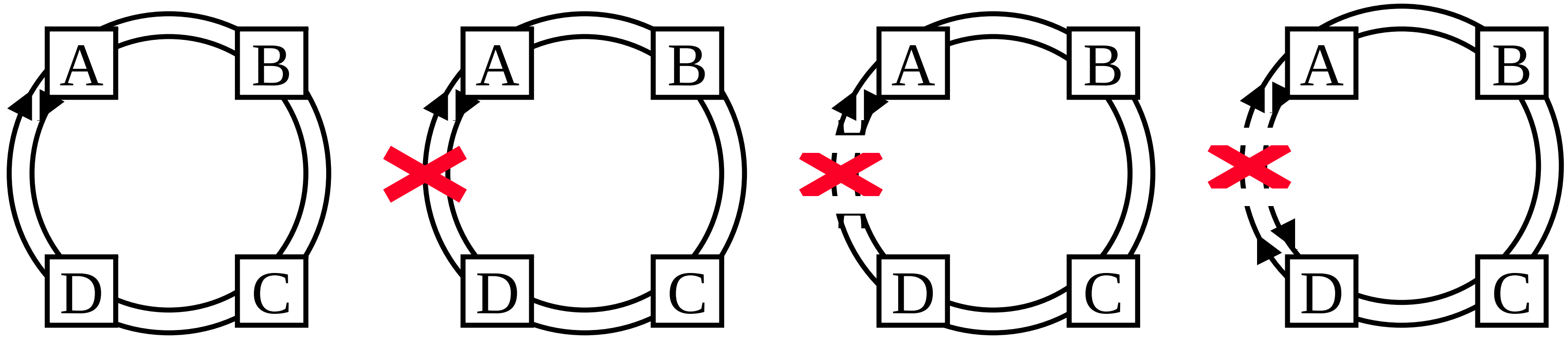
- Both rings are used (unlike SONET)
- Normal transmission on the shortest path
- Destination stripping ⇒ Spatial reuse
  Multicast packets are source stripped
- Five Classes of traffic: Reserved, High-Priority, Medium Priority, Low Priority, Control

RPR (Cont)



- Buffer Insertion Ring: Absolute but non-preemptive priority to pass-through traffic
- Cut-through of transit packets optional.
- Bandwidth management: Unused bandwidth is advertised so that others can use it
- Fairness Algorithm for fair and efficient bandwidth use
- Physical Layer Independent: GbE/10GE or SONET with GFP or PoS

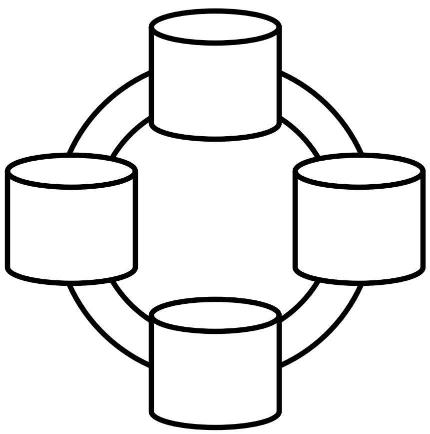
RPR Protection Mechanisms

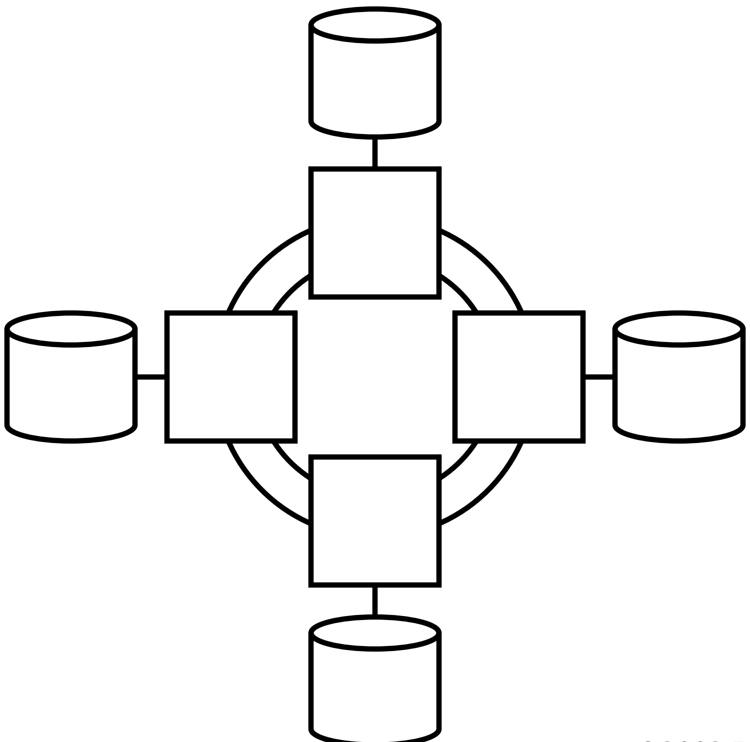


1. **Wrapping**: Stations adjacent to failure wrap. After re-org, packets sent on shortest path. Multicast packets are sent on **one** ring with TTL=Total number of stations.
2. **Source Steering**: Failure detecting station sends a Protection Request message to every station. Sources select appropriate ringlet to reach their destination. Multicast packets are sent on **both** rings with TTL=Total number of stations

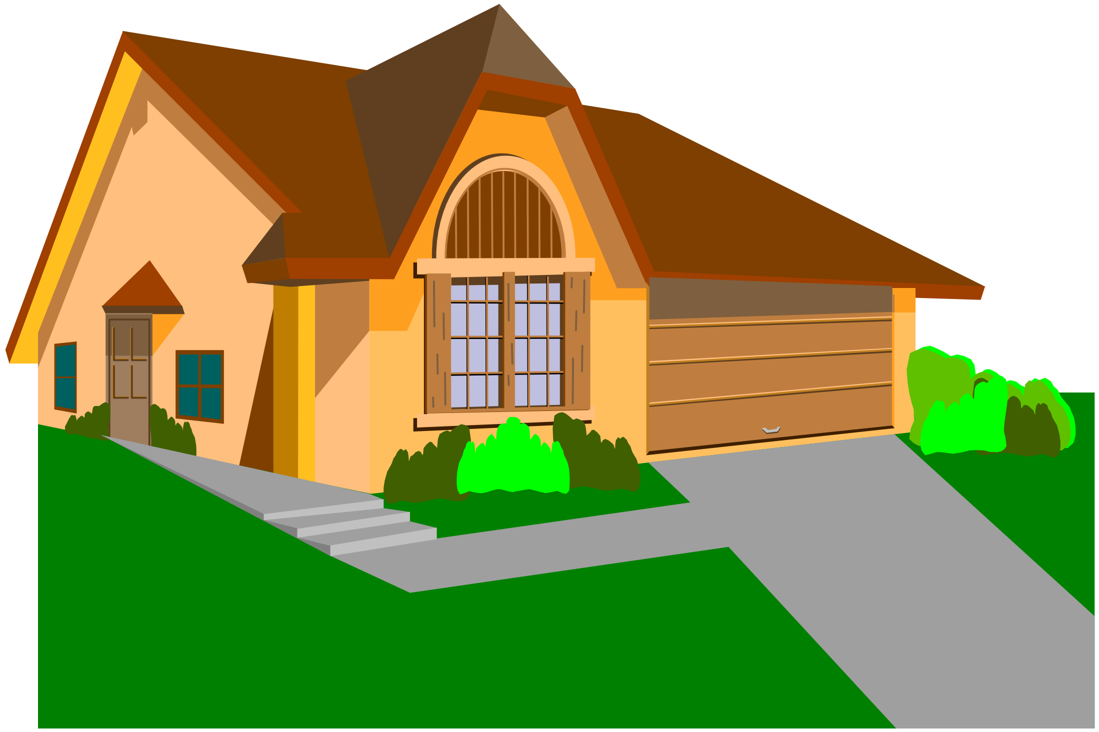
RPR Issues

- Ring vs Mesh (Atrica)
- Router Feature vs Dedicated RPR Node (Cisco, Redback, Riverstone vs Luminous)





Old House vs New House



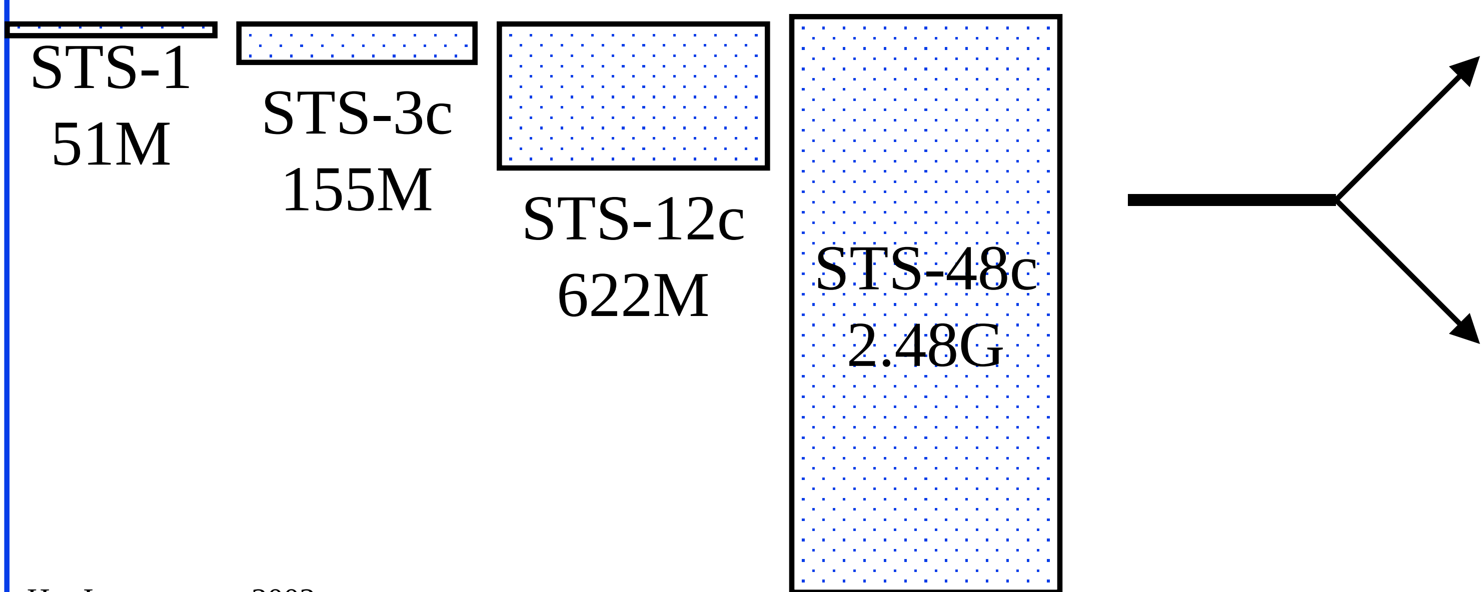
- New needs:

  Solution 1: Fix the old house (cheaper initially)

  Solution 2: Buy a new house (pays off over a long run)

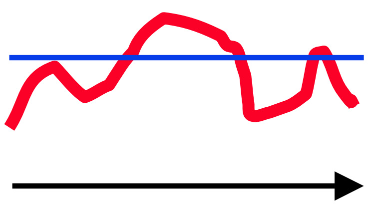
Data over SONET: Problems

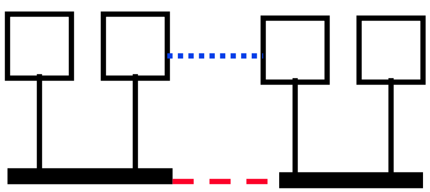
1. Rates highly discrete: In units of STS-3c's. Can't do STS-2c.
2. Entire payload on one path. No splitting, no multipath.
3. Size mismatch: 10 Mbps over 51.84, 100 Mbps over 155 Mbps, 1 Gbps over 1.24 Gbps

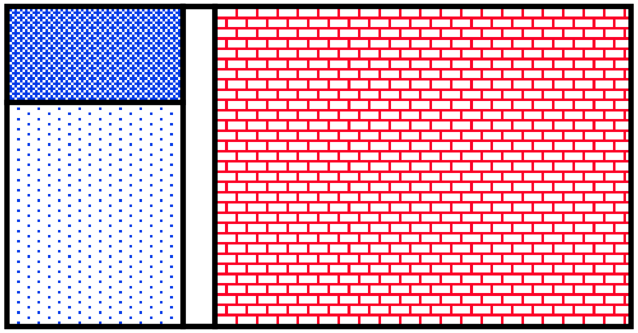


SONET Problems (Cont)

4. Data is bursty (Dynamic). SONET is fixed (static).
5. Inefficient Transparent Connections:
   1 GE = 1.25 Gbps at PHY layer ⇒ Needs OC-48c
6. Only one type of payload per stream: TDM, ATM, FDDI, Packets, Ethernet, Fiber Channel



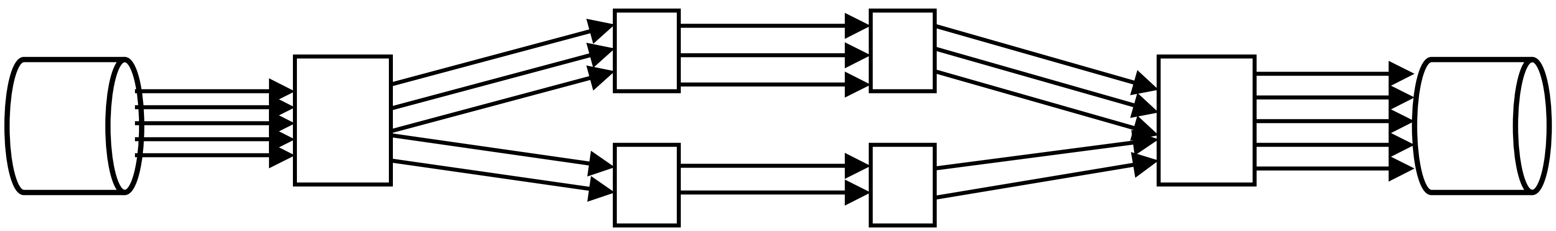




Data over SONET: Solutions

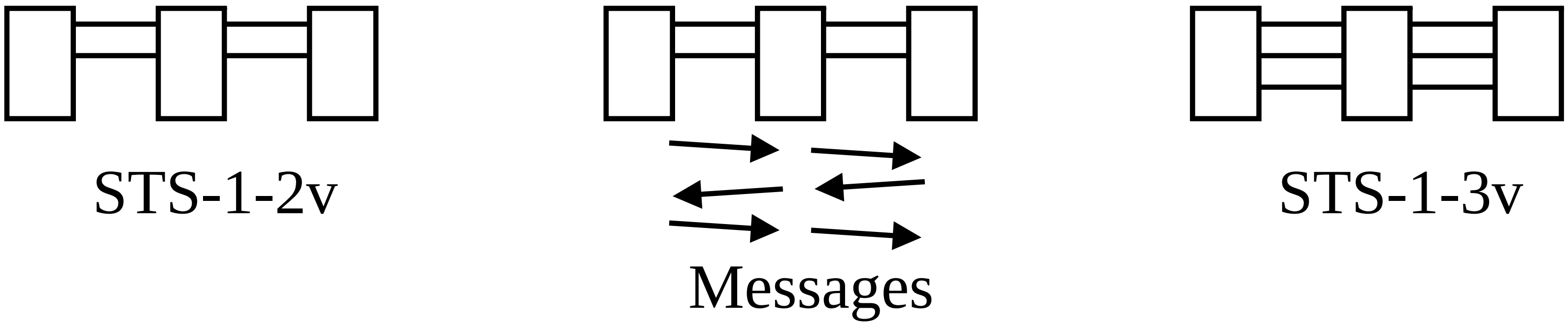
- Virtual Concatenation: n-STS-1's over multiple paths
  1. A channel can be n×STS-1 or nxT1 for any n
  2. Different STS-1's can follow different path
  3. Size match: 10 Mbps over 7 T1,
     100 Mbps over 2 STS-1, 1 Gbps over 21 STS-1
- LCAS: Link Capacity Adjustment Scheme
  4. Can dynamically change number of STS-1's
- GFP: Generic Framing Procedure
  5. Efficient Transparent Connections:
  6. Allows multiple type of payload per stream

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
  $\Rightarrow$ Need buffering at the ends to equalize delay
- All channels are administered together.
  Common processing only at end-points.

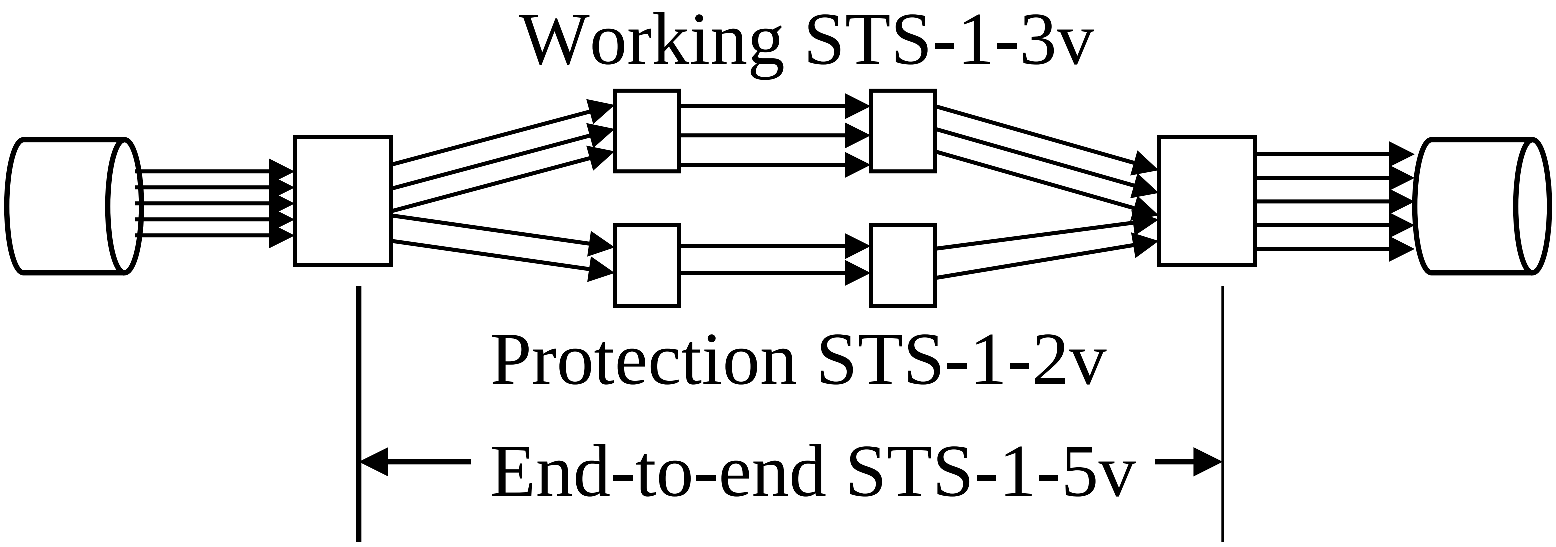
SONET LCAS



- 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

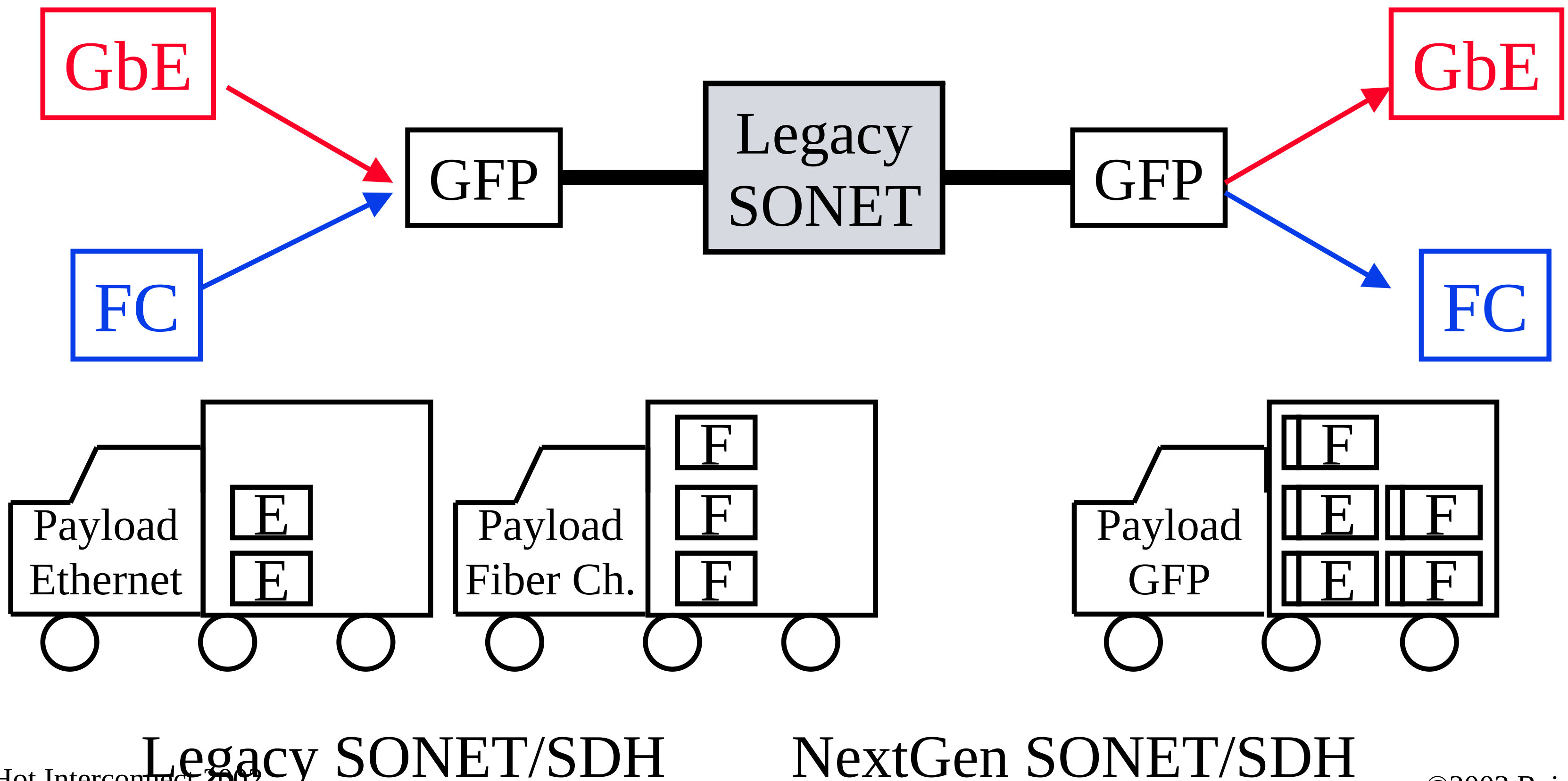
LCAS (Cont)

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



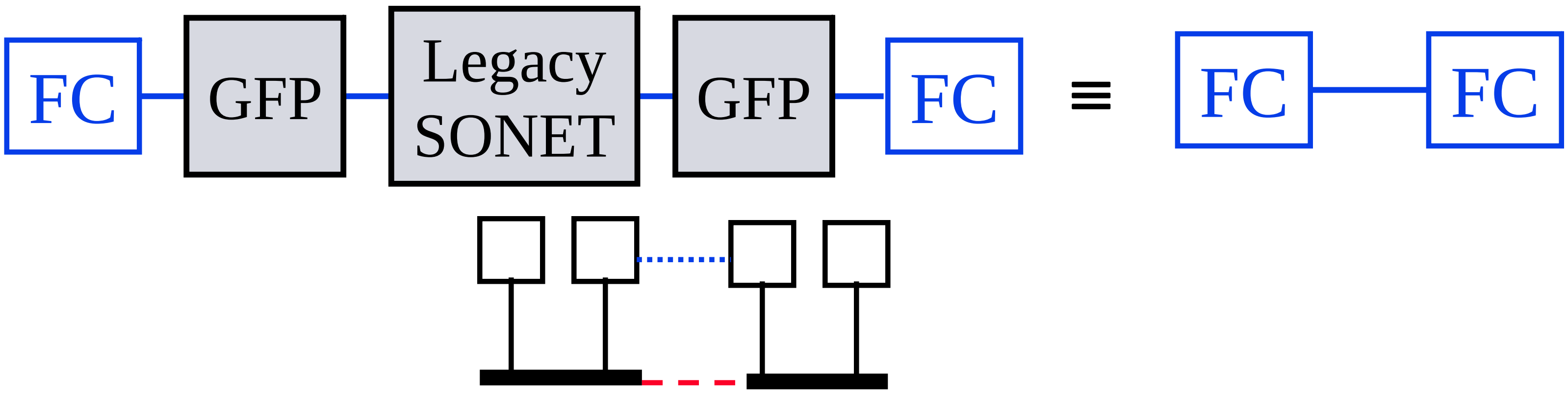
Generic Framing Procedure (GFP)

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



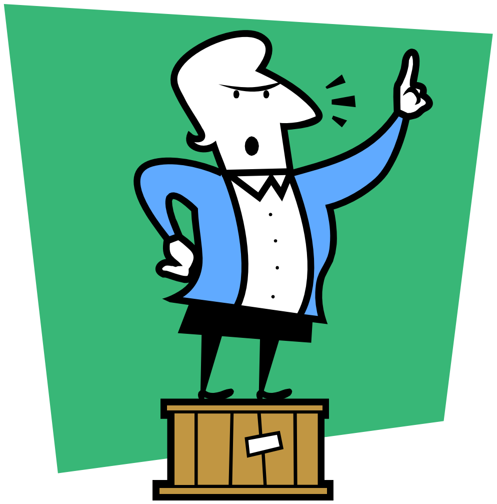
Transparent GFP

- 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



- Gigabit Ethernet runs at 1000 Mbps
- 10 GbE for full duplex LAN and WAN links
- 1000 Mbps and 9,584.640 Mbps
- RPR will make it more suitable for Metro

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.

IP over DWDM

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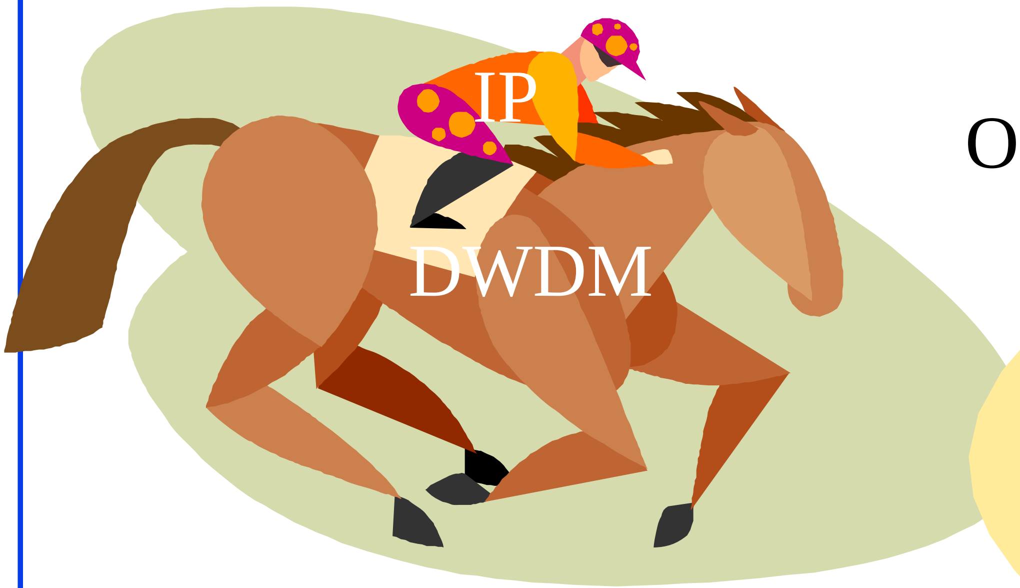
http://www.cis.ohio-state.edu/~jain/

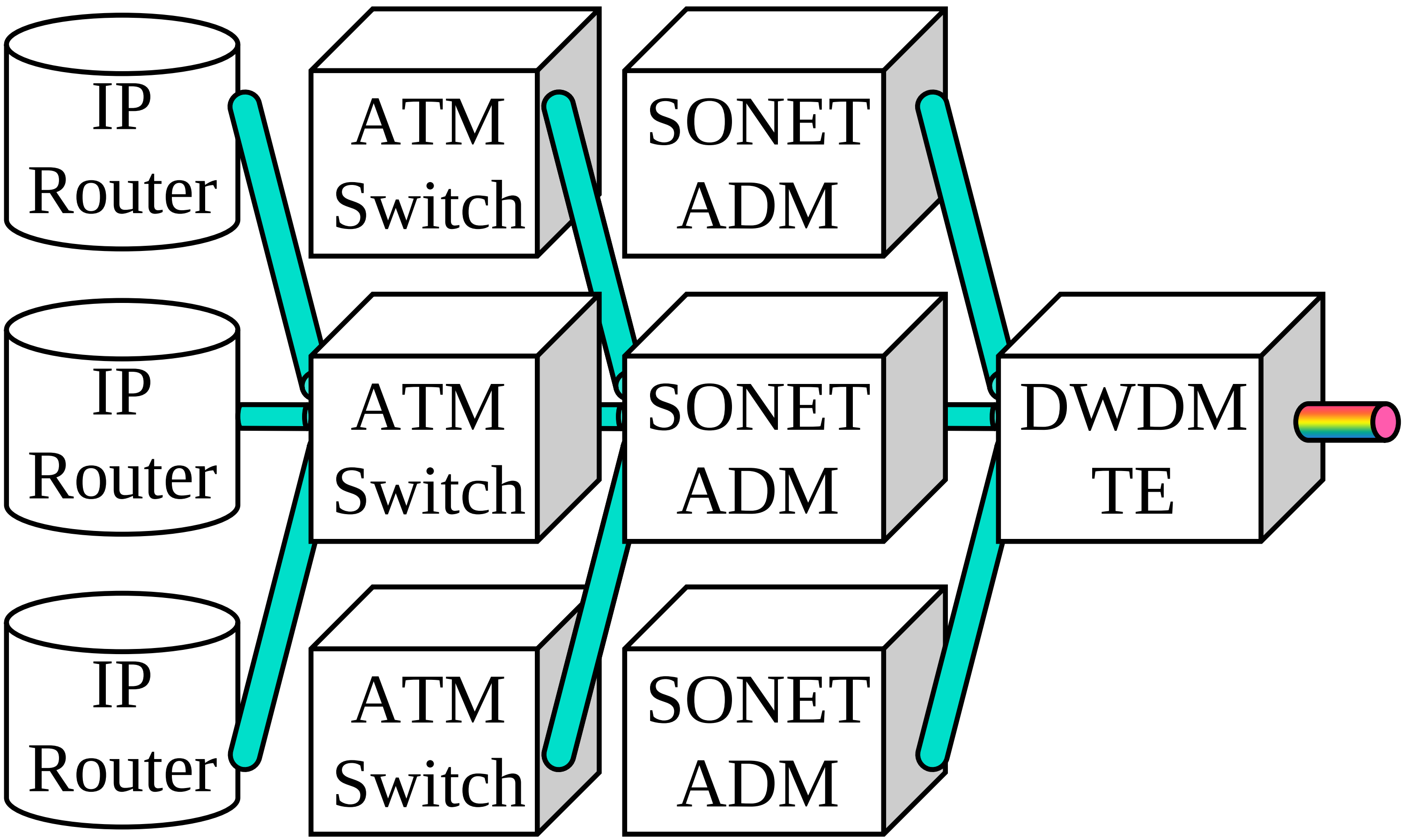
- IP over DWDM
- UNI
- ASTN/ASON
- MPLS, MPλS, GMPLS
- Upcoming optical technologies

IP over DWDM



Or?

IP over DWDM (Past)

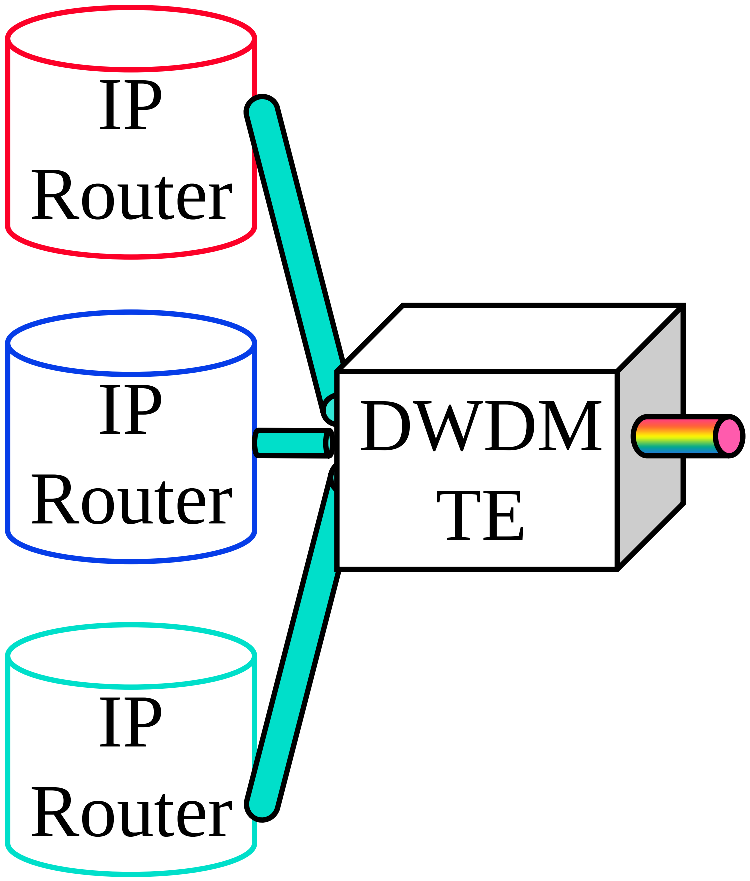


IP over DWDM: Protocol Layers

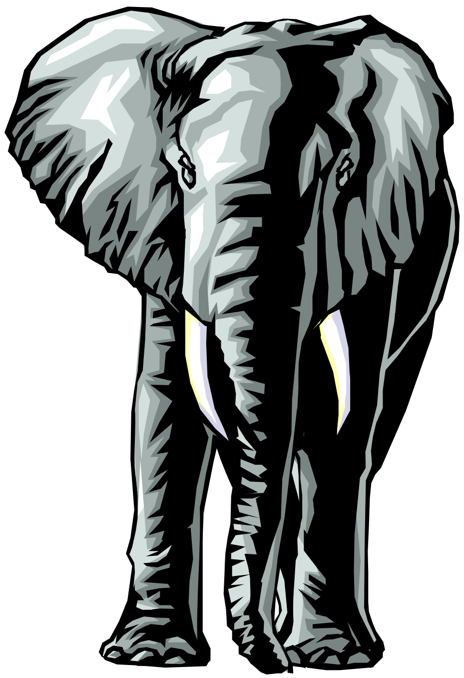
1993	1996	1999	2001	2005
IP	IP	IP/MPλS	IP/GMPLS	IP/GMPLS
ATM	PPP	PPP	Ethernet	Ethernet
SONET	SONET	SONET Framing	SONET Framing	
DWDM	DWDM	DWDM	DWDM	DWDM
Fiber	Fiber	Fiber	Fiber	Fiber

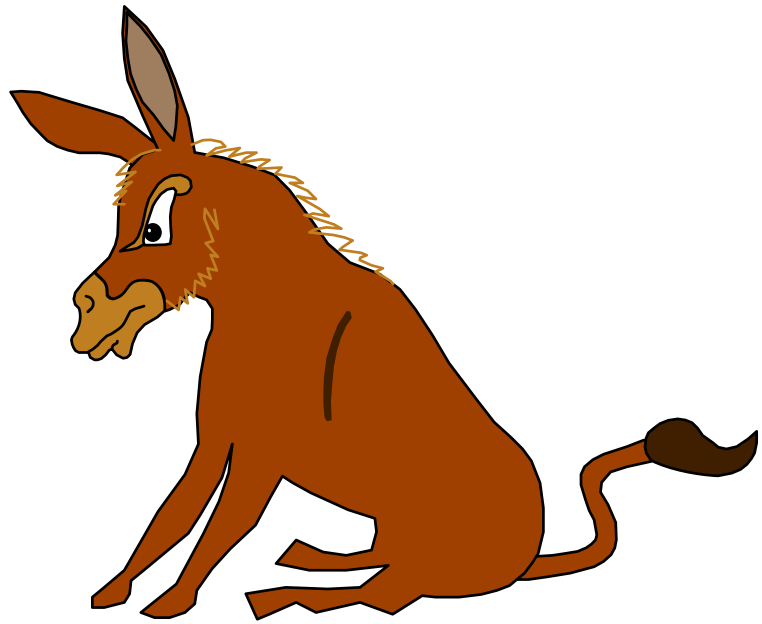
- IP is good for routing, traffic aggregation, resiliency
- ATM for multi-service integration, QoS/signaling
- SONET for traffic grooming, monitoring, protection
- DWDM for capacity
- Problem: Restoration in multiple layers, Sonet Manual
  $\Rightarrow$ Intersection of features and union of problems

IP over DWDM (Future)



Telecom vs Data Networks

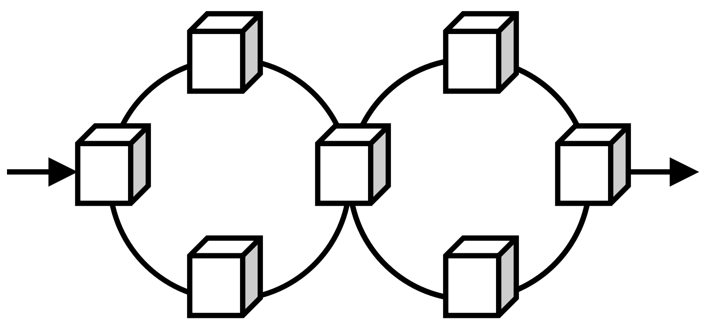


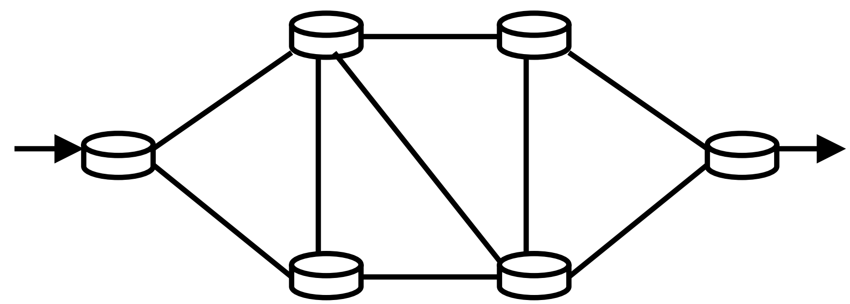


Telecom	Data
Complex	Simple
QoS, Protection	Need QoS, Protection…
Expensive	Cheap

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



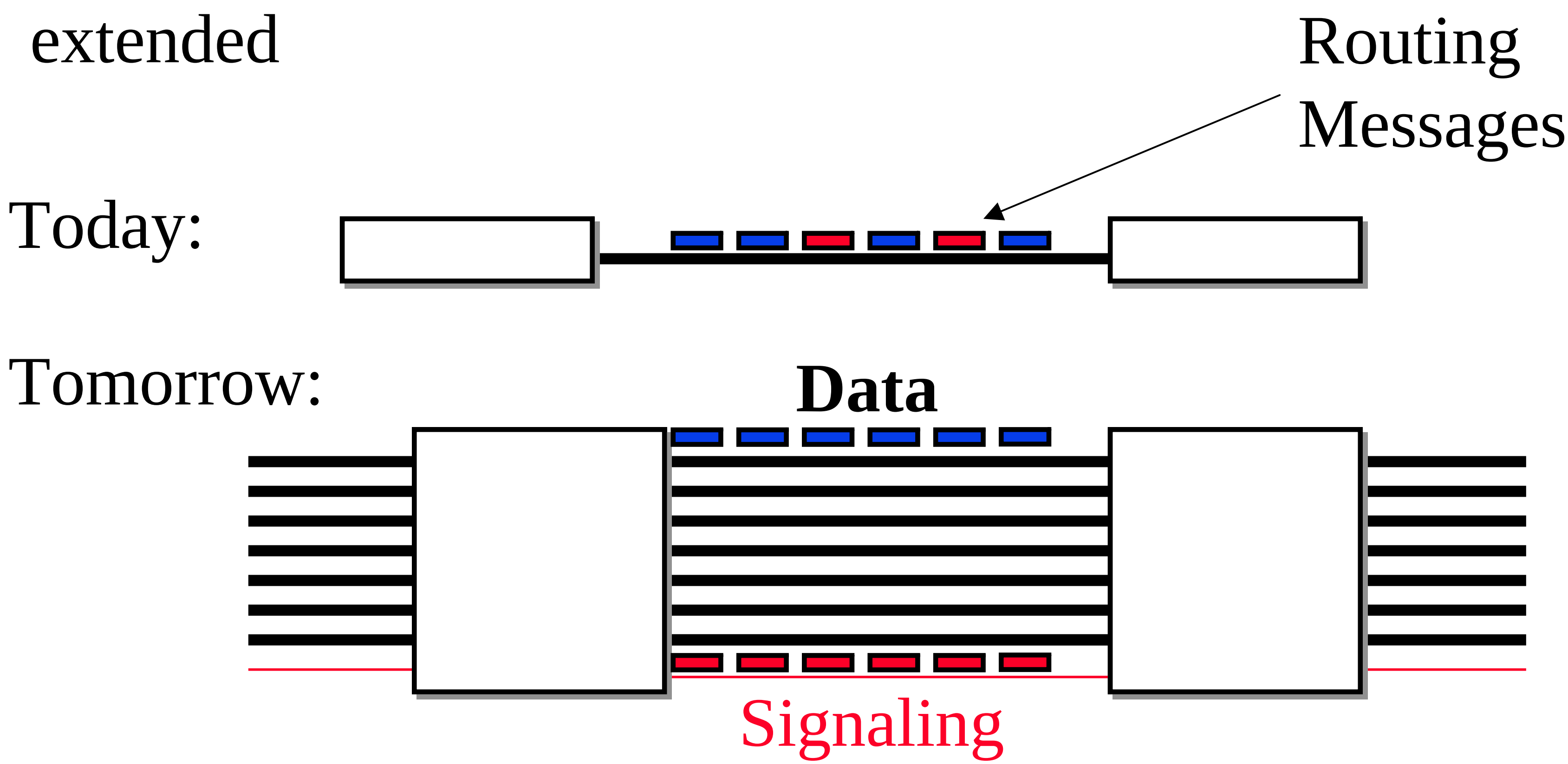


IP over DWDM Issues

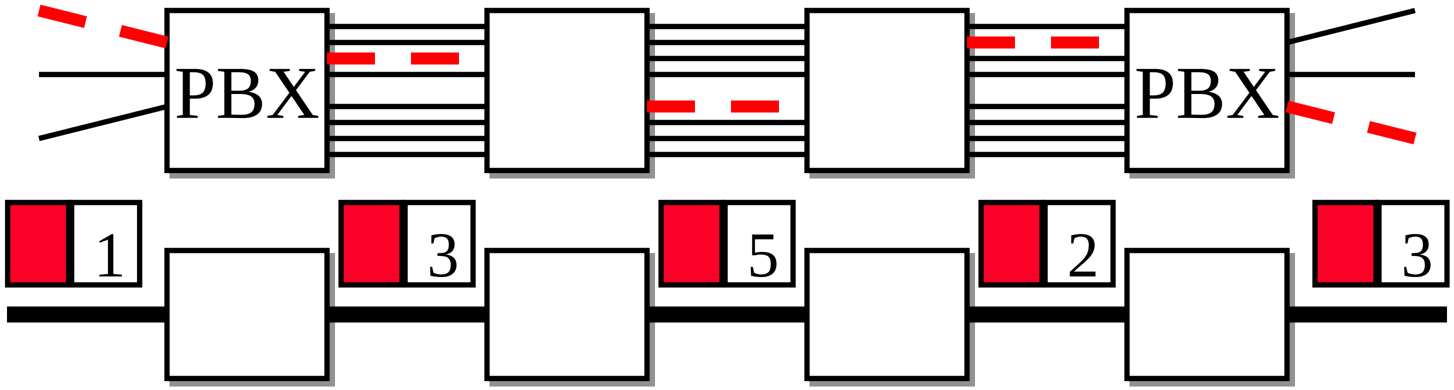
1. Data and Control plane separation
2. Circuits
3. Signaling
4. Addressing
5. Protection and Restoration

Issue: Control and Data Plane Separation

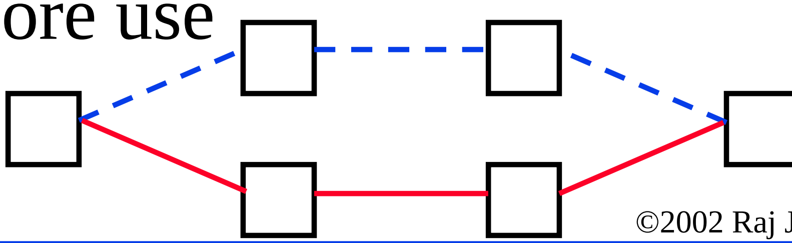
- Separate control and data channels
- IP routing protocols (OSPF and IS-IS) are being extended



Multiprotocol Label Switching (MPLS)



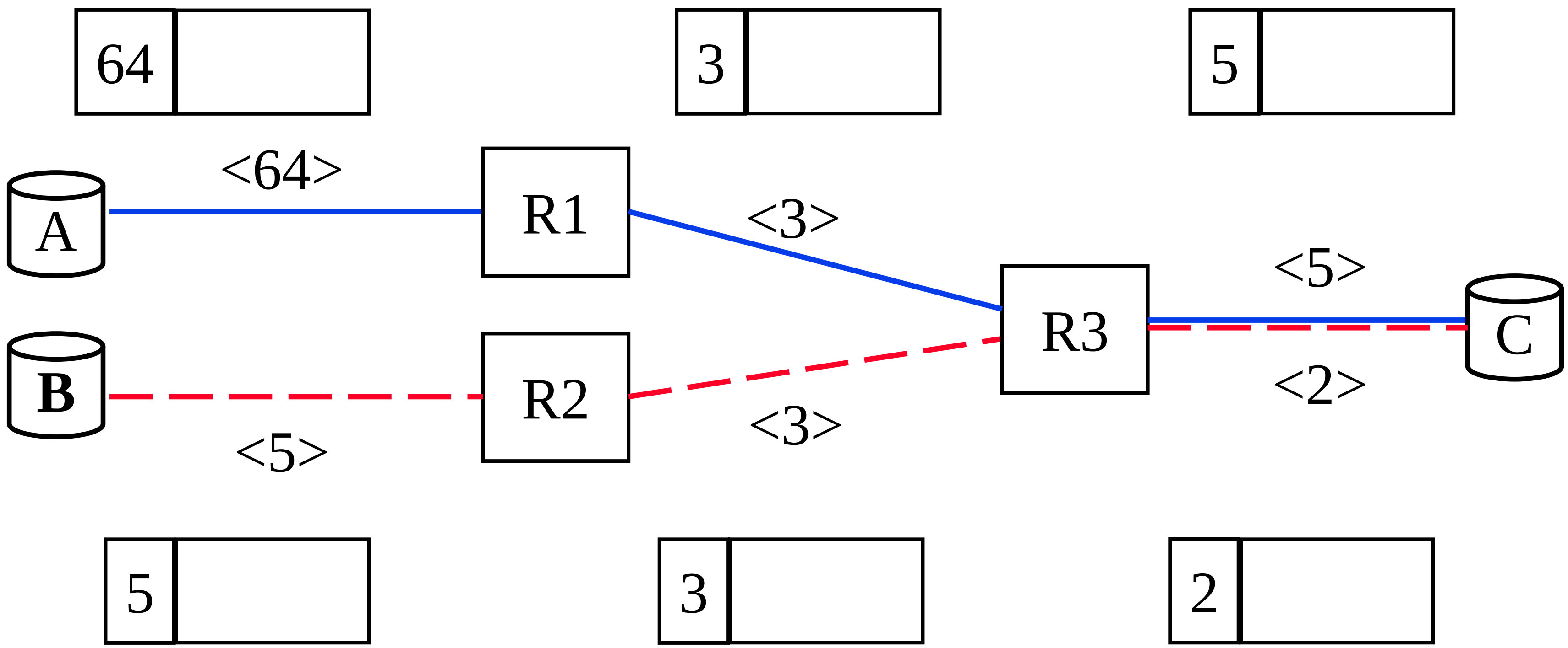
- Allows virtual circuits in IP Networks (May 1996)
- Each packet has a virtual circuit number called 'label'
- Label determines the packet's queuing and forwarding
- Circuits are called Label Switched Paths (LSPs)
- LSP's have to be set up before use
- Allows traffic engineering



Label Switching Example

Ethernet Header	IP Header	Payload

Ethernet Header	Label	IP Header	Payload

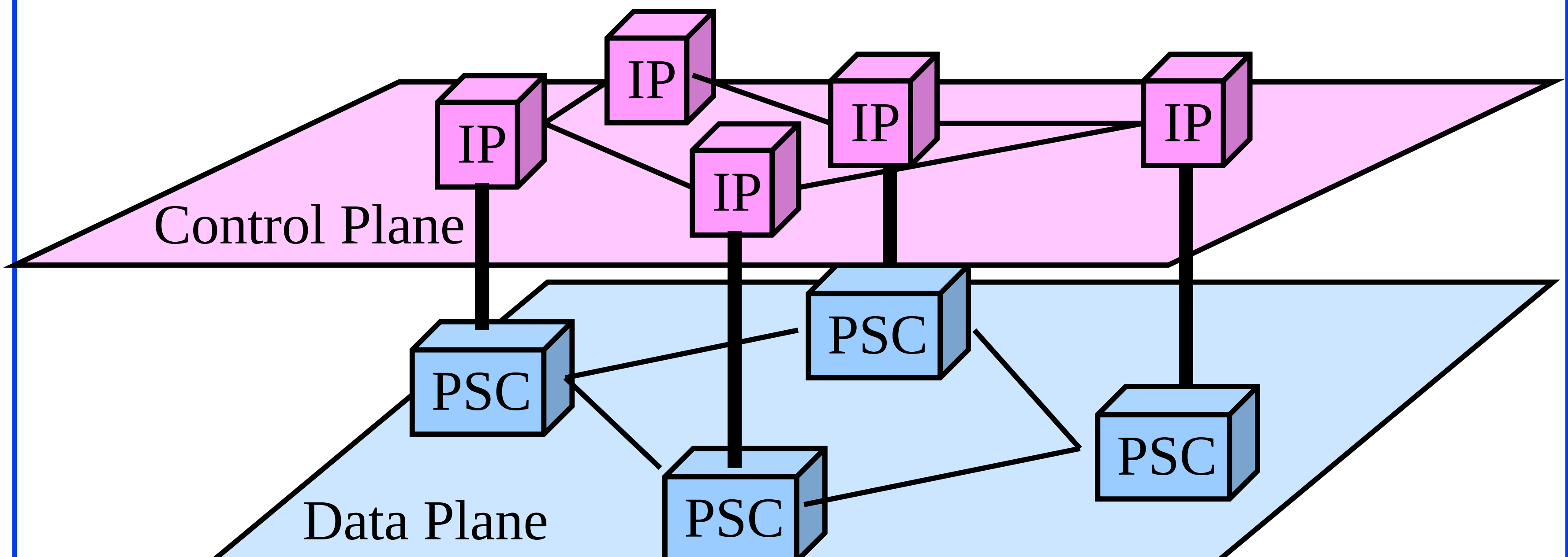


Label Assignment

- Unsolicited: Topology driven ⇒ Routing protocols exchange labels with routing information.
  Many existing routing protocols are being extended: BGP, OSPF
- On-Demand:
  ⇒ Label assigned when requested,
  e.g., when a packet arrives ⇒ latency
- Label Distribution Protocol called **LDP**
- **RSVP** has been extended to allow label request and response

IP-Based Control Plane

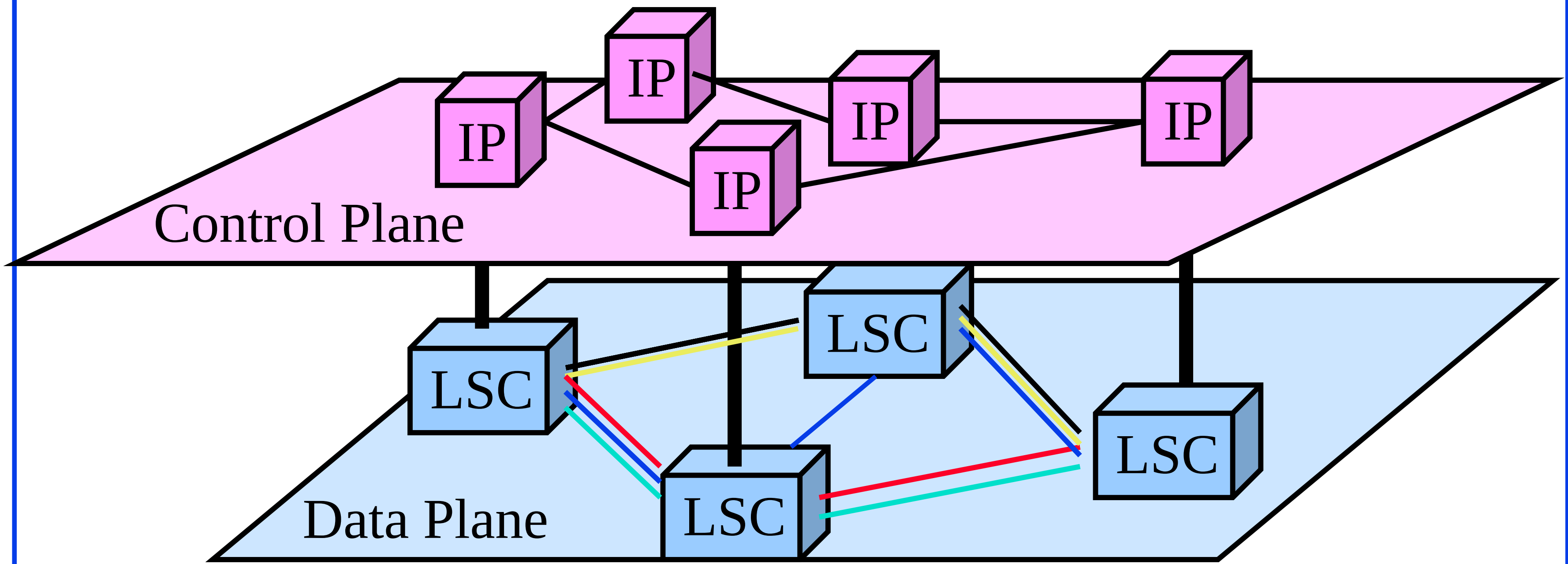
- Control is by IP packets (electronic).
  Data can be any kind of packets (IPX, ATM cells).
  ⇒ MPLS



PSC = Packet Switch Capable Nodes

MPλS

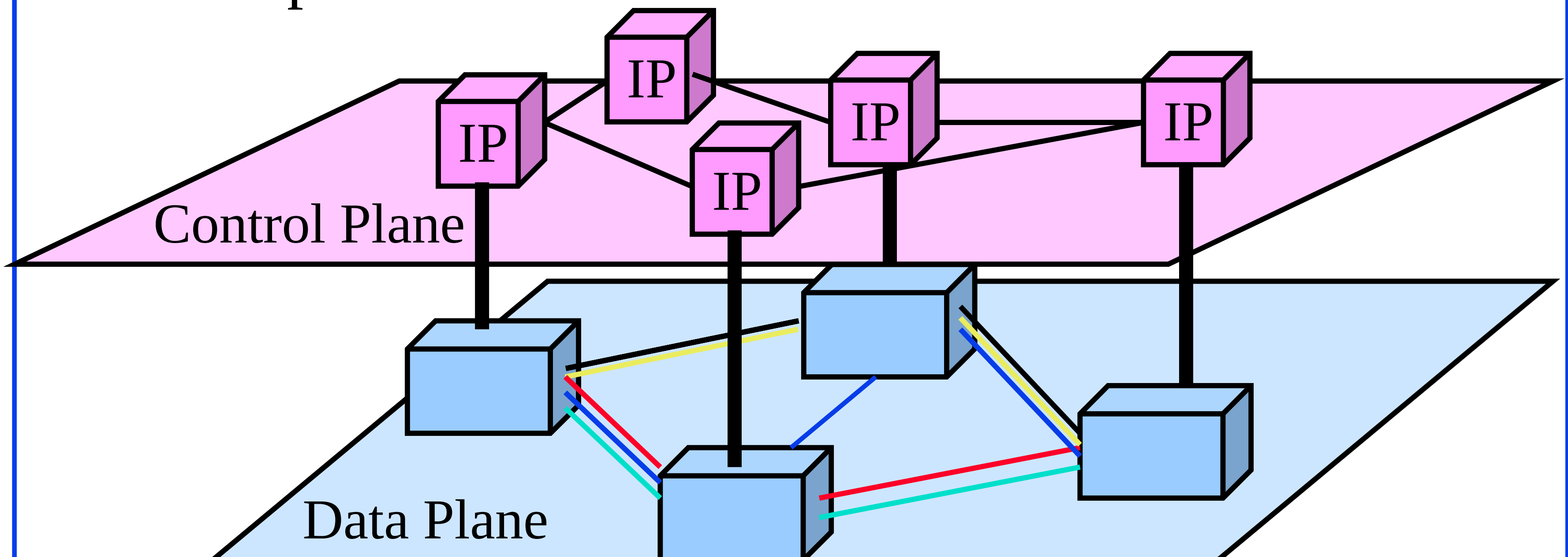
- Control is by IP packets (electronic).
  Data plane consists of wavelength circuits
  ⇒ Multiprotocol Lambda Switching (October 1999)



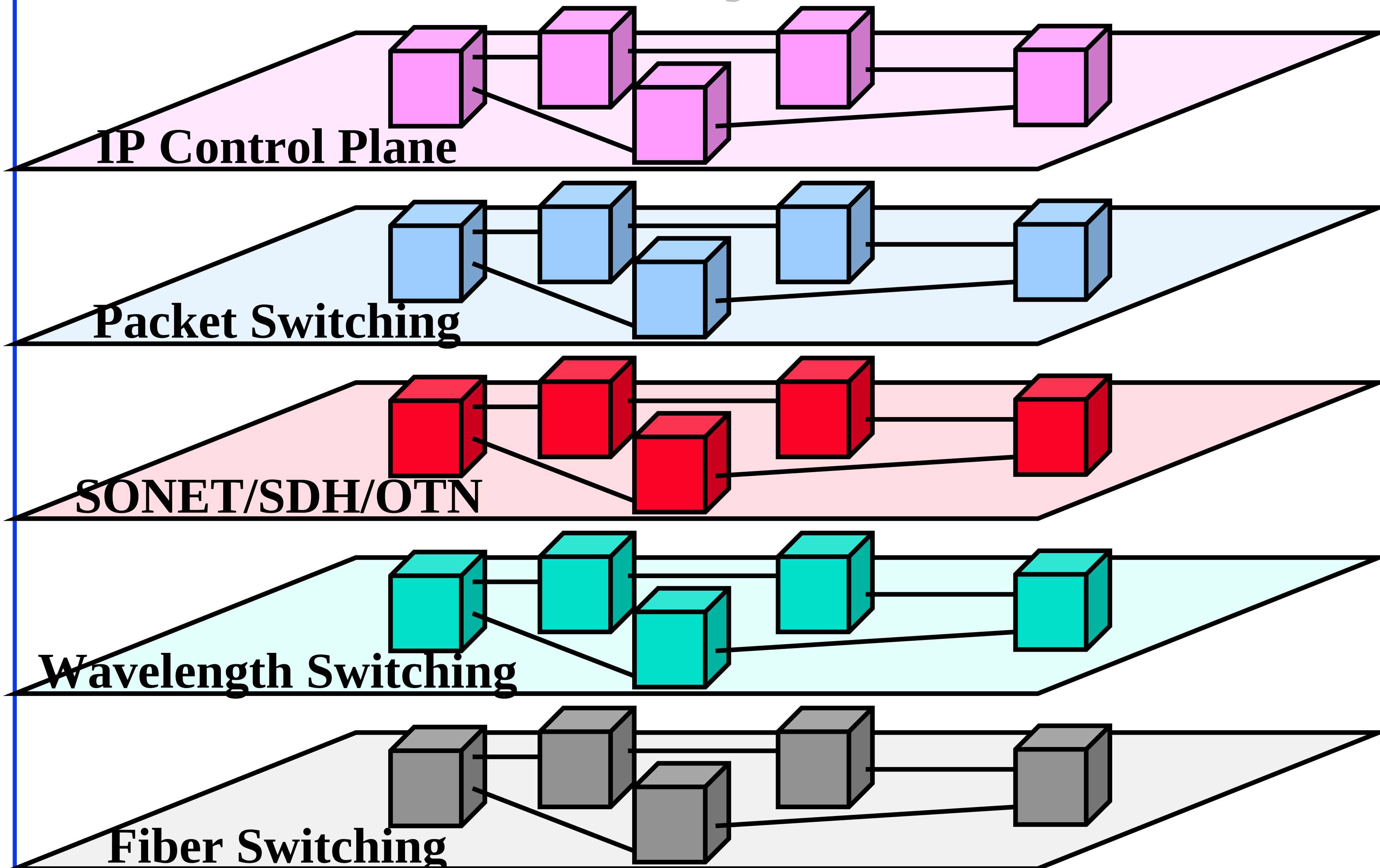
LSC = Lambda Switch Capable Nodes
= Optical Cross Connects = OXC

GMPLS

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

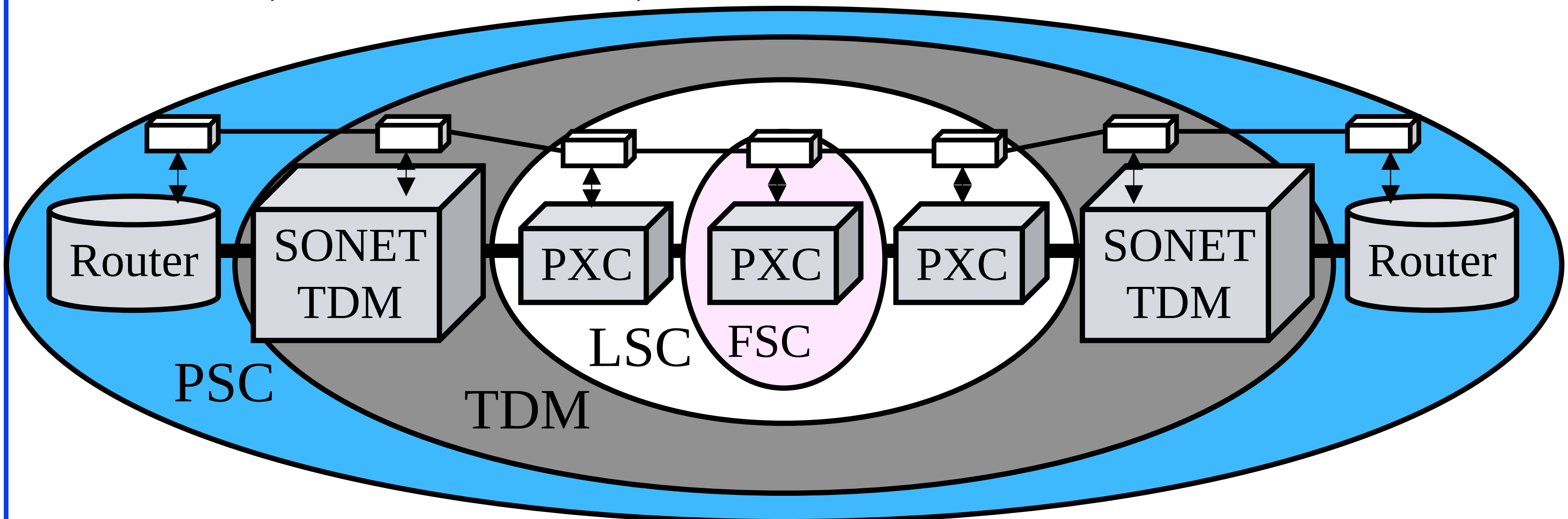


GMPLS: Layered View



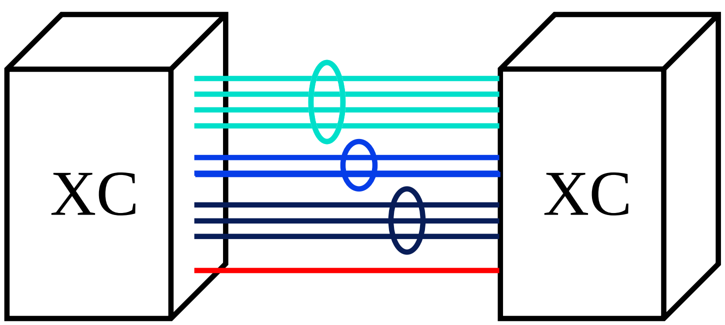
GMPLS: Hierarchical View

- 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

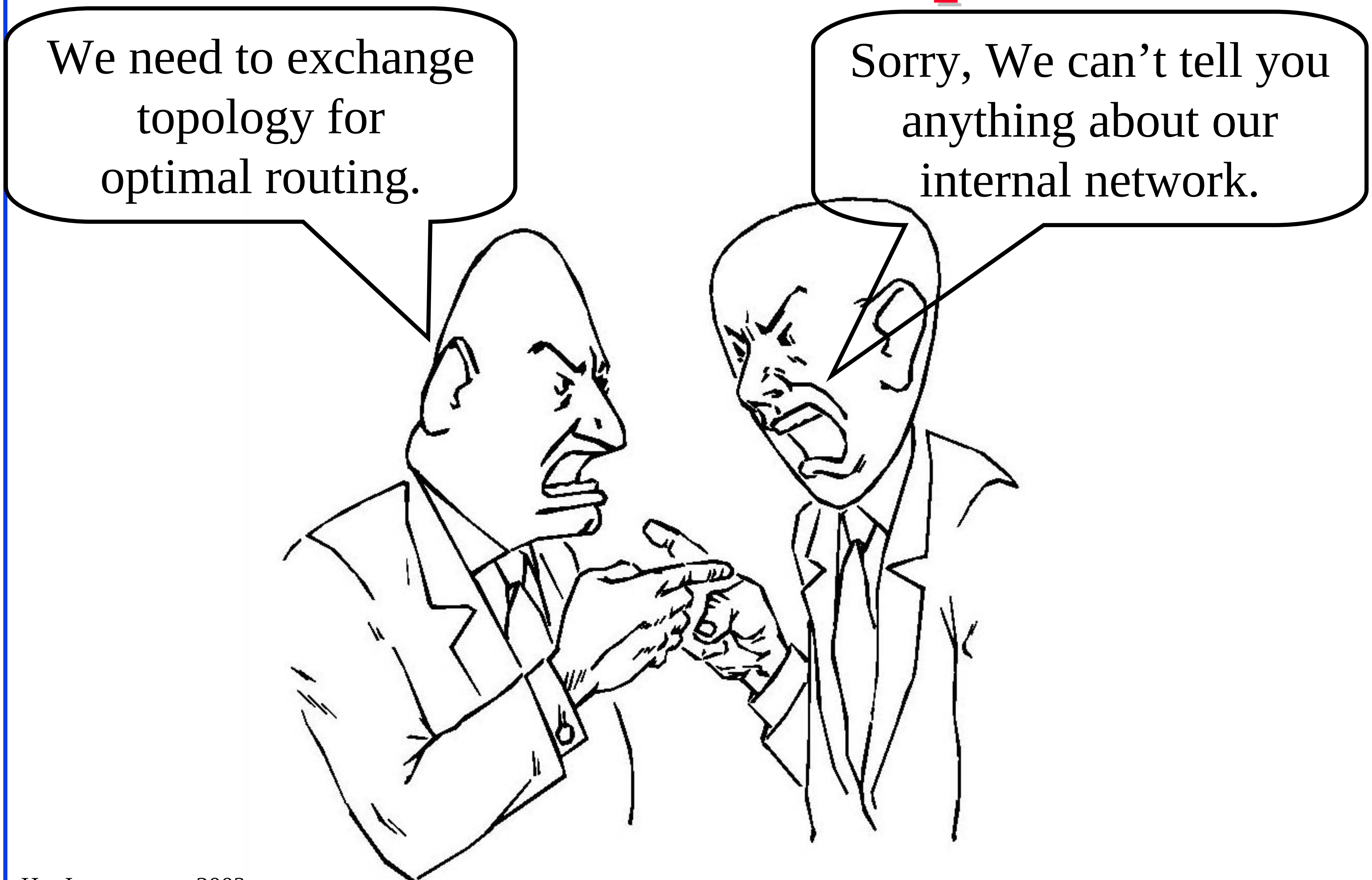


MPLS vs GMPLS

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

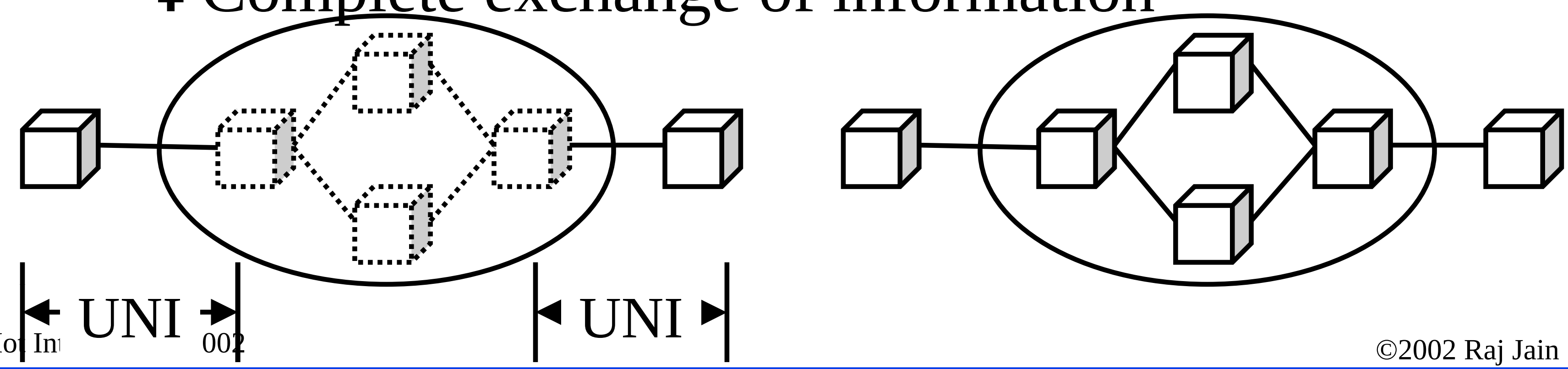


Carriers vs Enterprise



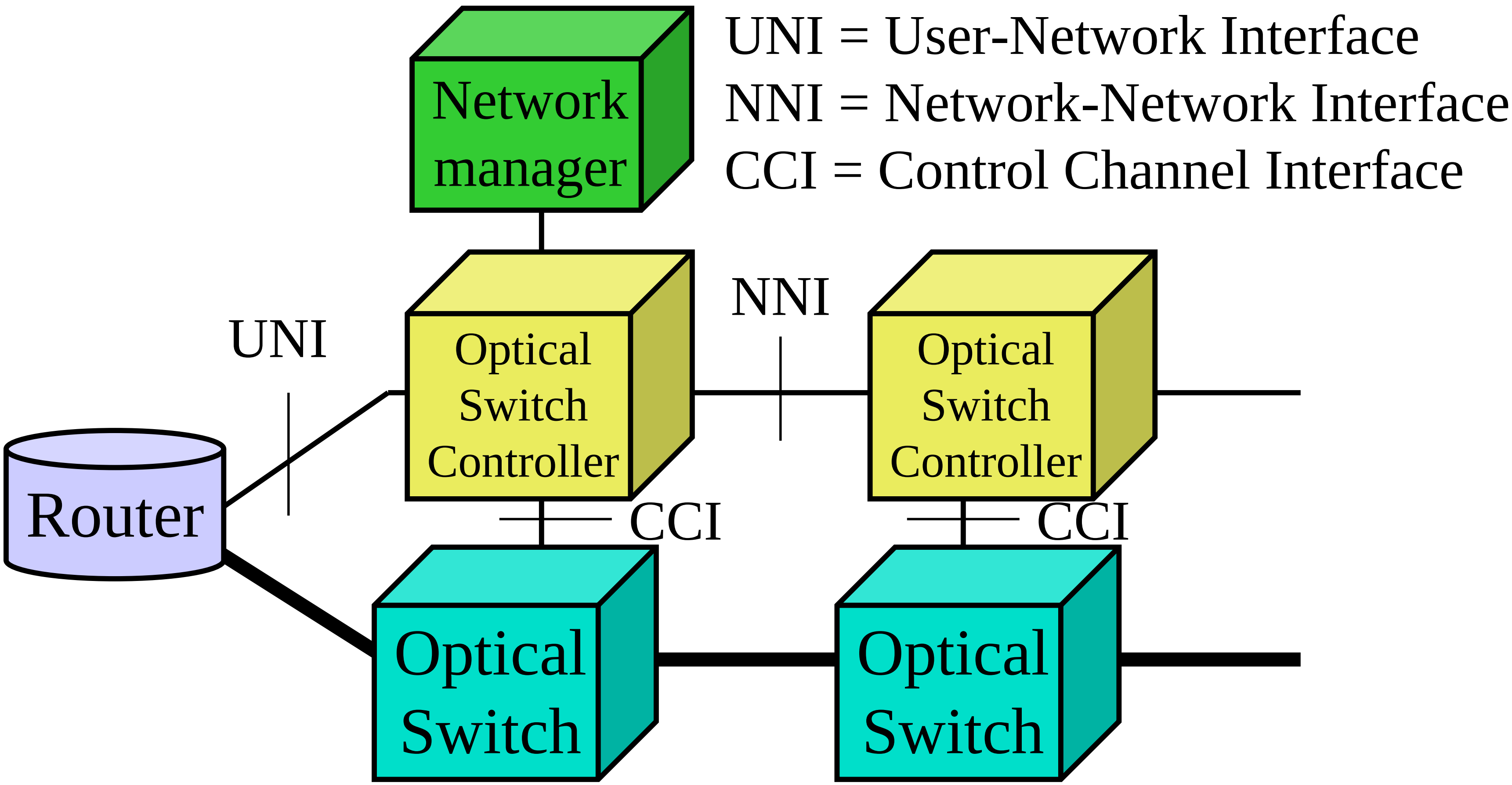
Issue: UNI vs Peer-to-Peer Signaling

- Two Business Models:
  - Carrier: Overlay or cloud
    - Network is a black-box
    - User-to-network interface (UNI) to create/destroy light paths (in OIF)
  - Enterprise: Peer-to-Peer
    - Complete exchange of information



ASTN/ASON

- Automatically Switched Transport Networks



Draft Martini

- 1995-1999: IP over ATM,
  Packet over SONET,
  IP over Ethernet

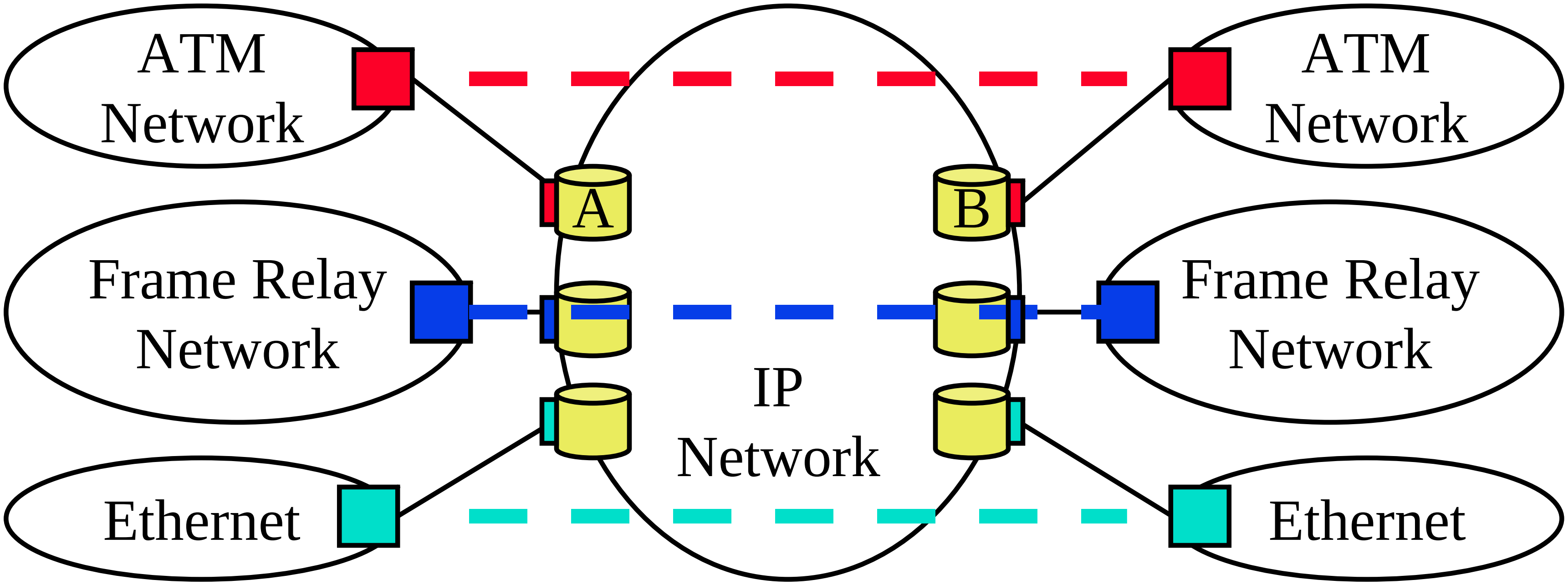
IP		
Ethernet	ATM	PPP

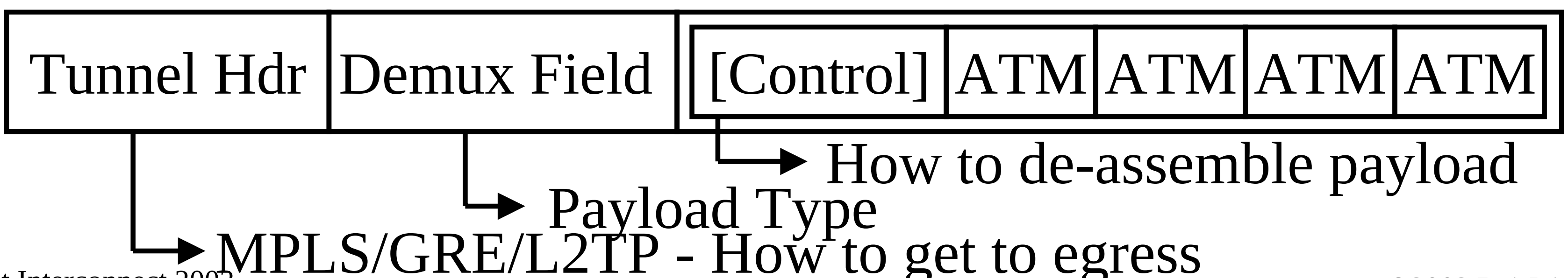
- 2000+: ATM over IP
  Ethernet over IP
  SONET over IP

Ethernet	ATM	PPP
IP		

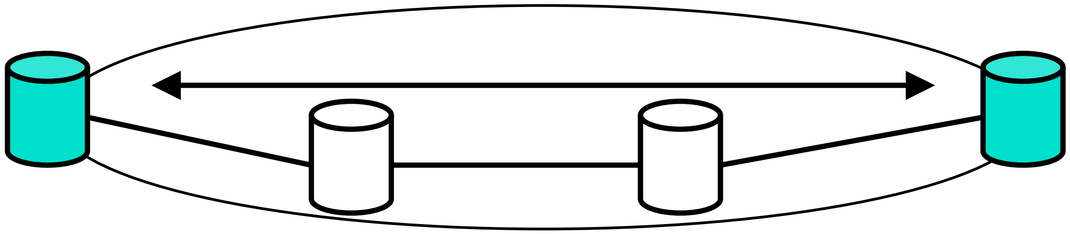
- Ref: draft-martini-*.txt

L2 Circuits over IP





VC Label



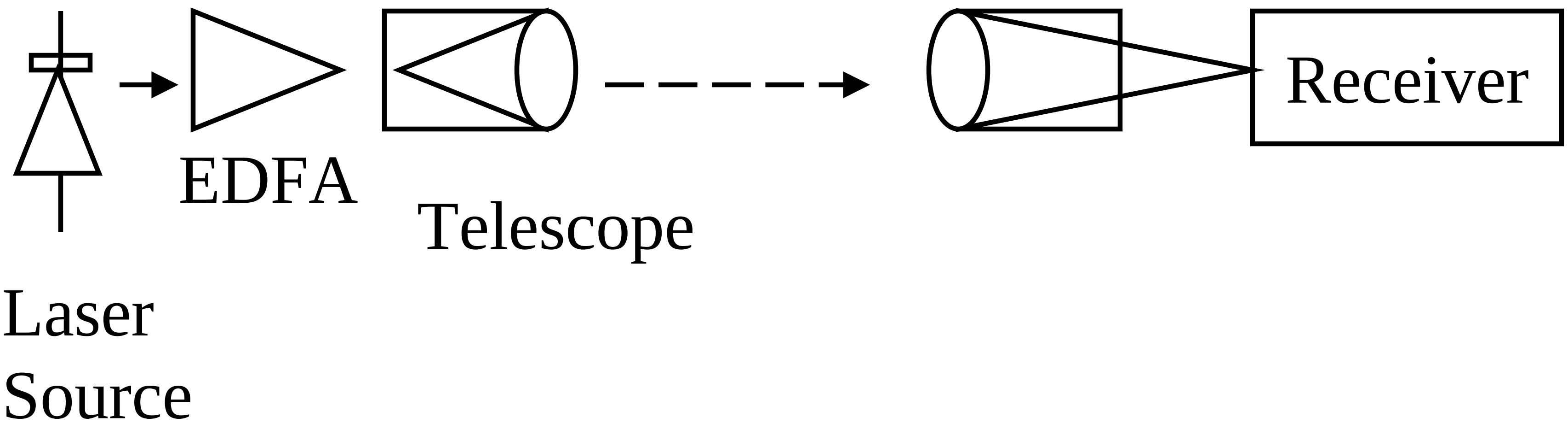
- VC Label bindings distributed using LDP downstream unsolicited mode between ingress and egress LSRs
- Circuit specific parameters such as MTU, options are exchanged at the time VC Label exchange
- VC Label: S=1 $\Rightarrow$ Bottom of stack, TTL=2
- VC Type:

1 Frame Relay DLCI	6 HDLC
2 ATM AAL5 VCC Transport	7 PPP
3 ATM Transparent Cell Transport	8 Circuit Emulation
4 Ethernet VLAN	9 ATM VCC Cell Transport
5 Ethernet	10 ATM VPC Cell Transport

Upcoming Technologies

- Higher bit rate, more wavelengths, longer distances
- Optic Wireless
- Optical Packet Switching

Free Space Optical Comm



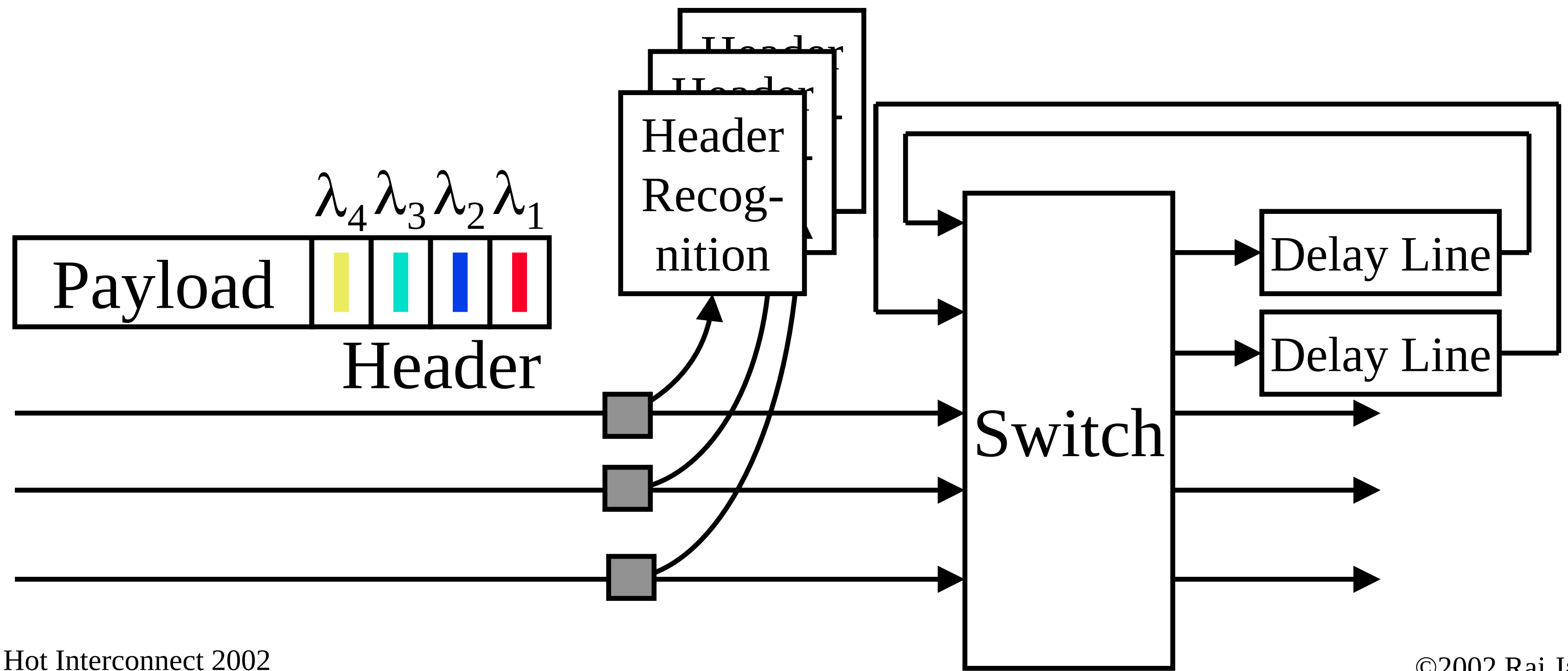
- Uses WDM in open air
- Sample Product:
  Lucent WaveStar OpticAir: 4×2.5Gbps to 5 km
  Available March'00.
- EDFA = Erbium Doped Fiber Amplifier

Free Space Optical Comm

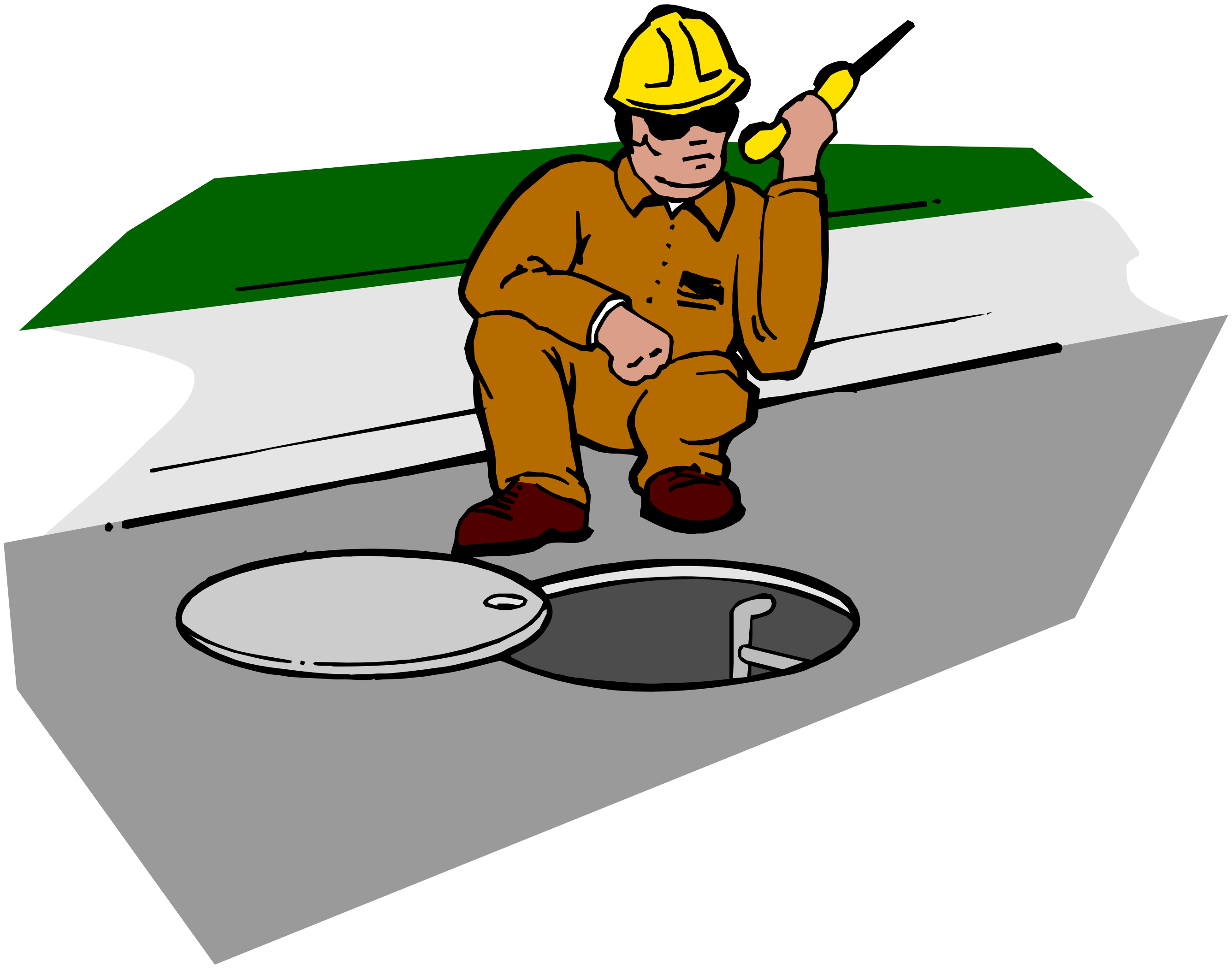
- No FCC Licensing required
- Immunity from interference
- Easy installation
  ⇒ Unlimited bandwidth, Easy Upgrade
- Transportable upon service termination or move
- Affected by weather (fog, rain)
  ⇒ Need lower speed Microwave backup
- Example Products: Optical Crossing Optibridge 2500 2.5Gbps to 2km, Texas Instruments TALP1135 Chipset for 10/100 Mbps up to 50m

Optical Packet Switching

- Header Recognition: Lower bit rate or different λ
- Switching
- Buffering: Delay lines, Dispersive fiber



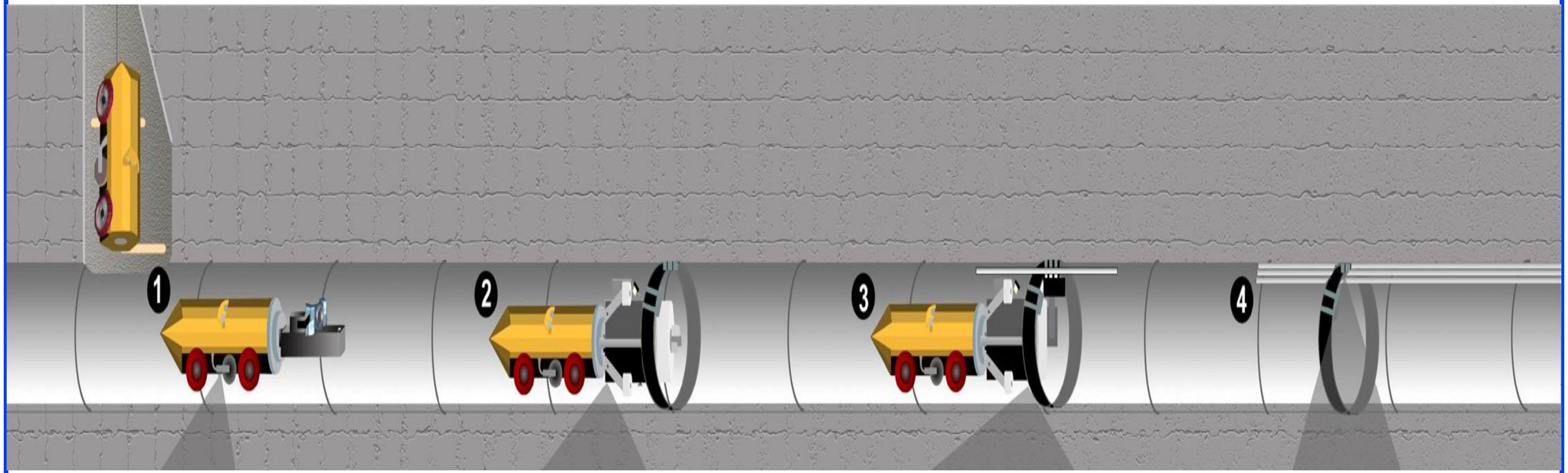
Sewer Networking



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


Thank You!