Broadband Metro and Access Networks

Raj Jain
CTO and Co-founder
Navna Networks, Inc.

Raj Jain is now at
Washington University in Saint Louis
Jain@cse.wustl.edu
http://www.cse.wustl.edu/~jain/

International Conference on
Broadband Networking
(ICBN 2004)
Kobe, Japan
April 7, 2004

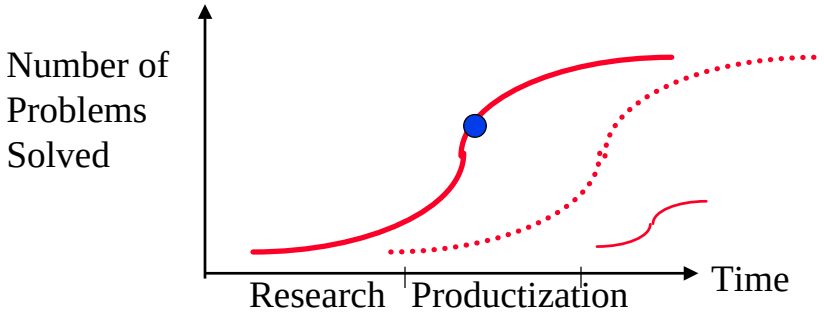
Broadband Metro and Access Networks

Raj Jain
CTO and Co-founder
Nayna Networks, Inc.
180 Rose Orchard Way, San Jose, CA 95134
Email: jain@acm.org
www.nayna.com and http://www.cis.ohio-state.edu/~jain/

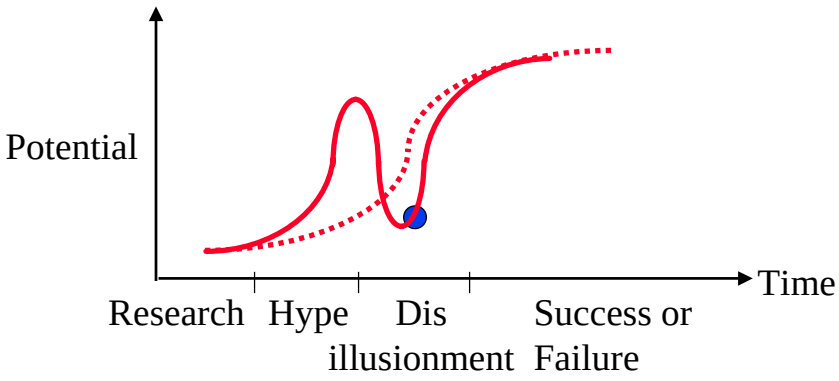
Overview

1. Trends in Networking
2. Metro Networks:
   1G and 10G Ethernet, Resilient Packet Ring,
   SONET/SDH vs Ethernet, Next Gen SDH
3. Access Networks: xDSL, Cable Modems, Broadband Wireless Access, WiMAX, Optical Wireless, Satellite, Passive Optical Networks

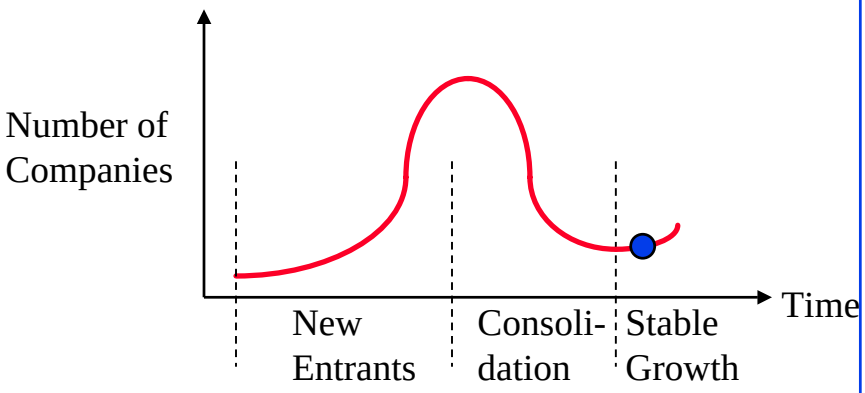
Life Cycles of Technologies



Hype Cycles of Technologies



Industry Growth



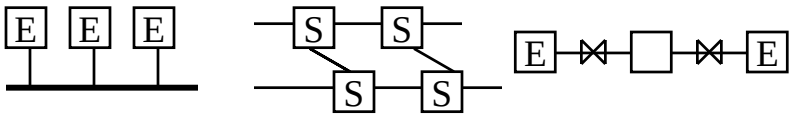
Trend: Back to ILECs

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

Core Networks

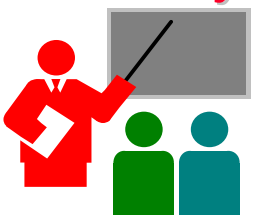
- Higher Speed/λ: 10 Gbps to 40 Gbps to 160 Gbps
- Longer Distances/Regens: 600 km to 6000 km
- More Wavelengths: 16 λ's to 160 λ's

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:$50/mo 100Mbps

Summary



- Hype Cycles of Technologies
  ⇒ Recovering from the bottom
- Trend: Back to ILECs
  ⇒ Compatibility more important than latest technology
- Core market stagnant. Metro and Access more important.

Metro Networks

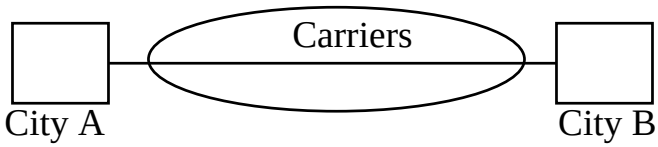
Raj Jain
CTO and Co-founder
Nayna Networks, Inc.
180 Rose Orchard Way, San Jose, CA 95134
Email: jain@acm.org
www.nayna.com and http://www.cis.ohio-state.edu/~jain/

Overview

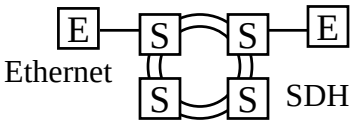
- SONET/SDH
- 1 GbE and 10GbE: Key Design Decisions
- Metro Ethernet Services
- SONET/SDH vs Ethernet: Issues and Remedies
- Resilient Packet Ring
- Networking Technologies: Failures vs Successes
- Next Generation SDH: VCAT, GFP, LCAS

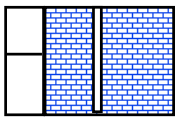
SONET/SDH

- 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 SDH connection from carriers



SDH 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

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

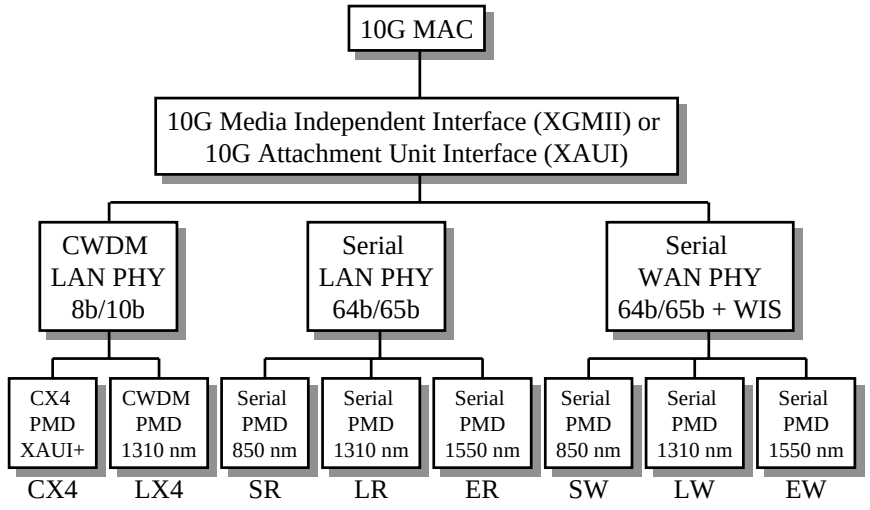
- P802.3ae ⇒ Update to 802.3
  Compatible with 802.3 frame format, services, management
- 10 Gbps vs. 9.5 Gbps. **Both** rates.
- LAN and **MAN** distances
- Full-duplex only ⇒ **No Shared** Mode
  Only switch based networks. No Hubs.
- Same min and max frame size as 10/100/1000 Mbps
  Point-to-point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

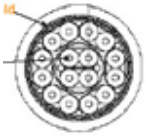
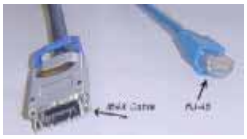
- S = Short Wave, L=Long Wave, E=Extra Long Wave
- R = Regular reach (64b/66b), W=WAN (64b/66b + SONET Encapsulation), X = 8b/10b
- 4 = 4 λ's

10GbE PHYs



10GBASE-CX4

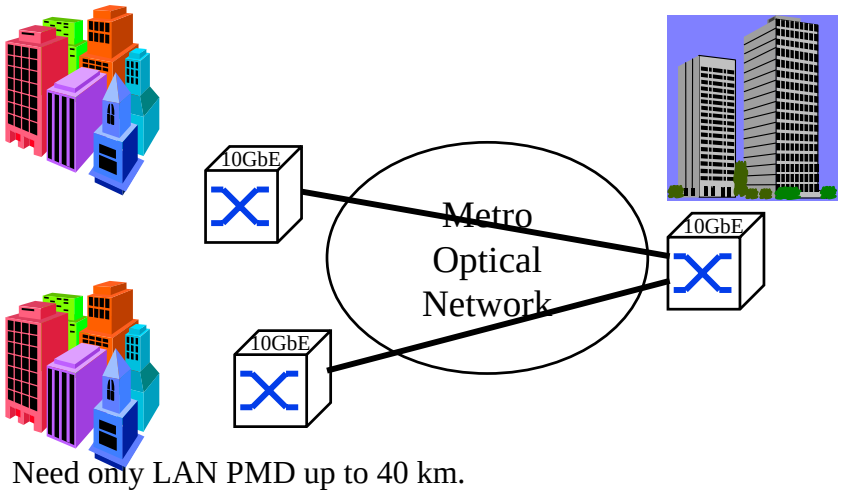
- For data center applications (Not for horizontal wiring):
  - Switch-to-switch links
  - Switch-to-server links
  - External backplanes for stackables
- Twinax cable with 8 pairs
- Based on Infiniband 4X copper PHY. IB4X connectors.
- Standard: Dec 2003. Passed Sponsor Ballot.
- IEEE 802.3ak, http://www.ieee802.org/3/ak

10GBASE-T

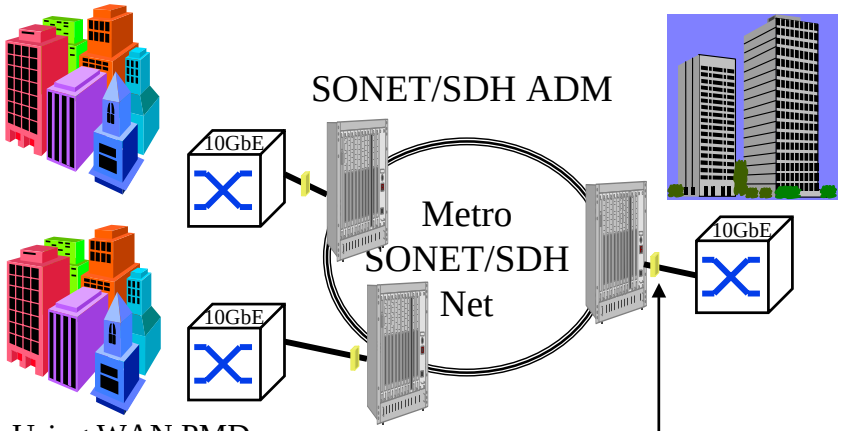
- New PHY for data center and horizontal wiring
- Compatible with existing 802.3ae MAC, XGMII, XAUI
- Standard: Start: Nov 2003 Finish: Jul 2005
- 100 m on Cat-7 and 55+ m on Cat-6
- Cost 0.6 of optical PHY. Greater reach than CX4
- 10-level coded PAM signaling with 3 bits/symbol
  833 MBaud/pair => 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.
- IEEE 802.3an, http://www.ieee802.org/3/an/index.html

10 GbE over Dark Fiber



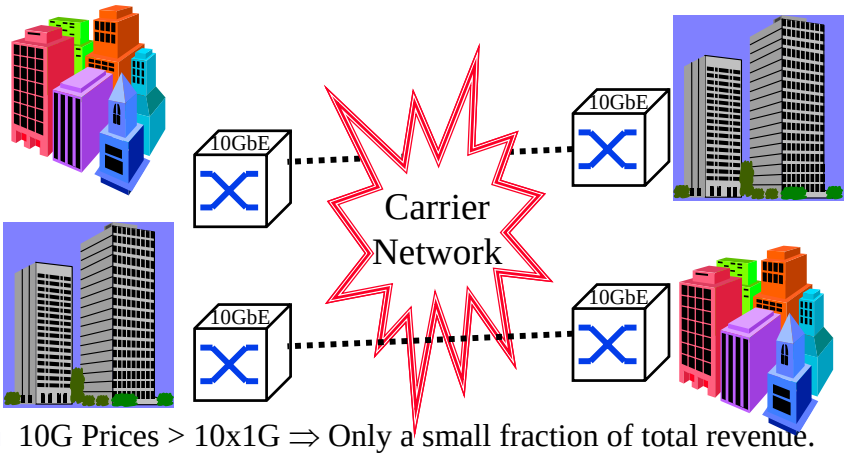
- Need only LAN PMD up to 40 km.
  No SONET/SDH overhead. No protection.

10 GbE over SONET/SDH



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

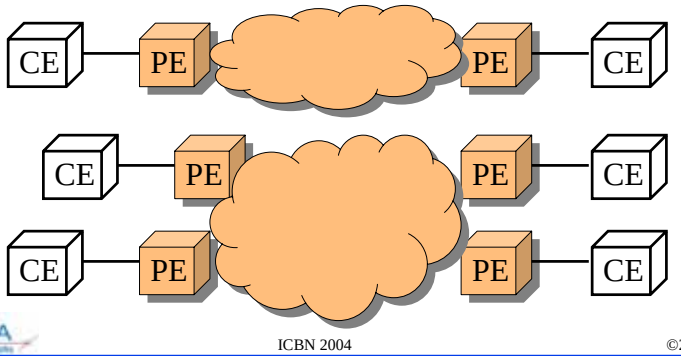
Metro Ethernet Market



- 10G Prices > 10x1G ⇒ Only a small fraction of total revenue. Prices decreasing fast ⇒300% Growth in 10G Q4'03.
- Growth in 1G ports > Growth rate of 100M ports (instat.com)

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/SDH 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

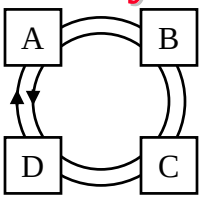
SONET/SDH vs Ethernet: Remedies

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

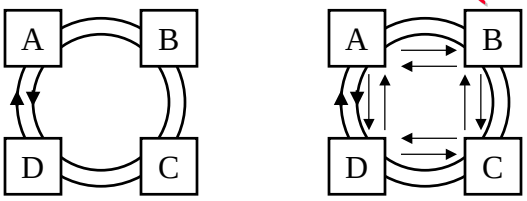
Enterprise	Carrier
Distance: up to 2km	Up to 100 km
Scale:	
Few K MAC addresses	Millions of MAC Addresses
4096 VLANs	Millions of VLANs Q-in-Q
Protection: Spanning tree	Rapid spanning tree (Gives 1s, need 50ms)
Path determined by spanning tree	Traffic engineered path
Simple service	SLA
Priority ⇒ Aggregate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

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/SDH)
- 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 (702 pages)

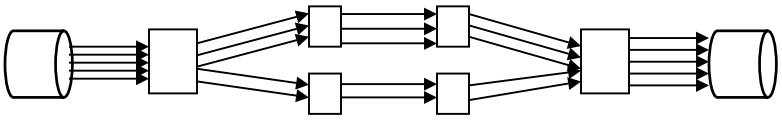
Networking: Failures vs Successes

- 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

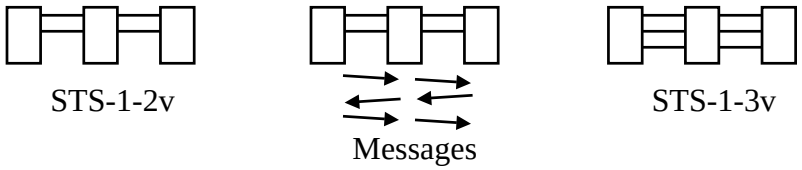
- Low Cost: Low startup cost ⇒ Evolution
- High Performance
- Killer Applications
- Timely completion
- Manageability
- Interoperability
- Coexistence with legacy LANs
  Existing infrastructure is more important than new technology

SONET/SDH 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.

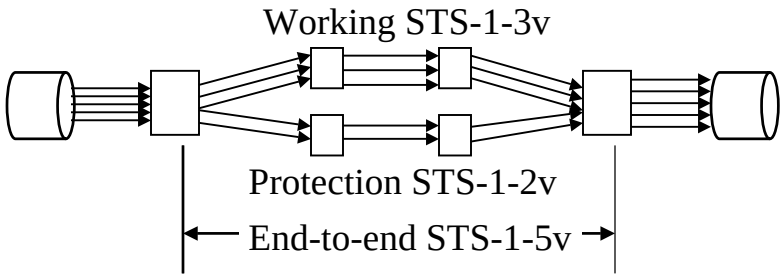
SONET/SDH LCAS



- 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

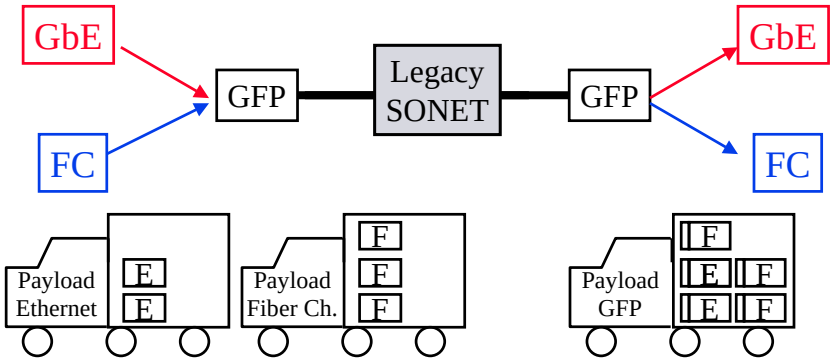
LCAS (Cont)

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



Generic Framing Procedure (GFP)

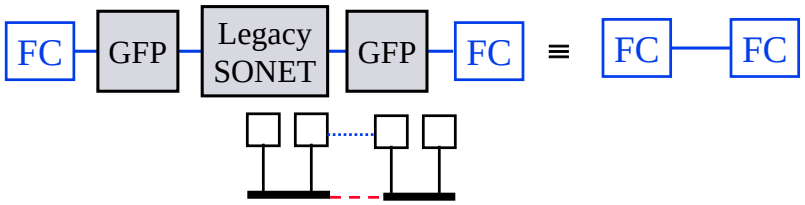
- Allows multiple payload types to be aggregated in one SONET/SDH path and delivered separately at dest.



Legacy SONET/SDH NextGen SONET/SDH

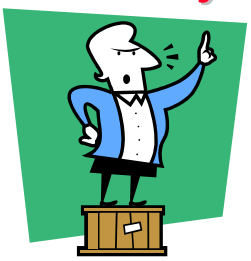
Transparent GFP

- Allows LAN/SAN PHY extension over SONET/SDH 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/SDH payload per GbE

Summary



- 1 GbE supports but does not use CSMA/CD.
- 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.

Access Networks

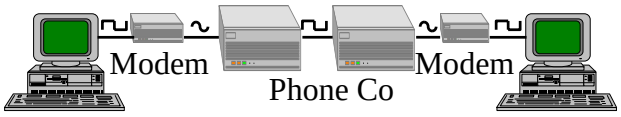
Raj Jain
CTO and Co-founder
Nayna Networks, Inc.
180 Rose Orchard Way, San Jose, CA 95134
Email: jain@acm.org
www.nayna.com and http://www.cis.ohio-state.edu/~jain/

Overview

- xDSL
- Cable Modems and Hybrid Fiber Coax (HFC)
- Fiber To The X (FTTx)
- Bi-Directional Satellite
- Broadband Wireless Access (BWA) and WiMAX
- Mobile Broadband Wireless Access (MBWA)
- Optical Wireless Access
- Passive Optical Network (PON)

56 kbps Modems

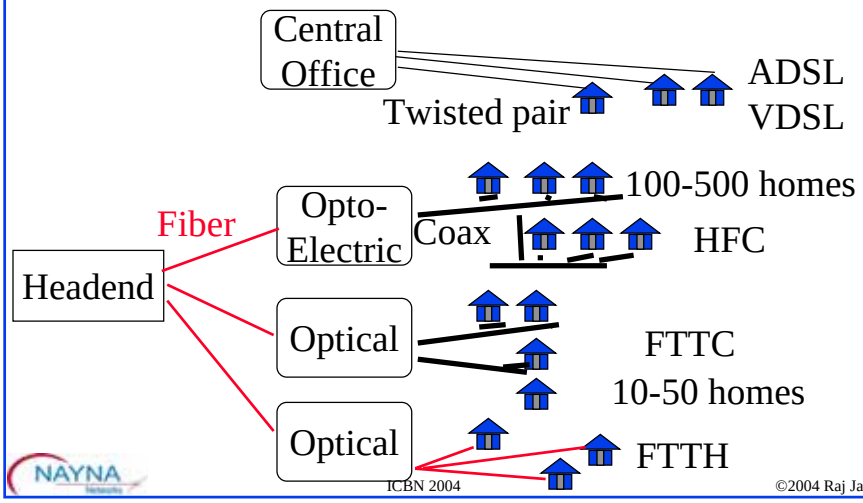
- Past:



- Current:

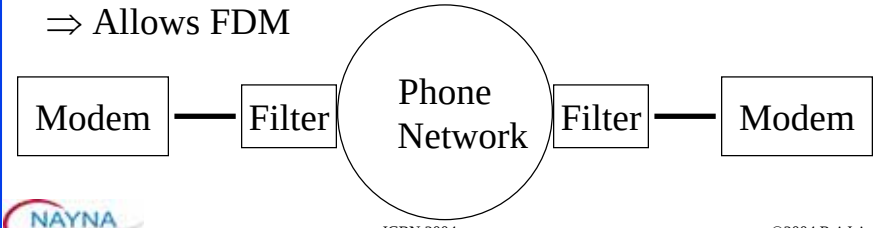
- ISP's have direct digital link (T1 or T3)
- Only one D/A/D conversion ⇒ Higher speed possible

Residential Access Networks (RANs)



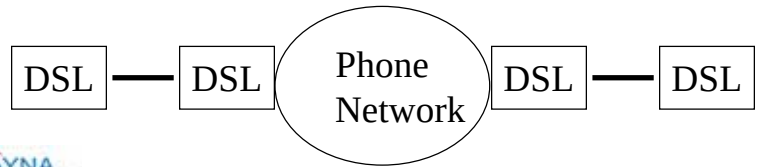
Why Modems are Low Speed?

- Telephone line bandwidth = 3.3 kHz
- V.34 Modem = 28.8 kbps ⇒ 10 bits/Hz
- Better coding techniques. DSP techniques.
- Cat 3 UTP can carry higher bandwidth
- Phone companies put 3.3 kHz filters at central office ⇒ Allows FDM



DSL

- Digital Subscriber Line = ISDN
- 64×2 + 16 + overhead = 160 kbps up to 18,000 ft
- DSL requires two modems (both ends of line)
- Symmetric rates ⇒ transmission and reception on same wire ⇒ Echo cancellation
- ISDN uses 0 to 80 kHz ⇒ Can't use POTS simultaneously



DSL Technologies

- DSL: Digital Subscriber Line (ISDN)
- HDSL: High data rate DSL (T1/E1 on 2 pairs)
- SDSL: Single line DSL (T1/E1+POTS on 1 pair)
- ADSL: Asymmetric DSL
- RADSL: Rate-adaptive ADSL
- VDSL: Very high data rate DSL
- VADSL: Very high data rate Asymmetric DSL = VDSL
- BDSL: Another name for VDSL
- VDSLe: European version of VDSL

HDSL

- Initially T1/E1 over copper used AMI coding ⇒ Repeaters every 3000 - 6000 ft
- Uses 1.5 MHz for 1.5 Mbps ⇒ Wasteful of bandwidth ⇒ Interference ⇒ Can't put more than 1 circuit in a 50 pair cable
- HDSL transmits T1/E1 over two pairs using 80 to 240 kHz ⇒ repeaters at 12,000 ft
- Used in PBX interconnection, cellular antenna stations, interexchange POPs
- SDSL = Single pair version of HDSL. Allows POTS and T1/E1 simultaneously. Up to 10000 ft.

ADSL

- Asymmetric Digital Subscriber Line
- Asymmetric ⇒ upstream << Downstream
- Symmetric ⇒ Significant decrease in rate
- 6 Mbps downstream, 640 kbps upstream
- Using existing twisted pair lines
- No interference with phone service (0-3 kHz)
  ⇒ Your phone isn't busy while netsurfing
- Up to 7500 m
- ANSI T1.413 Standard
- Quickest alternative for Telcos. Low cost winner.

Why Asymmetric?

- Unshielded twisted pair ⇒ Crosstalk
- Downstream signals are all same amplitude ⇒ Not affected
- Upstream signals start at different distances ⇒ Different amplitudes ⇒ Weak signals are highly affected
- Solutions:
  1. Use asymmetric rates
  2. Use lower frequencies for upstream
     (Cross talk increases with frequencies)

VDSL

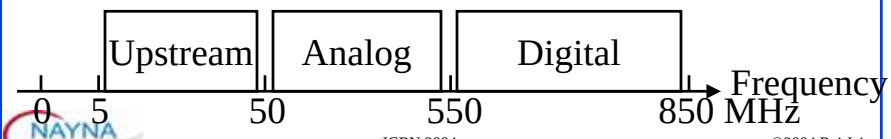
- Very High-Speed Digital Subscriber Lines
- Also called VADSL, BDSL, VHDSL
- ANSI T1E1.4 standardized the name VDSL and ETSI also adopted it
- VDSLe to denote European version
- For use in FTTC systems
- Downstream Rates: 51.84 -55.2 Mbps (300 m), 25.92-27.6 Mbps (1000 m), 12.96 - 13.8 Mbps (1500 m)

VDSL (Cont)

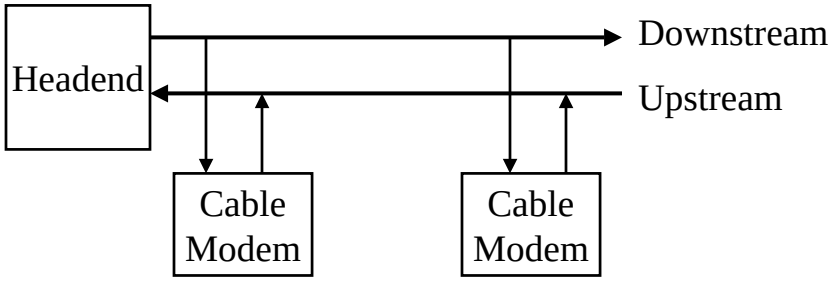
- Upstream Rates: 1.6-2.3 Mbps,
  19.2 Mbps, Same as downstream
- Admits passive network termination
  ⇒ Can connect multiple VDSL modems like extension phones
  (ADSL requires active termination)
- Unlike ADSL, VDSL uses ATM to avoid packet handling and channelization
- Orkit Communications (Israel) demoed VDSL modems at Supercomm'96

Cable TV Spectrum

- 50-550 MHz reserved for NTSC analog cable in USA
- Divided into 6 MHz channels
- 5-50 MHz can be used for upstream channel and 550-850 MHz for downstream digital channel
  Low-Split system. Most Common.

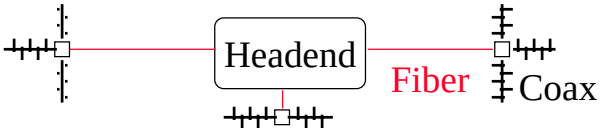


Media Sharing



- Headend controls all transmissions
- Downstream broadcast. Each modem picks up its information
- Upstream slots allocated by headend

Hybrid Fiber Coax (HFC)

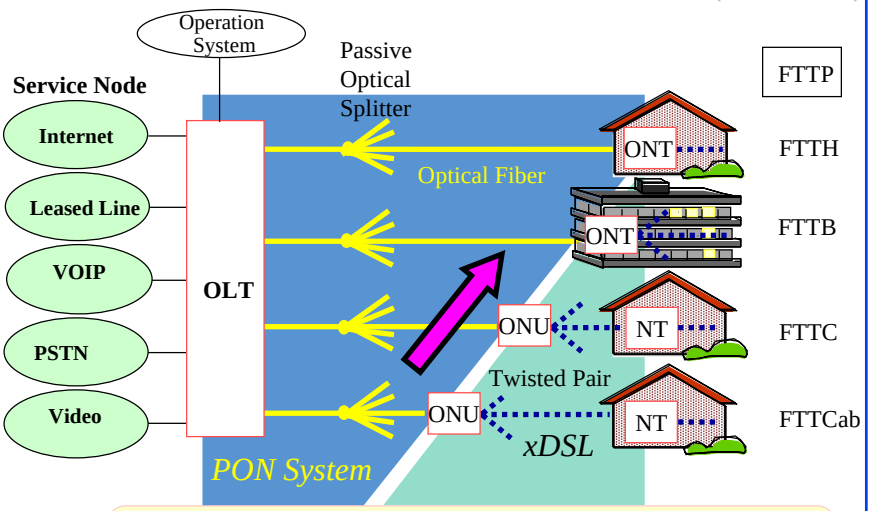


- Reuse existing cable TV coax
- Replace trunks to neighborhoods by fibers
- 45 Mbps downstream, 1.5 Mbps upstream
- MAC protocol required to share upstream bandwidth
- 500 to 1200 homes per HFC link
- Sharing ⇒ Security issues
- IEEE 802.14 standard for MAC and PHY

Cable Modems

- Modulate RF frequencies into cable.
  Signal received at the headend and
  converted to optical
- If cable is still one-way, upstream path through POTS
- $30 to $40 per month flat service charge

Access: Fiber To The X (FTTx)



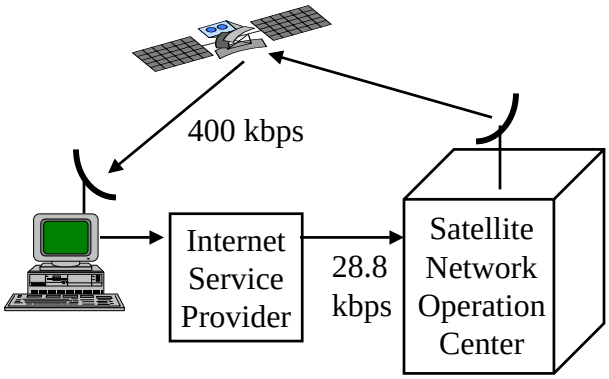
Comparison of RANs

Tech-nology	Typical Downstream Rate	Typical Upstream Rate	Max Distance	Homes Per Opt. Unit
HFC	45 Mbps Shared	1.5 Mbps Shared	N/A	500
FTTC	25-50 Mbps	25-50 Mbps	100 m	10-50
FTTH	1000 Mbps	1000 Mbps	N/A	10-200
ADSL	6 Mbps	640 kbps	4,000 m	1,000
VDSL	13-50 Mbps	1.6-5 Mbps	2,000 m	100

xDSL Vs Cable Modems

xDSL	Cable Modems
Phone company	Cable company
Switching experience but low bandwidth ckts	No switching but high bandwidth infrastructure
Point-to-point ⇒ Data privacy	Broadcast. Sharing ⇒ More cost effective
Currently 1.5 to 50 Mbps	10 to 30 Mbps
Perf = fn(location)	Independent of location
Phone everywhere	Cable only in suburbs (not in office parks)
Existing customers ⇒ ISDN and T1 obsolete	New Revenue

Satellites for Data

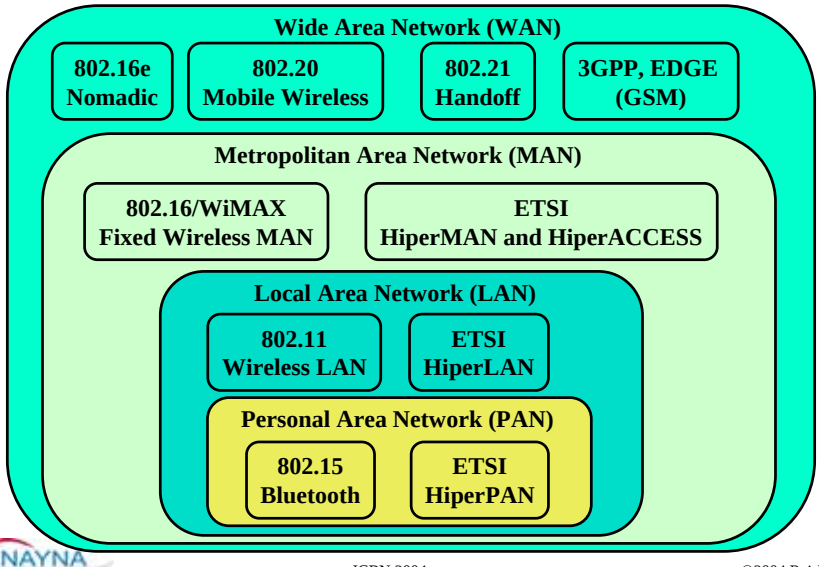


- DirecPC from Hughes
- One-way high-speed connection

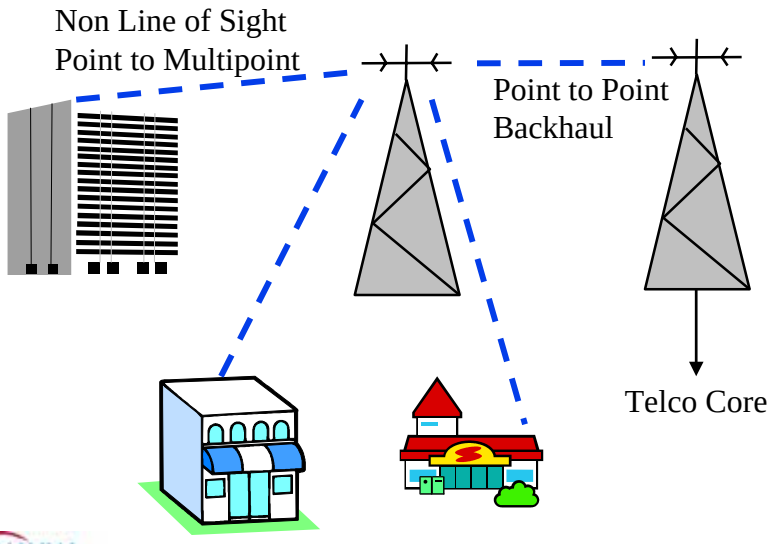
Bi-Directional Satellite

- Asymmetric: 500 kbps down, 50 kbps up
- Long propagation delays: Accelerator software
- Bi-directional satellite systems for mobile applications
- www.starband.com and www.motosat.com

Wireless Standards



Broadband Wireless Access



Broadband Wireless Access (BWA)

- IEEE 802.16 Broadband wireless Access WG
- Delivers >1 Mbps per user
- Up to 50 km
- Data rate vs Distance trade off using adaptive modulation. 64QAM to QPSK
- Offers non-line of site operation
- 1.5 to 20 MHz channels
- Hundreds of simultaneous sessions per channel
- Both Licensed and unlicensed spectrum
- QoS for voice, video, and T1/E1

WiMAX

- A vendor organization for ensuring interoperability
- A WiMAX certified product will work with other WiMAX certified products
- Plugfests planed from Dec 2004 on wards
- WiMAX certified products will be available Q1'05

IEEE 802.11 vs 802.16

	802.11	**802.16**
Range	Optimized for 00m	Optimized for 7-10 km Up to 50 km Multi-path delays tolerated
Coverage	Optimized for indoor	Optimized for outdoor Adaptive modulation Advanced Antenna
Scalability	Fixed 20 MHz channel (3 Non-overlapping channels in 802.11b, 5 in 802.11a)	1.5 MHz to 20 MHz Channels License and license exempt bands Allows Cell Planning
Spectral Efficiency	2.7 bps/Hz ⇒54 Mbps in 20 MHz	3.8 bps/Hz ⇒ 75 Mbps in 20 MHz 5 bps/Hz ⇒ 100 Mbps in 20 MHz
MAC	Contention based	Grant based
QoS	Simple	Sophisticated

802.16 Flavors

- 802.16 (December 2001):
  - Fixed broadband wireless interface
  - 10-66 GHz ⇒ Line of sight only ⇒ Point-to-point
- 802.16c (December 2002):
  - WiMAX system Profiles added
- 802.16a (January 2003):
  - Extensions for 2-11 GHz non line of sight
  - Point-to-multipoint applications
- 802.16REVd (Q3 2004):
  - Add WiMAX system profiles
- 802.16e (2005):
  - Vehicular speed mobility in 2-6 GHz licensed bands
  - Enables roaming

IEEE 802.16 Flavors

	802.16	802.16a	802.16e
Date	Dec 2001	802.16a: Jan 2003 802.16a Rev d: Q3'04	Q3'04
Spectrum	10-66 GHz	<11 GHz	<6 GHz
Conditions	Line of Sight only	Non line of Sight	Non Line of sight
Bit Rate	32-134 Mbps at 28 MHz Channels	Up to 75 Mbps at 20 MHz	Up to 15 Mbps at 5 MHz
Modulation	QPSK, 16QAM, 64 QAM	OFDM 256 Sub carriers, QPSK, 16 QAM, 64 QAM	OFDM 256 Sub carriers, QPSK, 16 QAM, 64 QAM
Mobility	Fixed	Fixed	Pedestrian

Mobile Broadband Wireless Access (MBWA)

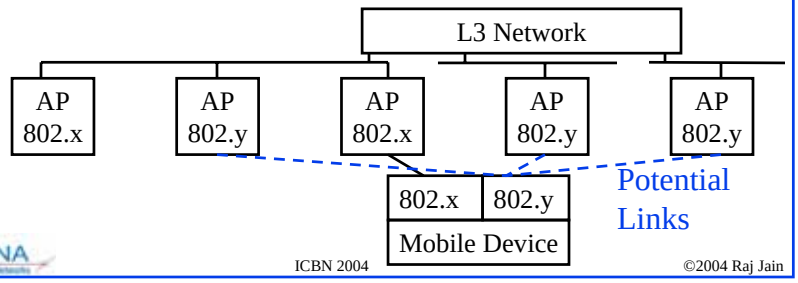
- IEEE 802.20 working group
- Optimized for IP data transport
- Licensed band below 3.5 GHz
- >1 Mbps data rate
- Vehicular mobility up to 250 Km/h
- Designed for green field wireless data providers
- Incumbent cellular providers with voice services may prefer 3G

Comparison of MBWA Stds

	802.16e	802.20	3G
Provider	Fixed Wireless adding mobility as enhencement	Wireless data service provider	Cellular voice service provider evolving to data support
Technology	Extension to 802.16a MAC and PHY	New MAC and PHY	W-CDMA, CDMA-2000
Design Restrictions	Optimized for backward compatibility	Optimized for full mobility	Evolution of GSM or IS-41
Bands	Licensed 2-6 GHz	Licensed below 3.5 GHz	Licensed below 2.7 GHz
Orientation	Packet oriented	Packet Oriented	Circuit oriented
Latency	Low Latency data	Low Latency data	High Latency data

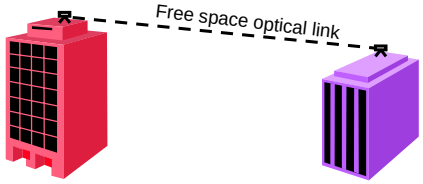
Handoff

- IEEE 802.21 Working group (formed Nov 03)
- Handoff between 802.3, 802.11, 802.15, 802.16, …
- Example Scenario:
  - Docked Laptop with 802.3, 802.11, and 802.16e
  - Laptop undocks and switches to 802.11
  - User moves outside the building, laptop switches to 802.16e



Optical Wireless Access

- Also known as "Free Space Optics (FSO)"
- Optical transceiver
  - Laser diode transmitter (780 nm, 1550 nm)
  - Photo detector (PIN diode, APD)
- Wireless ⇒ Fast rooftop deployment, No spectrum licenses
- Optical link requires line of site ⇒ Alignment critical
- Very high bandwidth (OC-3, OC-12, OC-48, 1GbE)

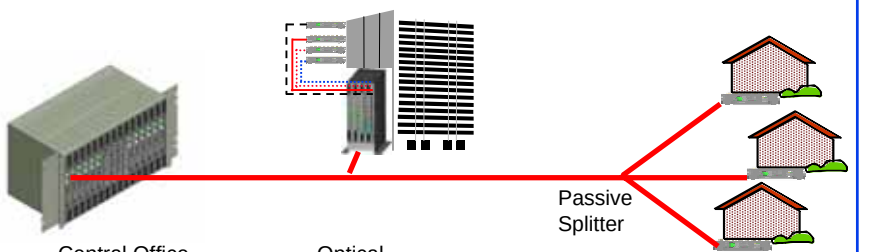


Optical Wireless (Cont)

- Immunity from interference
- Easy installation
  ⇒ Unlimited bandwidth, Easy Upgrade
- Transportable upon service termination or move
- Affected by weather (fog, rain, sun)
  ⇒ Need lower speed Microwave backup
- Depends on location
  - San Diego, CA (coastal fog)
  - Sacramento, CA (radiant fog)
  - Tucson, AZ (almost no fog)

Passive Optical Network (PON)

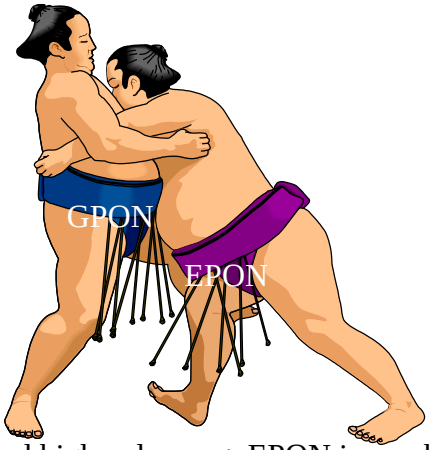
- A single fiber is used to support multiple customers
- No active equipment in the path ⇒ Highly reliable
- OLT assigned time slots upstream.
- Optical Line Terminal (OLT) in central office
- Optical Network Terminal (ONT) on customer premises
  Optical Network Unit (ONU) at intermediate points w xDSL



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

EPON vs GPON

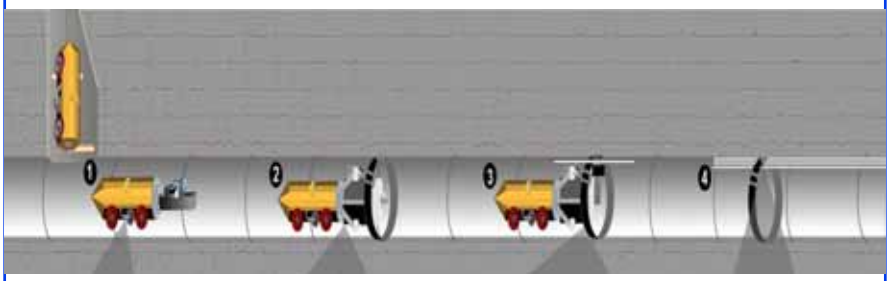


- Low-cost optics and high volume ⇒ EPON is much cheaper. EPON being planned by US Community networks and by carriers in Japan, Korea, China

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

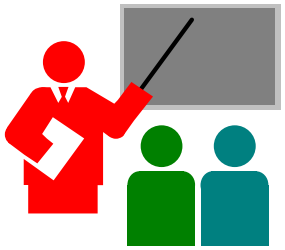
FAST Installation



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

Fast Restoration: Broken sewer pipes replaced with minimal disruption

Summary



- High Speed Access to Home: VDSL is here.
- 1 to 50 Mbps downstream, 1.5 - 50 Mbps upstream
- Broadband Wireless 802.16 devices coming soon
- Fiber to the home is finally happing.

Broadband: Key References

- For a detailed list of references, see http://www.cis.ohio-state.edu/~jain/refs/rbb_refs.htm
- Recommended books on optical networking, http://www.cis.ohio-state.edu/~jain/refs/opt_book.htm
- IEEE 802.14 Working group, http://www.walkingdog.com
- The ADSL Forum, http://www.sbexpos.com/sbexpos/associations/adsl/home.html
- Cable Labs, http://www.cablemodem.com
- EFM Alliance, www.efmalliance.org
- FTTH Council, www.ftthcouncil.org

Gigabit Ethernet, 10 Gigabit Ethernet and RPR: References

Note: A periodically updated version of this list is kept on-line at http://www.cis.ohio-state.edu/~jain/refs/gbe_refs.htm
Back to Hot Topics in Networking References
Back to Raj Jain's Home Page

Our Talks and Papers

- Gigabit Ethernet, http://www.cis.ohio-state.edu/~jain/cis788-97/gigabit_ethernet/index.htm
- 10 Gigabit Ethernet, http://www.cis.ohio-state.edu/~jain/cis788-99/10gbe/index.html
- Gigabit Ethernet [Audio/Video recording], http://www.cis.ohio-state.edu/~jain/cis788-97/h_8gbe.htm
- Gigabit Ethernet: Architectural Design and Issues, http://www.cis.ohio-state.edu/~jain/talks/gbether.htm
- Gigabit Networking: High-Speed Routing and Switching, http://www.cis.ohio-state.edu/~jain/cis788-97/gigabit_nets/index.htm

Books on Gigabit Ethernet, 10 Gigabit Ethernet and RPR

- See http://www.cis.ohio-state.edu/~jain/refs/gbe_book.htm

Standards Group and Consortia

- IEEE P802.3ae 10 Gigabit Ethernet Task Force, http://grouper.ieee.org/groups/802/3/ae/
- Ethernet in the First Mile Alliance, http://www.efmalliance.org/
- Metro Ethernet Forum, http://www.metroethernetforum.org/index.htm
- 10 Gigabit Ethernet Alliance, http://www.gigabit-ethernet.org/
- Gigabit Ethernet Consortium, http://www.iol.unh.edu/consortiums/ge/index.html
- The Resilient Packet Ring Alliance, http://www.rpralliance.org
- IP over Resilient Packet Rings (iporpr) Charter, http://www.ietf.org/html.charters/iporpr-charter.html
- Ethernet Interfaces and Hub MIB (hubmib), http://www.ietf.org/html.charters/hubmib-charter.html

Recently Completed IEEE 802 LAN Standards and Study Groups

- IEEE P802.3 Trunking Study Group, http://www.ieee802.org/3/trunk_study/index.html
- IEEE P802.3 Higher Speed Study Group, http://www.ieee802.org/3/10G_study/public/index.html
- IEEE P802.3 DTE Power via MDI Study Group, http://www.ieee802.org/3/power_study/public/index.html
- IEEE Std 802.3z-1998, Gigabit Ethernet, http://www.ieee802.org/3/z/index.html
- IEEE Std 802.3aa-1998, Maintenance Revision #5 (100BASE-T), http://www.ieee802.org/3/aa/index.html
- IEEE Std 802.3ab-1999, 1000BASE-T, http://www.ieee802.org/3/ab/index.html
- IEEE Std 802.3ac-1998, VLAN TAG, http://www.ieee802.org/3/ac/index.html
- IEEE Std 802.3ad-2000, Link Aggregation, http://www.ieee802.org/3/ad/index.html
- IEEE P802.3 Ethernet over LAPS liaison Ad hoc, http://www.ieee802.org/3/ad_hoc/etholaps/public/index.html
- IEEE 802.3 Static Discharge in Copper Cables Ad hoc.
- IEEE 802.3ag-2002, Maintenance Revisions #6.
- IEEE 802.1D MAC bridges
- IEEE 802.1G Remote MAC bridging
- IEEE 802.1Q Virtual LANs
- IEEE 802.1aa 802.1X Maintenance
- IEEE 802.1s Multiple Spanning Trees
- IEEE 802.1t 802.1D Maintenance
- IEEE 802.1u 802.1Q Maintenance
- IEEE 802.1v VLAN Classification by Protocol and Port
- IEEE 802.1w Rapid Reconfiguration of Spanning Tree
- IEEE 802.1x Port Based Network Access Control
- IEEE 802.1y 802.1D Maintenance

Active IEEE 802 LAN Projects:

- IEEE 802.17 RPR Working Group, http://grouper.ieee.org/groups/802/17/
- P802.3, Ethernet in the First Mile Study Group, http://www.ieee802.org/3/efm/index.html
- P802.3ae, 10Gb/s Ethernet, http://www.ieee802.org/3/ae/index.html
- P802.3af, DTE Power via MDI, http://www.ieee802.org/3/af/index.html
- P802.3ag, Maintenance Revisions #6, http://www.ieee802.org/3/ag/index.html
- P1802.3rev, Conformance Test Maintenance #1, http://www.ieee802.org/3/1802rev/index.html
- P802.3 Static Discharge in Copper Cables Ad hoc, http://www.ieee802.org/3/ad_hoc/copperdis/public/index.html

Gigabit and 10 Gigabit Ethernet References

- 10 - Gigabit Ethernet - a whatis definition, http://whatis.techtarget.com/definition/0,289893,sid9_gci535824,00.html
- 10 G Ethernet: Technology and Standards Update [May 2001 N+I Presentation

- 10 G PCS Cores, http://www.agere.com/redirect.html
- 10 Gigabit Ethernet Alliance, http://www.10gea.org/
- 10 Gigabit Ethernet Tutorial, http://www.ieee802.org/3/tutorial/nov99/index.html
- 10 Gigabit Ethernet, http://www.cis.ohio-state.edu/~jain/cis788-99/10gbe/index.html
- 10-Gigabit Ethernet And The Broadband Revival, http://bcr.com/bcrmag/2000/10/p28.asp
- 10-Gigabit Ethernet Mastering The Migration, http://www.bcr.com/bcrmag/2000/04/p56.asp
- Bell Labs team demonstrates world's first 10-gigabit-per-second Ethernet multiplexer, http://www.lucent.com/press/0599/990510.bla.html
- Business Communications Review - 10 - Gigabit Ethernet --Mastering ..., http://www.bcr.com/bcrmag/2000/04/p56.asp
- Charles Spurgeon's Ethernet (IEEE 802.3) Web Site, http://www.ots.utexas.edu/ethernet/
- Cisco - Introduction to 10 Gigabit Ethernet, http://www.cisco.com/warp/public/cc/techno/lnty/etty/ggetty/tech/10gig_wp.htm
- Cisco Switching Solutions: Gigabit Ethernet Solutions, http://www.cisco.com/warp/public/729/gigabit/index.html
- Ethernet, http://www.cisco.com/univercd/cc/td/doc/cisintwk/ito_doc/ethernet.htm
- FAQ's - 10 Gigabit Ethernet Alliance, http://www.10gea.org/Tech-FAQ_S.HTM
- Gigabit Ethernet Alliance, http://www.gigabit-ethernet.org/
- Gigabit Ethernet Overview, http://www.cis.ohio-state.edu/~jain/cis788-97/gigabit_ethernet/index.htm
- Gigabit-Ethernet (IEEE 802.3 z), http://www11.informatik.tu-muenchen.de/lehre/lectures/ws2000-01/komponentenrn/extension/html-kurz/komprn-ws00014.3.5.html
- IEEE 802.3 Higher Speed Study group, http://grouper.ieee.org/groups/802/3/10G_study/public/index.html
- IEEE 802.3ab, "An Introduction to 1000Base-T," March 10, 1997, http://grouper.ieee.org/groups/802/3/tutorial/march98/mick_170398.pdf
- IEEE 802.3ae 10 Gb/s Ethernet Task Force, http://grouper.ieee.org/groups/802/3/ae/index.html
- IEEE 802.3ae email list: send a message with "subscribe stds-802-3-hssg <your email adr> in body to majordomo@majordomo.ieee.org
- IEEE 802.3ae email reflector, http://grouper.ieee.org/groups/802/3/10G_study/email/thrd1.html
- IEEE 802.3z ftp site, http://grouper.ieee.org/groups/802/3/z/index.html
- IEEE Gigabit Ethernet working groups papers, presentations, http://grouper.ieee.org/groups/802/3/z/index.html
- Intel Network Connectivity - Gigabit Ethernet, http://www.intel.com/network/technologies/gigabit_ethernet.htm
- K. Tolly, "Planning for Gigabit Ethernet," Network World, April 28, 1997, p. 49-52.
- Light Reading - The Global Site For Optical Networking, http://www.lightreading.com/document.asp?doc_id=3260
- Market Report - 10 Gigabit Networks - A Gigabit & 10 Gigabit ... , http://www.igigroup.com/st/pages/gigabitethernet.html
- RPR Alliance, http://www.rpralliance.org/
- Resilient Packet Ring Study Group, http://www.ieee802.org/rprsg/public/presentations/may2000/
- Resilient Packet Ring Working Group, http://www.ieee802.org/rprsg/
- Resilient Packet Rings, 12/20/00, http://www.nwfusion.com/newsletters/lans/2000/00292193.html
- Riverstone Networks | Packet Ring Technology, http://www.riverstonenet.com/technology/packet_ring.shtml
- S. Ebert, et al, "Gigabit Ethernet and Low-Cost Supercomputing," http://www.scl.ameslab.gov/Publications/Gigabit/tr5126.html
- The Emergence of End-to-End Ethernet, http://www.lightreading.com/opticalintellect/document.asp?doc_id=72&mode=print

- The metro optical market, http://lw.pennwellnet.com/Articles/Article_Display.cfm?Section=Articles&Subsection=Display&ARTICLE_ID=90196&KEYWORD=ethernet
- XenPak.org - 10 Gigabit Ethernet, 10 GbE, IEEE ... , http://www.xenpak.org/
- You should know about "jumbo frames", http://www.nwfusion.com/newsletters/lans/0614lan1.html

Resilient Packet Ring: References

- **RPR Alliance**, http://www.rpralliance.org/
- **An Introduction to Resilient Packet Ring Technology**, http://www.rpralliance.org/articles/Whitepaper10-01.pdf
- Nortel Networks, Resilient Packet Ring, http://www.nortelnetworks.com/corporate/technology/rpr/
- Resilient Packet Ring Standards for Metropolitan Area Networks, http://www.luminous.com/sub/pdf/rpr_standards.pdf
- Appian Communications'Strategy for IEEE 802.17 Resilient Packet ... , http://www.appiancom.com/RPR_Strategy.pdf
- Resilient Packet Ring Technology Overview, http://www.corrigent.com/pdfs/RPRoverview.pdf
- An Introduction to Resilient Packet Ring Technology, http://www.lanterncom.com/documents/whitepaper_rpra.pdf
- Lantern's Resilient Optical Packet Ring Technology, http://www.lanterncom.com/documents/ad_evolve_clay.pdf
- Packet Ring Technology: The Future of Metro Transport, http://www.riverstonenet.com/technology/packet_ring.shtml
- Network Manias, RPR Study group, http://netmanias.com/contents/studygroup/rpr/study_rpr.htm

High Speed Access From Home References

- IETF Working Groups
- Residential Broadband: Books
- IEEE 802.14: References
- Residential Broadband: References
- **RFCs**
- **Internet Drafts**

Note: A periodically updated version of this list is kept on-line at http://www.cis.ohio-state.edu/~jain/refs/rbb_refs.htm

See also:
Books on Residential Broadband, xDSL and Cable Modems
Digital Subscriber Lines and Cable Modems
Residential Broadband: High-Speed Access to Home
Residential Broadband: Technologies for High-Speed Access to Homes

Back to Hot Topics in Networking References
Back to Raj Jain's Home Page

IETF Working Groups

- ADSL MIB (adslmib), http://www.ietf.org/html.charters/adslmib-charter.html
- IP over Cable Data Network (ipcdn), http://www.ietf.org/html.charters/ipcdn-charter.html

Residential Broadband: Books

- See http://www.cis.ohio-state.edu/~jain/refs/rbb_book.htm

IEEE 802.14: References

- IEEE 802.14 WG, "Cable-TV Functional Requirements and Evaluation Criteria," IEEE 802.14/94-002R2, February 1995.

Residential Broadband: References

- Digital Subscriber Lines and Cable Modems, http://www.cis.ohio-state.edu/~jain/cis788-97/rbb/index.htm
- Cable Data Networks, http://www.cis.ohio-state.edu/~jain/cis788-97/cable_modems/index.htm
- Marlis Humphrey, John Freeman, Paradyne Corp., "How xDSL supports Broadband Services to the Home", IEEE Network Jan./Feb 1997.
- T. Kwok, "A vision for Residential Broadband Services: ATM to the Home," IEEE Network, September/October 1995, pp. 14-28.
- M. Laubach, "To Foster Residential Area Broadband Internet Technology," ConneXion,

December 1995, pp. 18-30.
- D. Zgodzinski, "The Cable Chase," Internet World, June 1996, pp. 63-66.
- Cable Modem Resources on the Web, http://rpcp.mit.edu/~gingold/cable/
- Cable Modem Home Page, http://www.cablemodem.com/
- High Bandwidth Web Page: Wireless & Cable, http://www.specialty.com/hiband/wireless.html
- Cable Modem Univesity: Standards, http://www.catv.org/modem/standards/
- http://www.spie.org/web/abstracts/2600/2609.html
- The ADSL Forum, http://www.dslforum.org/
- ADSL Forum, "ADSL Forum System Reference Model", http://www.dslforum.org/
- ADSL Forum, "ADSL Tutorial", http://www.adsl.com/adsl_tutorial.html
- tele.com, "DSL, from A to V", http://www.teledotcom.com/1096/features/tdc1096coverstory1.html
- Philip Kyees, Ronald C McConnell, Kamran Sistanizadeh, "ADSL: A New Twisted-Pair Access to the Information Highway", IEEE Communications Magazine, April 1995.
- Angela Littwin, "ADSL: Ready for Prime Time?", Telecommunications, Dec. 1996.
- Arielle Emmett, "Motorola plays ADSL chip, CopperGold bets on single-chip transceiver", America's Network, Dec. 1, 1996, http://www.americasnetwork.com/
- ADSL Forum, "VDSL Tutorial, Fiber-Copper Access to the Information Highway", http://www.dslforum.org/
- IETF IP over Cable Data Network working group, http://www.ietf.org/html.charters/ipcdn-charter.html,Mailing list: ipcdn-request@terayon.com, Archive: ftp://ftp.terayon.com/pub/ipcdn
- Imagen Communications HDSL/ADSL Information Pages, http://204.244.138.1/
- Cable Modem FAQs, http://paragonpdx.com/cablemod.html
- In Search of Speed and Bandwidth. Bee, Adrianne. Computer. December 1996, v29n12.
- Cable Access Beyond the Hype. Bisdikian, Chatschik et al. IEEE Communications Magazine. December 1996, v29.
- "Data Over Cable Interface Specifications - Cable Modem to Customer Premise Equipment Interface Specification", http://www.cablelabs.com
- Carl Weinschenk, "The Great Wired Hope", http://www.teledotcom.com/1296/features/tdc1296modem.html
- David Kopf, "Striking while the Copper is HOT", America's Network,
- The Pelorus Group, "The Future of ADSL", http://www.pelorus-group.com
- "Break the Bandwidth Barrier." Halfhill, Tom R. Byte v21n9. September 1996.
- "On-ramp Prospects for the Information Superhighway Dream." Bell, Gorden and Gemmell, Jim. Communications of the ACM, v39n7. July 1996.
- The IP over Cable Data Network (IPCDN) Working Group (Charter). http://www.ietf.org/html.charters/ipcdn-charter.html
- Who is working on standards for cable modems?" http://www.catv.org/modem/standards/
- Data over Cable Interface Specifications, Security System Specification (SP-SSI-I01-970506 Interim Spec). MCNS Holdings, May 6, 1997.
- Data over Cable Interface Specifications, Cable Modem Telephony Return Interface Specification (SP-CMTRI-I01-970804 Interim Spec). MCNS Holdings, August 4, 1997.
- Cable Modems -- Ready Or Not, Here They Come. Dunn, Darrell. Electronic Buyer's News. February 17, 1997. Issue 1045. http://www.techweb.com/search/advancedSearch
- Modem's Growth Difficult to Predict. Electronic Buyer's News. February 17, 1997. Issue 1045. http://www.techweb.com/se/directlink.cgi?EBN19970217S0101
- Daniel Minoli, "Video Dialtone Technology", McGraw-Hill Inc. 1995.
- Cable Modems Bring Back Excitement. Dunn, Darrell. Electronic Buyer's News. February 17, 1997. Issue 1045. http://www.techweb.com/search/advancedSearch
- New Cable Modem Standard Embraced. Yoshida, Junko. EETimes. March 23, 1997. http://www.techweb.com/se/directlink.cgi?WIR1997032302

- Cable Modems: Maybe Next Year? Mayer, John H. Electronic Buyer's News. June 23, 1997. Issue 1063. http://www.techweb.com/search/advancedSearch
- The Point of No Return. Weinschenk, Carl. tele.com. June 1997. http://www.teledotcom.com/0697/features/tdc0697cable.html

RFCs

- RFC 3083, Baseline Privacy Interface Management Information Base for DOCSIS Compliant Cable Modems and Cable Modem Termination Systems. R. Woundy. March 2001. ftp://ftp.isi.edu/in-notes/rfc3083.txt
- RFC 2669, DOCSIS Cable Device MIB Cable Device Management Information Base for DOCSIS compliant Cable Modems and Cable Modem Termination Systems. M. St. Johns, Ed.. August 1999. ftp://ftp.isi.edu/in-notes/rfc2669.txt
- RFC 2662, Definitions of Managed Objects for the ADSL Lines. G. Bathrick, F. Ly. August 1999. ftp://ftp.isi.edu/in-notes/rfc2662.txt

Internet Drafts

- Search for "adsl", "cable", or "home" at http://search.ietf.org/or click on the following queries:
  - http://search.ietf.org/cgi-bin/htsearch?restrict=http://www.ietf.org/internet-drafts/&words=adsl
  - http://search.ietf.org/cgi-bin/htsearch?restrict=http://www.ietf.org/internet-drafts/&words=cable
  - http://search.ietf.org/cgi-bin/htsearch?restrict=http://www.ietf.org/internet-drafts/&words=home

Broadband Metro and Access Networks: Acronyms

Raj Jain
Co-Founder and CTO
Nayna Networks
481 Sycamore Drive, Milpitas, CA 95035
Raj@nayna.com
http://www.nayna.com and http://www.cis.ohio-state.edu/~jain/

ADSL	Asynchronous Digital Subscriber Line
AMI	Alternate Mark Inversion
ANSI	American National Standards Institute
BDSL	Another name for VDSL
BWA	Broadband Wireless Access
CIR	Committed Information Rate
CLEC	Competitive Local Exchange Carrier
CMIP	Common Management Information Protocol
CSMA/CD	Carrier Sense Multiple Access with Collision Detection
DSL	Digital Subscriber Line
DSP	Digital Signal Processing
EFM	Ethernet in the First Mile
ELS	Ethernet Line Service
EPON	Ethernet Passive Optical Network
FAST	Fiber Access Thru Sewer Tubes
FDM	Frequency Division Multiplexing
FSAN	Full Service Access Network
FTTx	Fiber To The X
10GBASE-T	10Gbps over unshielded twisted pair
GE	Gigabit Ethernet
GFP	Generic Framing Procedure
GHz	Giga Hertz
GPON	Gigabit Passive Optical Networks
HFC	Hybrid Fiber Coax
IEEE	Institution of Electrical and Electronic Engineers
ILECs	Incumbent Local Exchange Carriers
ISDN	Integrated Subscriber Digital Network
ISP	Internet Service Providers
LAN	Local Area Network
LCAS	Link Capacity Adjustment Scheme
MAC	Media Access Control
MAN	Metropolitan Area Network
MBaud	Mega Baud
MHz	Mega Hertz
MPLS	Multiprotocol Label Switching
OAM	Operations Administration and Management
OLT	Optical Line Terminal
ONT	Optical Network Terminal

OSI	Open System Interconnections
PBX	Private Branch Exchange
PHY	Physical Layer
PON	Passive Optical Network
POTS	Plane Old Telephone
QAM	Quadrature Amplitude Modulation
RADSL	Rate-adaptive ADSL
RAN	Residential Access Network
RF	Radio Frequency
RPR	Resilient Packet Ring
SAM	Sewer Access Module
SDH	Synchronous Digital Hierarchy
SDSL	Single line DSL
SONET	Synchronous Optical Network
STS	Synchronous Transport Service
TV	Television
UNI	User-to-network Interface
USA	United States of America
VADSL	Very high data rate Asymmetric DSL
VDSL	Very high data rate DSL
VDSLe	VDSL European version
VT	Virtual Tributary
WAN	Wide Area Network