1. Trends in Networking
2. Core Network Issues: DWDM, OEO VS OOO
3. Metro Network Issues:
   Next Gen SONET vs Ethernet with RPR
5. IP Control Plane: MPLS, GMPLS
Life Cycles of Technologies

Number of Problems Solved

Time

Research  Productization
Hype Cycles of Technologies

Potential

Research  Hype  Dis  Success or Failure

Time
Industry Growth

Number of Companies

Time

New Entrants
Consolidation
Stable 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 $\Rightarrow$ Closely spaced $\approx$ 0.1 - 2 nm separation
- Coarse = 2 to 25 nm = 4 to 12 $\lambda$’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)
- 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

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

Potential: $58$ THz = $50$ Tbps on 10,000 $\lambda$’s

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

\[ \omega_1 - \Delta, \quad \omega_1, \quad \omega_2, \quad \omega_2 + \Delta \]

\[ \Delta = \omega_2 - \omega_1 \]
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

<table>
<thead>
<tr>
<th>Product</th>
<th>λ’s</th>
<th>Gb/s</th>
<th>km</th>
<th>Availability</th>
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<tbody>
<tr>
<td>Siemens/Optisphere TransXpress</td>
<td>80</td>
<td>40</td>
<td>250</td>
<td>2001</td>
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<tr>
<td></td>
<td>160</td>
<td>10</td>
<td>250</td>
<td>2001</td>
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<tr>
<td>Alcatel 1640 OADM</td>
<td>160</td>
<td>2.5</td>
<td>2300</td>
<td>2001</td>
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<td></td>
<td>80</td>
<td>10</td>
<td>330</td>
<td>2001</td>
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<tr>
<td>Corvis Optical Network Gateway</td>
<td>160</td>
<td>2.5</td>
<td>3200</td>
<td>2000</td>
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<tr>
<td></td>
<td>40</td>
<td>10</td>
<td>3200</td>
<td>2000</td>
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<td>Ciena Multiwave CoreStream</td>
<td>160</td>
<td>10</td>
<td>1600</td>
<td>2001</td>
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<tr>
<td>Nortel Optera LH4000</td>
<td>56</td>
<td>10</td>
<td>4000</td>
<td>2000</td>
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<tr>
<td>Optera LH 5000</td>
<td>104</td>
<td>40</td>
<td>1200</td>
<td>2002</td>
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<tr>
<td>Sycamore SN10000</td>
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<td>10</td>
<td>800</td>
<td>2001</td>
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<td></td>
<td>40</td>
<td>10</td>
<td>4000</td>
<td>2001</td>
</tr>
<tr>
<td>Cisco ONS 15800</td>
<td>160</td>
<td>10</td>
<td>2000</td>
<td>2002</td>
</tr>
</tbody>
</table>

Ref: “Ultra everything,” Telephony, October 16, 2000
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 into 16 substreams
  Each substream modulated by a 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.

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 ⇒ Synchronous Digital Hierarchy (SDH)
- You can lease a SONET connection from carriers

City A  Carriers  City B
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)
- OTN\(nr.k = \text{Reduced OTN}\n.k \Rightarrow \text{Without OSC}\)
OTN Layers and Frame Format

- **Optical Channel (Och)**
- **Optical Multiplex Section (OMSn)**
- **Optical Transmission Section (OTSn)**

- **OCh Payload Unit (OPUk)**
- **OCh Data Unit (ODUk)**
- **OCh Transmission Unit (OTUk)**

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

1 7 14 16 3824 4080

FA OH OTU OH ODU OH OPU OH Payload FEC
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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Overview

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

<table>
<thead>
<tr>
<th>PMD</th>
<th>Description</th>
<th>MMF</th>
<th>SMF</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>10GBASE-R:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10GBASE-SR</td>
<td>850nm Serial LAN</td>
<td>300 m</td>
<td>N/A</td>
</tr>
<tr>
<td>10GBASE-LR</td>
<td>1310nm Serial LAN</td>
<td>N/A</td>
<td>10 km</td>
</tr>
<tr>
<td>10GBASE-ER</td>
<td>1550nm Serial LAN</td>
<td>N/A</td>
<td>40 km</td>
</tr>
<tr>
<td><strong>10GBASE-X:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10GBASE-LX4</td>
<td>1310nm WWDM LAN</td>
<td>300 m</td>
<td>10 km</td>
</tr>
<tr>
<td><strong>10GBASE-W:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10GBASE-SW</td>
<td>850nm Serial WAN</td>
<td>300 m</td>
<td>N/A</td>
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<tr>
<td>10GBASE-LW</td>
<td>1310nm Serial WAN</td>
<td>N/A</td>
<td>10 km</td>
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<tr>
<td>10GBASE-EW</td>
<td>1550nm Serial WAN</td>
<td>N/A</td>
<td>40 km</td>
</tr>
<tr>
<td>10GBASE-LW4</td>
<td>1310nm WWDM WAN</td>
<td>300 m</td>
<td>10 km</td>
</tr>
</tbody>
</table>

- **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
    - CX4 PMD
    - CWDM PMD
    - CX4
    - LX4

- Serial LAN PHY
  - 64b/65b
    - Serial PMD
    - 850 nm
    - SR
    - LR
    - ER

- Serial WAN PHY
  - 64b/65b + WIS
    - Serial PMD
    - 850 nm
    - SW
    - LW
    - EW

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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
- 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
- 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](http://www.ieee802.org/3/10GBT)

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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

- 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

<table>
<thead>
<tr>
<th>Feature</th>
<th>SONET</th>
<th>Ethernet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload Rates</td>
<td>51M, 155M, 622M, 2.4G, 9.5G</td>
<td>10M, 100M, 1G, 10G</td>
</tr>
<tr>
<td>Payload Rate</td>
<td>Fixed</td>
<td>√ Any</td>
</tr>
<tr>
<td>Granularity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bursty Payload</td>
<td>No</td>
<td>√ Yes</td>
</tr>
<tr>
<td>Payload Count</td>
<td>One</td>
<td>√ Multiple</td>
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<tr>
<td>Protection</td>
<td>√ Ring</td>
<td>Mesh</td>
</tr>
<tr>
<td>OAM&amp;P</td>
<td>√ Yes</td>
<td>No</td>
</tr>
<tr>
<td>Synchronous Traffic</td>
<td>√ Yes</td>
<td>No</td>
</tr>
<tr>
<td>Restoration</td>
<td>√ 50 ms</td>
<td>Minutes</td>
</tr>
<tr>
<td>Cost</td>
<td>High</td>
<td>√ Low</td>
</tr>
<tr>
<td>Used in</td>
<td>Telecom</td>
<td>Enterprise</td>
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</tbody>
</table>
## SONET vs Ethernet: Remedies

<table>
<thead>
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<th>Feature</th>
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<th>Ethernet</th>
<th>Remedy</th>
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<tr>
<td>Payload Rates</td>
<td>51M, 155M, 622M, 2.4G, 9.5G</td>
<td>10M, 100M, 1G, 10G</td>
<td>10GE at 9.5G</td>
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<tr>
<td>Payload Rate Granularity</td>
<td>Fixed</td>
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<td>Virtual Concatenation</td>
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<td>Bursty Payload</td>
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<td>√Yes</td>
<td>Link Capacity Adjustment Scheme</td>
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<td>√Multiple</td>
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<td>√Ring</td>
<td>Mesh</td>
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<tr>
<td>OAM&amp;P</td>
<td>√Yes</td>
<td>No</td>
<td>In RPR</td>
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<tr>
<td>Synchronous Traffic</td>
<td>√Yes</td>
<td>No</td>
<td>MPLS + RPR</td>
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<tr>
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<td>√50 ms</td>
<td>Minutes</td>
<td>Rapid Spanning Tree</td>
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<td>Cost</td>
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<td>Enterprise</td>
<td></td>
</tr>
</tbody>
</table>

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Enterprise vs Carrier Ethernet

**Enterprise**
- Distance: up to 2km
- Scale:
  - Few K MAC addresses
  - 4096 VLANs
- Protection: Spanning tree
- Path determined by spanning tree
- Simple service
- Priority $\Rightarrow$ Aggregate QoS
- No performance/Error monitoring (OAM)

**Carrier**
- Up to 100 km
- Millions of MAC Addresses
- Millions of VLANs
- Q-in-Q
- Rapid spanning tree (Gives 1s, need 50ms)
- Traffic engineered path
- SLA
- Need per-flow QoS
- Need performance/BER
Networking and Religion

Both are based on a set of beliefs

I believe in God.
I believe in rings
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
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

STS-1-2v

Messages

STS-1-3v
LCAS (Cont)

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

Diagram:
- Working STS-1-3v
- Protection STS-1-2v
- End-to-end STS-1-5v
Generic Framing Procedure (GFP)

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

![Diagram showing GFP and payload types]

- Payload types: Ethernet (GbE), Fiber Ch. (FC), GFP
- 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
  $\Rightarrow$ 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)


Recent Developments
Access: Fiber To The X (FTTx)

Service Node
- Internet
- Leased Line
- VOIP
- PSTN
- Video

Operation System
- Passive Optical Splitter
- Optical Fiber
- OLT
- ONU
- ONT
- NT
- Twisted Pair
- xDSL

PON System

FTTP
- FTTH
- FTTB
- FTTC
- FTTCab

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
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
EFM PHYs

- 2BASE-TL: Baseband PHY based on SHDSL, L $\Rightarrow$ 2.7km
- 10PASS-TS: Duplex on a single voice UTP pair using VDSL QAM or DMT, S$\Rightarrow$0.7km. Pass$\Rightarrow$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
- 100BASE-LX10: Extended (10km) 1310nm long-wavelength laser
- 100BASE-BX10-D: Bidirectional 1490nm downstream laser
- 100BASE-BX10-U: Bidirectional 1310nm upstream laser
- 100BASE-PX10-D: PON 1490nm downstream laser 10 km
- 100BASE-PX10-U: PON 1310nm upstream laser 10 km
- 100BASE-PX20-D: PON 1490nm downstream laser 20 km
- 100BASE-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

OLT

ONT

ONU
Broadcast Video Over PON

- Analog or Digital Video on 1550 nm

OLT

ONT

ONT

ONT

3 Wavelengths
On One Fiber

Existing or New Coax

• MPEG/DVB-C
• GBE
• E1
• SDH

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PON Applications

1. FTTP

2. Cellular Backhaul

3. CATV MSO

4. DSLAM Aggregation

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Why PONs?

- **Reduced OpEx:** Passive network
  - High reliability ⇒ 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 ⇒ New customers can be added easily
  - Bandwidth is Shared ⇒ 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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Overview

- IP over DWDM
- UNI
- ASTN/ASON
- MPLS, MPLS, GMPLS
IP over DWDM (Past)
IP over DWDM (Future)
## Telecom vs Data Networks

<table>
<thead>
<tr>
<th></th>
<th>Telecom Networks</th>
<th>Data Networks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topology Discovery</td>
<td>Manual</td>
<td>Automatic</td>
</tr>
<tr>
<td>Path Determination</td>
<td>Manual</td>
<td>Automatic</td>
</tr>
<tr>
<td>Circuit Provisioning</td>
<td>Manual</td>
<td>No Circuits</td>
</tr>
<tr>
<td>Transport &amp; Control Planes</td>
<td>Separate</td>
<td>Mixed</td>
</tr>
<tr>
<td>User and Provider Trust</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Protection</td>
<td>Static using Rings</td>
<td>No Protection</td>
</tr>
</tbody>
</table>

![Telecom Network Diagram](image1)

![Data Network Diagram](image2)
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

Today:

Tomorrow:

Routing Messages

Data

Signaling
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
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)

Control Plane

Data Plane

LSC = Lambda Switch Capable Nodes

= Optical Cross Connects = OXC
- Data Plane = Wavelengths, Fibers, SONET Frames, Packets (October 2000)
- Two separate routes: Data route and control route
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, PXC. FSCs, in addition to routers
## MPLS vs GMPLS

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

![Diagram](image)
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](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
   ⇒ MP\(\lambda\)S
   Transport Plane = \(\lambda\), SONET, Packets
   ⇒ GMPLS

4. UNI allows users to setup paths on demand
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: MPLS, GMPLS, PWE3
Standards Organizations

- IETF: [www.ietf.org](http://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](http://www.oiforum.com)
- ANSI T1X1.5: [http://www.t1.org/t1x1/_x15-hm.htm](http://www.t1.org/t1x1/_x15-hm.htm)
- ITU, [www.itu.ch](http://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_ref.htm](http://www.cis.ohio-state.edu/~jain/refs/opt_ref.htm)
- Recommended books on optical networking, [http://www.cis.ohio-state.edu/~jain/refs/opt_book.htm](http://www.cis.ohio-state.edu/~jain/refs/opt_book.htm)
- Lightreading, [http://www.lightreading.com](http://www.lightreading.com)