Broadband Metro and Access Networks

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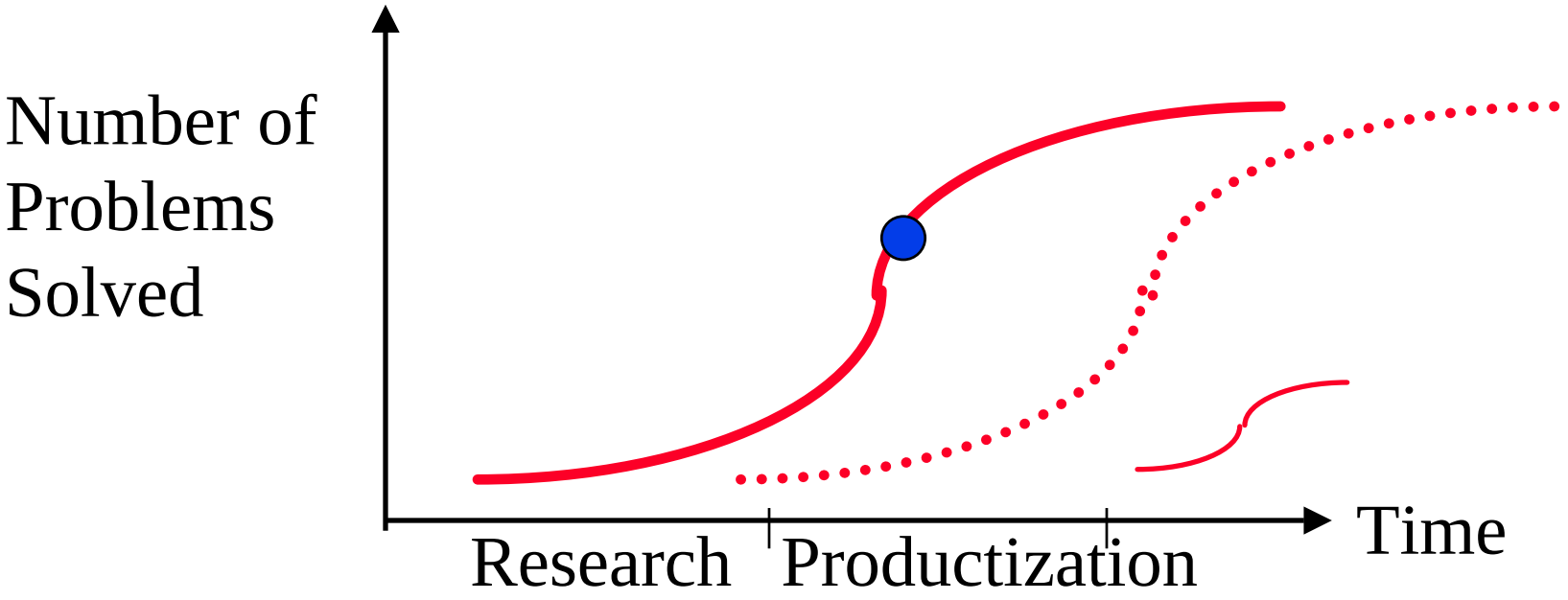
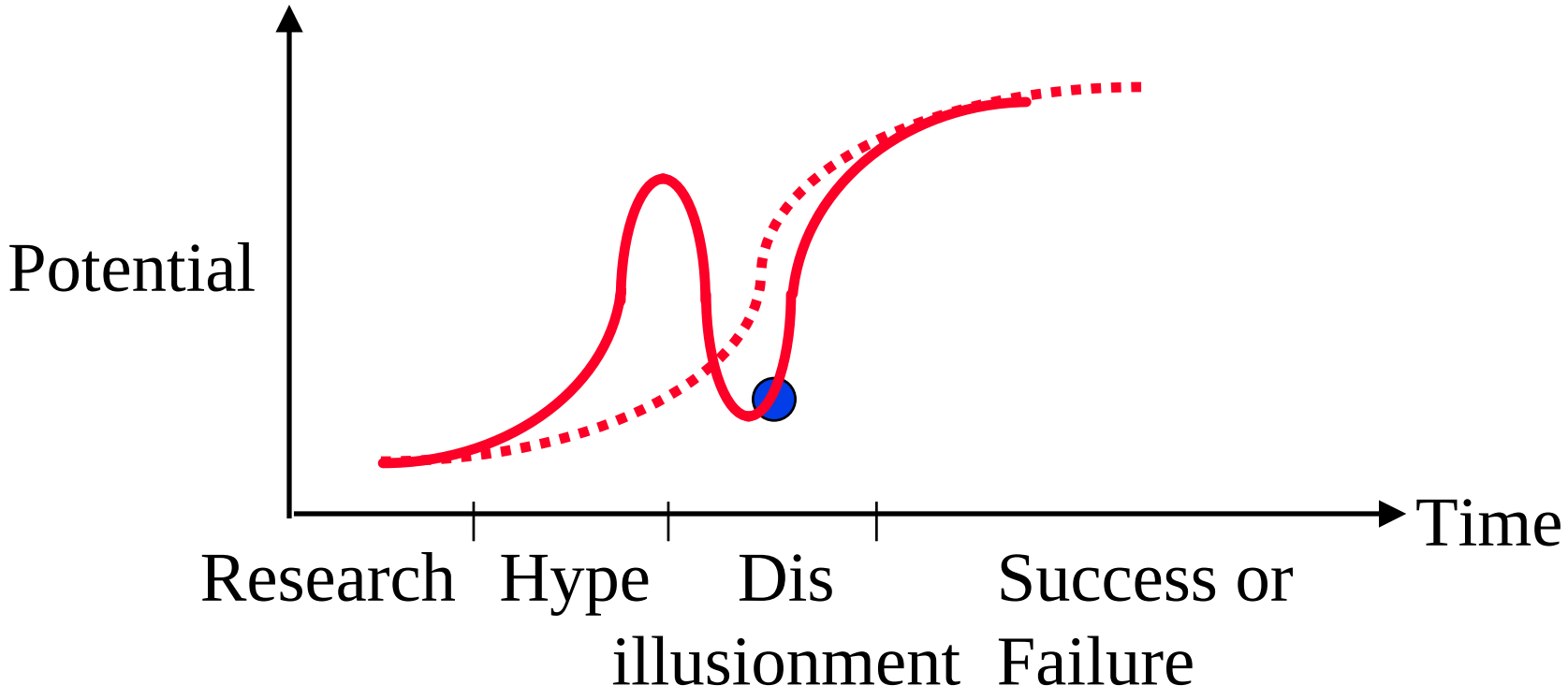
1. Trends in Networking
2. Metro Networks:
   1G and 10G Ethernet, Resilient Packet Ring,
   SONET/SDH vs Ethernet, Next Gen SDH
3. Access Networks: xDSL, Cable Modems, Broadband Wireless Access, WiMAX, Optical Wireless, Satellite, Passive Optical Networks

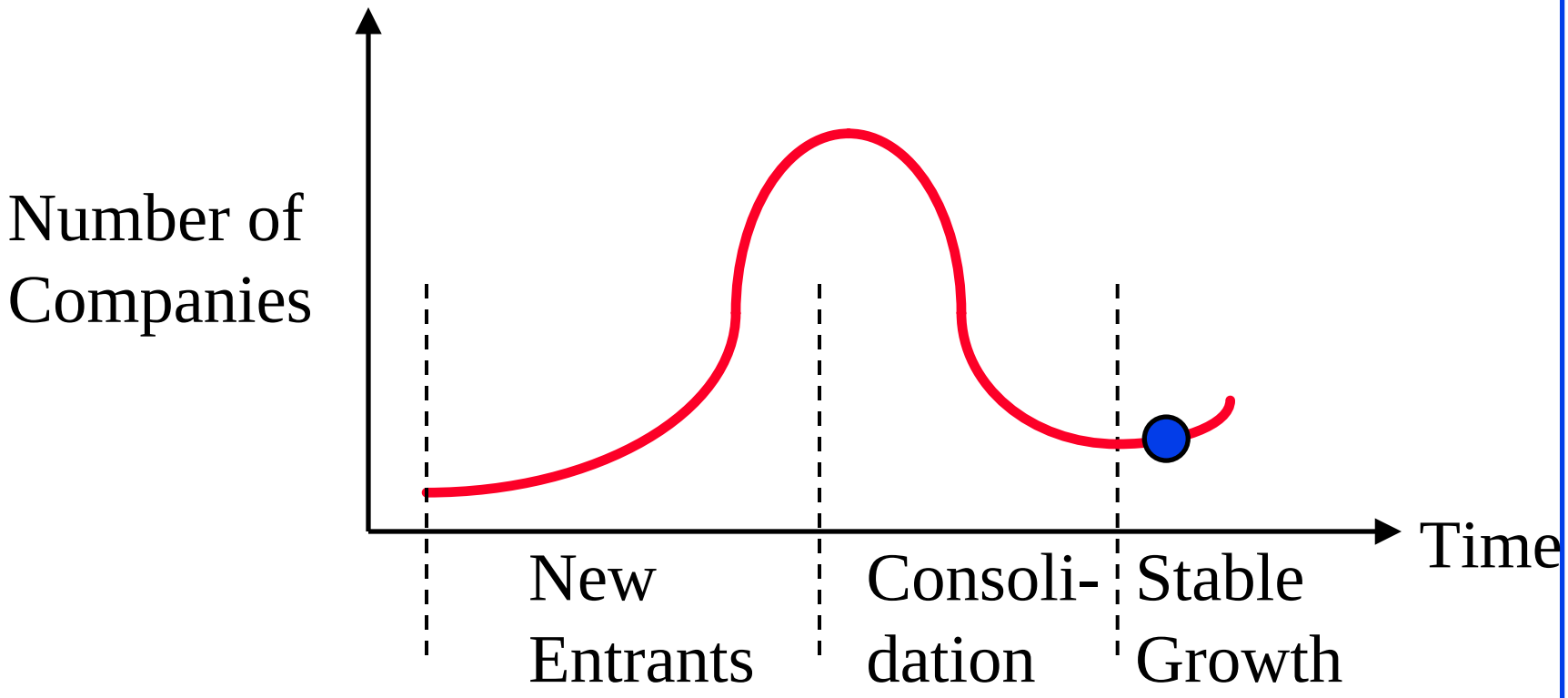
Life Cycles of Technologies



Hype Cycles of Technologies



Industry Growth



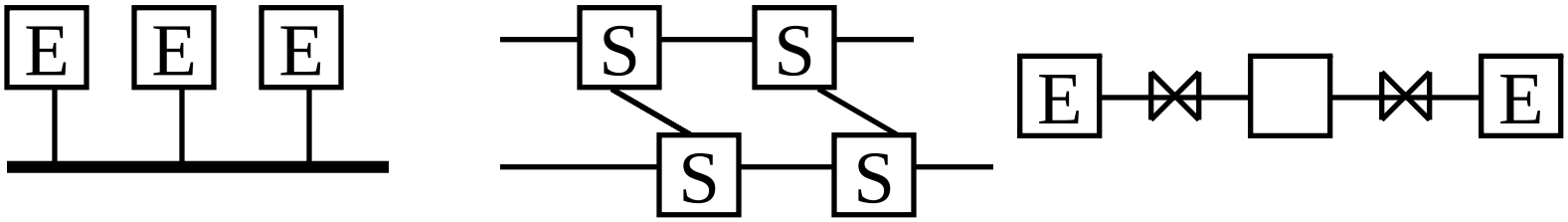
Trend: Back to ILECs

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
   $\Rightarrow$ Equipment that support voice circuits but allow packet based (hybrids) are more important than those that allow only packet based

Core Networks

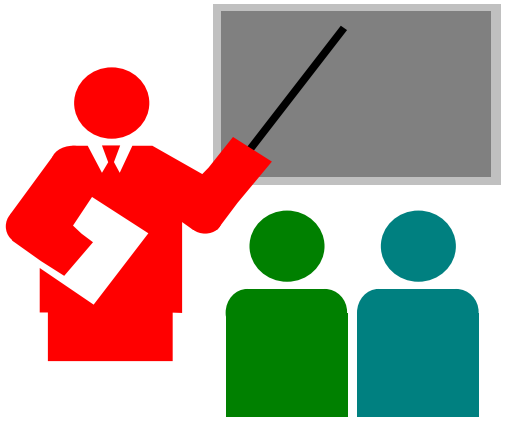
- Higher Speed/λ: 10 Gbps to 40 Gbps to 160 Gbps
- Longer Distances/Regens: 600 km to 6000 km
- More Wavelengths: 16 λ's to 160 λ's

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

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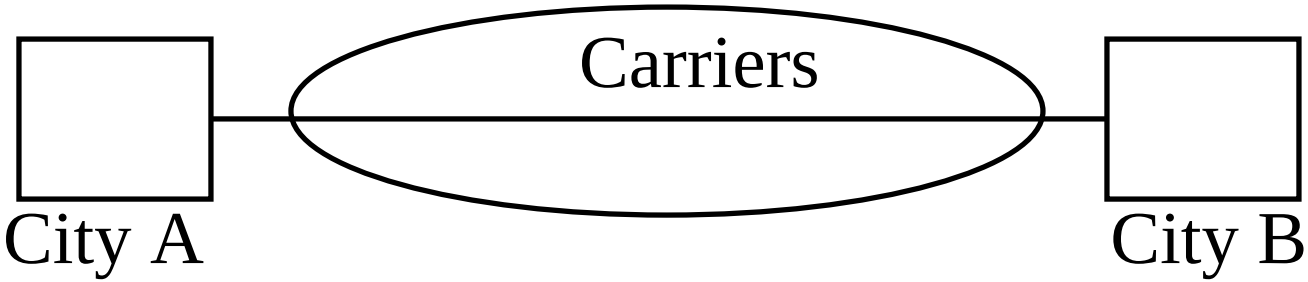
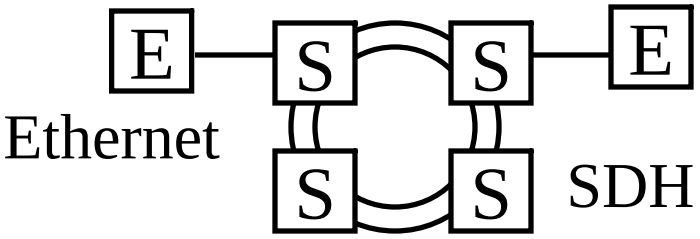
- SONET/SDH
- 1 GbE and 10GbE: Key Design Decisions
- Metro Ethernet Services
- SONET/SDH vs Ethernet: Issues and Remedies
- Resilient Packet Ring
- Networking Technologies: Failures vs Successes
- Next Generation SDH: VCAT, GFP, LCAS

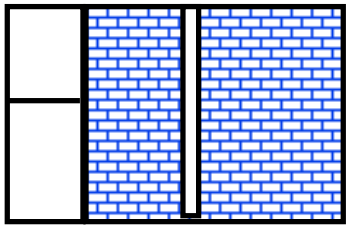
SONET/SDH

- 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

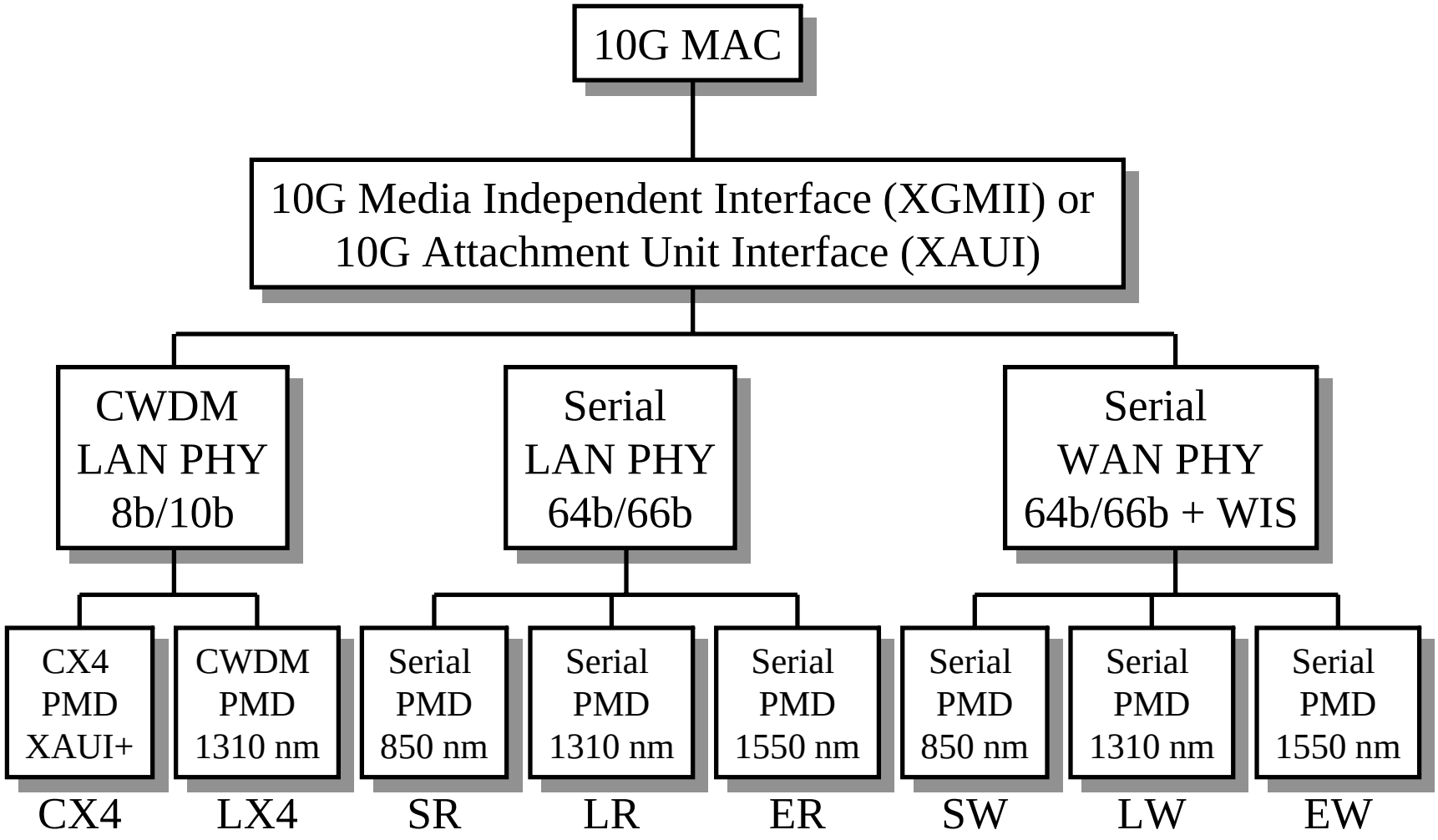
- P802.3ae ⇒ Update to 802.3
  Compatible with 802.3 frame format, services, management
- 10 Gbps vs. 9.5 Gbps. **Both** rates.
- LAN and **MAN** distances
- Full-duplex only ⇒ **No Shared** Mode
  Only switch based networks. No Hubs.
- Same min and max frame size as 10/100/1000 Mbps
  Point-to-point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

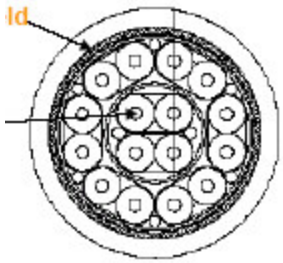
- S = Short Wave, L=Long Wave, E=Extra Long Wave
- R = Regular reach (64b/66b), W=WAN (64b/66b + SONET Encapsulation), X = 8b/10b
- 4 = 4 λ's

10GbE PHYs



10GBASE-CX4

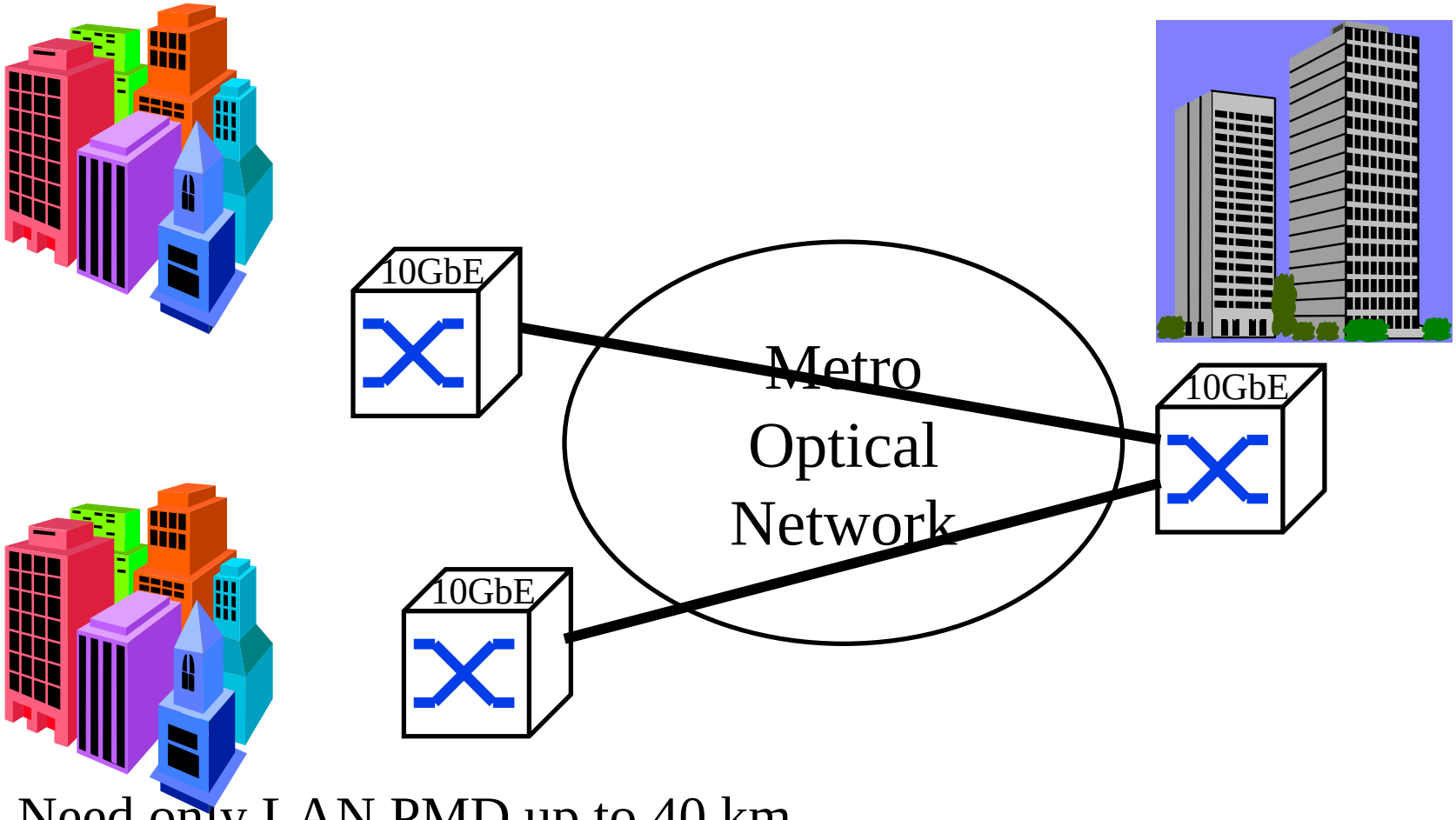
- For data center applications (Not for horizontal wiring):
  - Switch-to-switch links, Switch-to-server links
  - External backplanes for stackables
- Twinax cable with 8 pairs
- Based on Infiniband 4X copper PHY. IB4X connectors.
- 10G to 15m (std). Some vendors can do 25-30m.
- Standard: Dec 2003. Passed Sponsor Ballot.
- IEEE 802.3ak, http://www.ieee802.org/3/ak



10GBASE-T

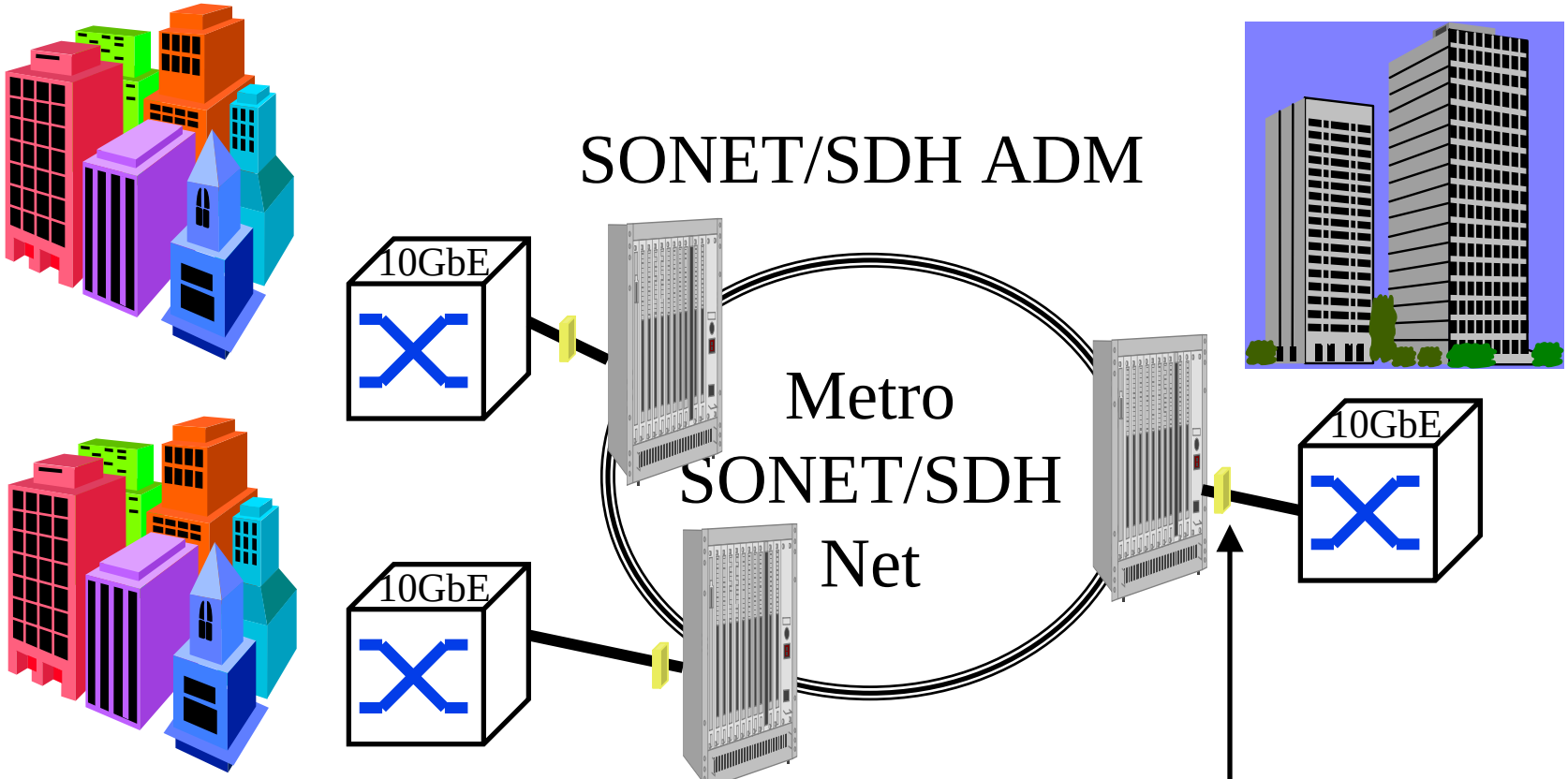
- New PHY for data center and horizontal wiring
- Compatible with existing 802.3ae MAC, XGMII, XAUI
- Standard: Start: Nov 2003 Finish: Jul 2005
- 100 m on Cat-7 and 55+ m on Cat-6
- Some startups working on Cat-5e
- Cost 0.6 of optical PHY. Greater reach than CX4
- 10-level coded PAM signaling with 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



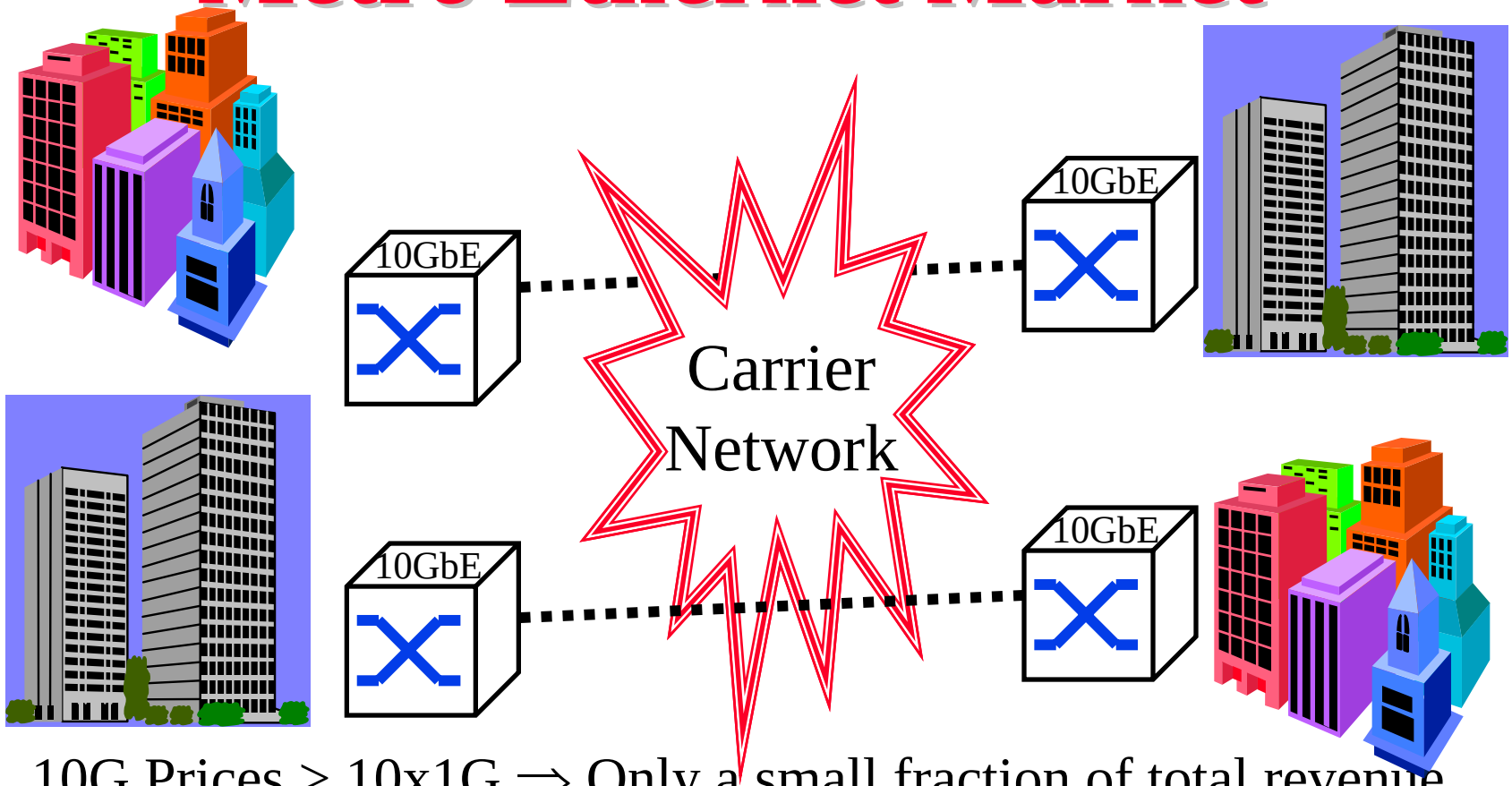
- Need only LAN PMD up to 40 km.
  No SONET/SDH overhead. No protection.

10 GbE over SONET/SDH



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

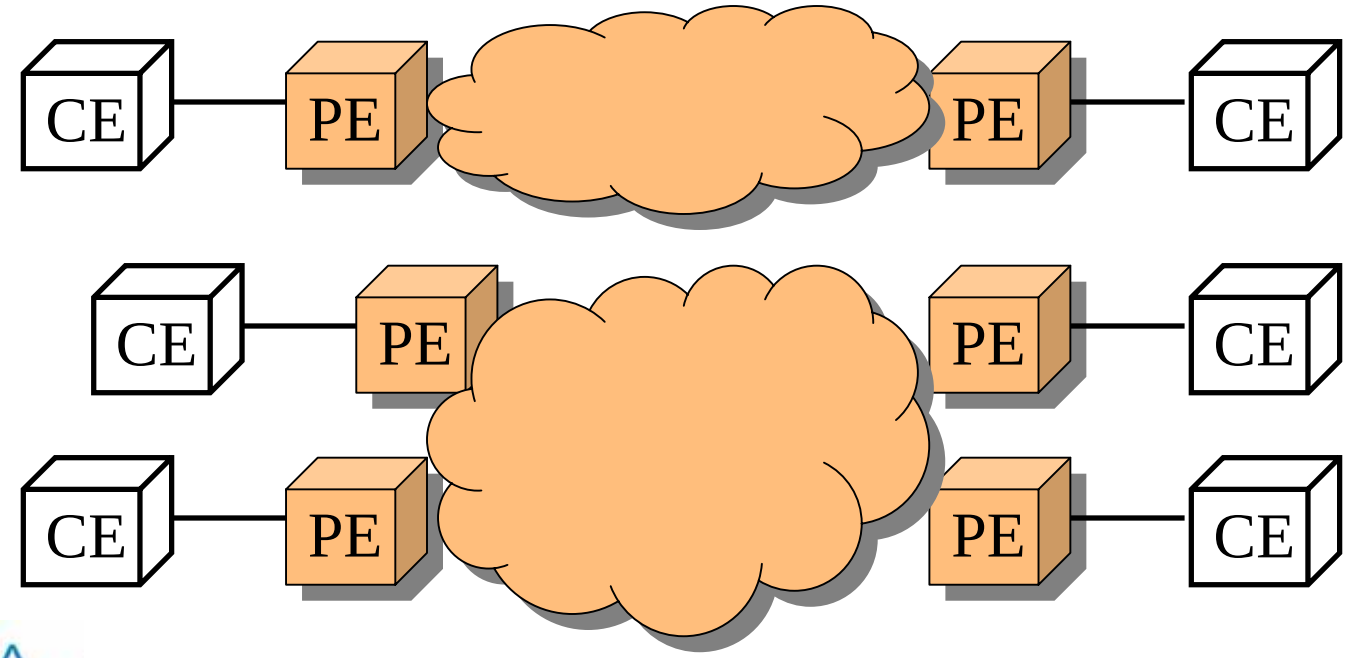
Metro Ethernet Market



- 10G Prices > 10x1G ⇒ Only a small fraction of total revenue. Prices decreasing fast ⇒300% Growth in 10G Q4'03.
- 10km XFP for $500
- 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

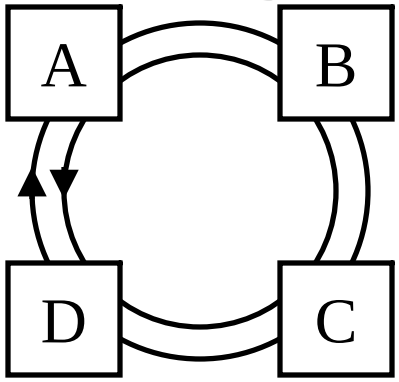
Enterprise

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

Carrier

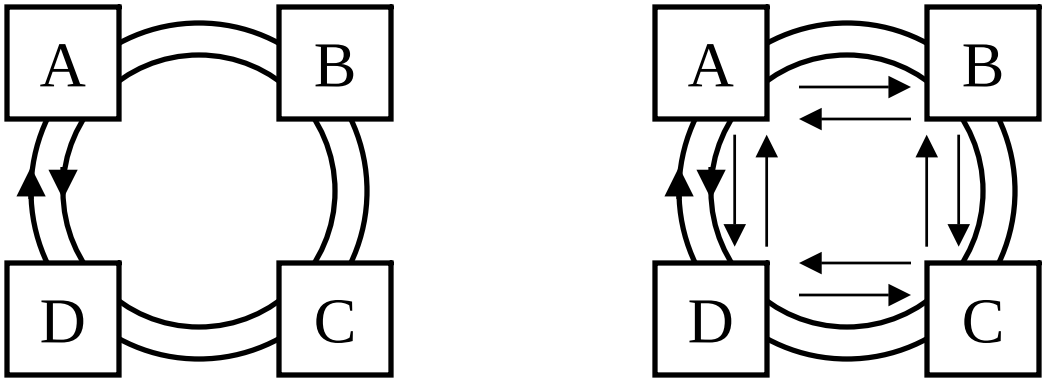
- Up to 100 km
- Millions of MAC Addresses
- Millions of VLANs
  Q-in-Q
- Rapid spanning tree
  (Gives 1s, need 50ms)
- Traffic engineered path
- SLA
- Need per-flow QoS
- Need performance/BER

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)

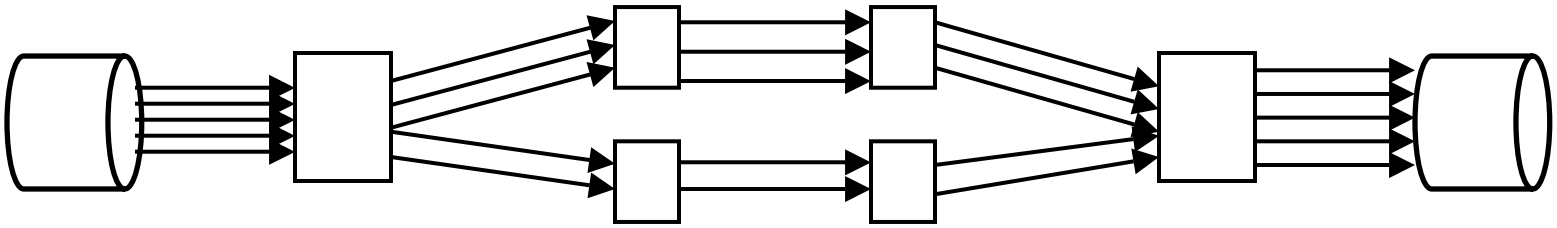
Networking: Failures vs Successes

- 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

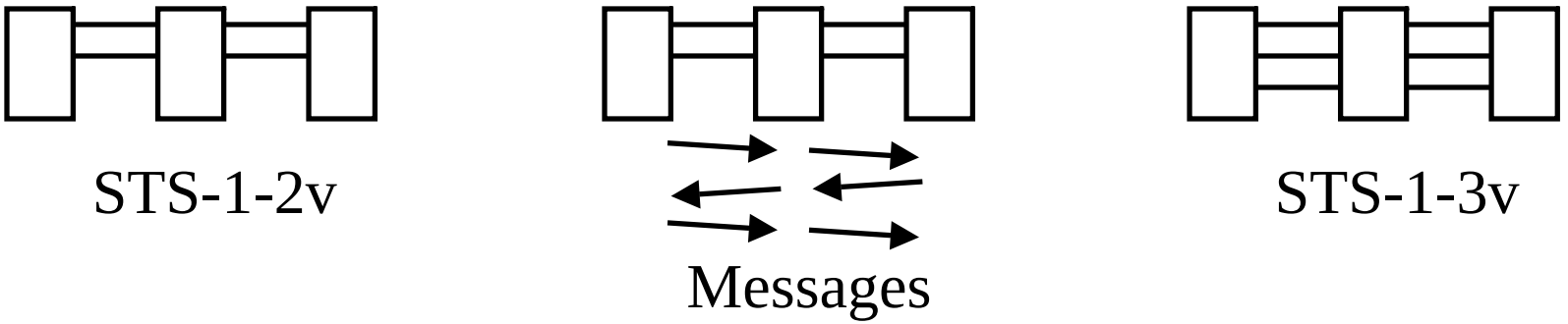
- Low Cost: Low startup cost ⇒ Evolution
- High Performance
- Killer Applications
- Timely completion
- Manageability
- Interoperability
- Coexistence with legacy LANs
  Existing infrastructure is more important than new technology

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

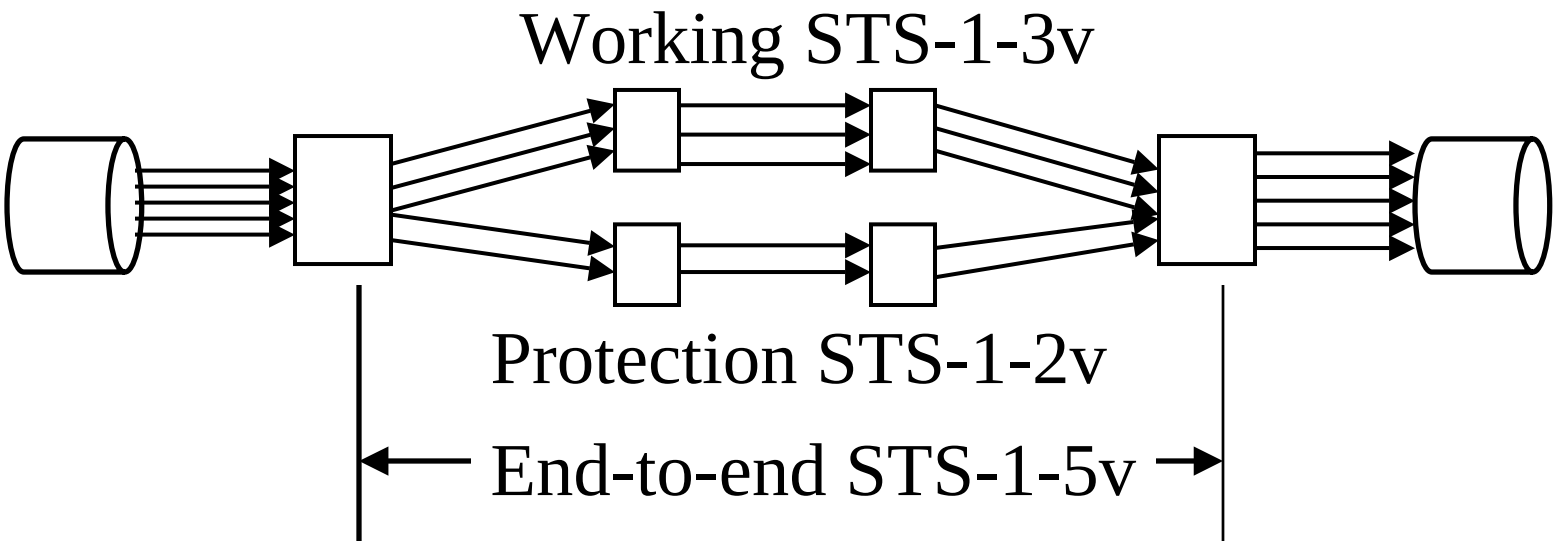
SONET/SDH LCAS



- 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

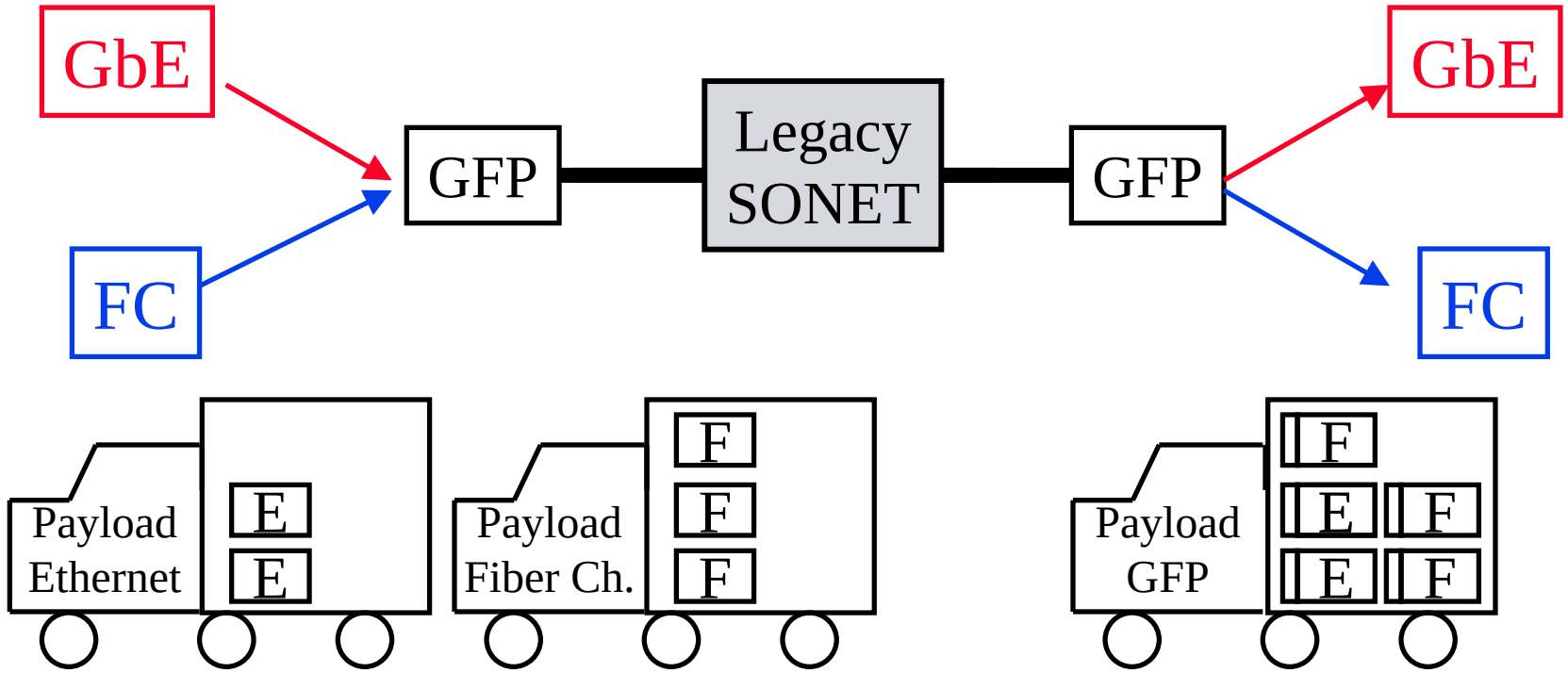
LCAS (Cont)

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



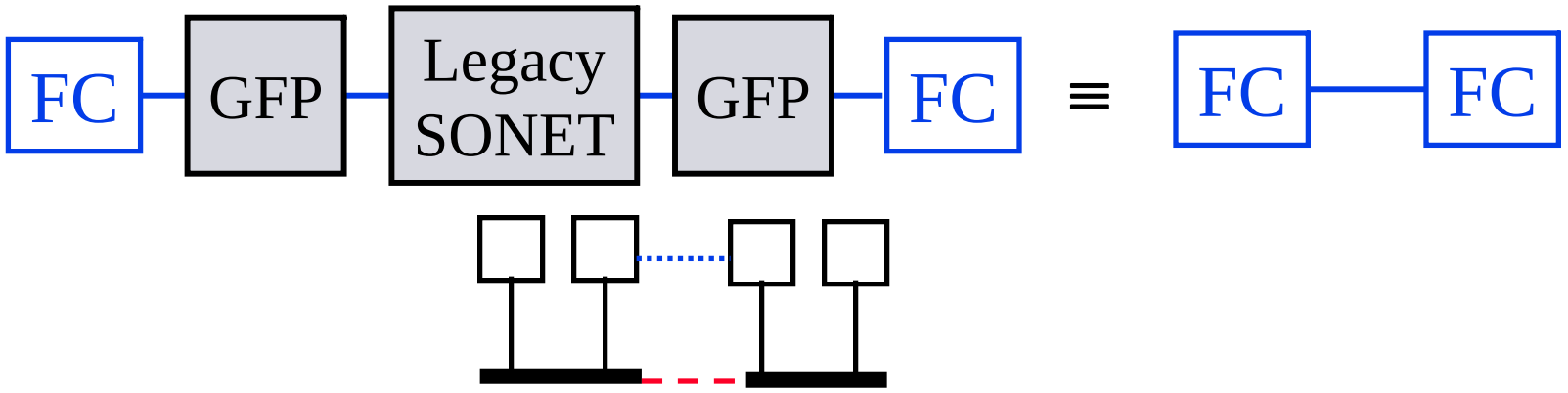
Generic Framing Procedure (GFP)

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



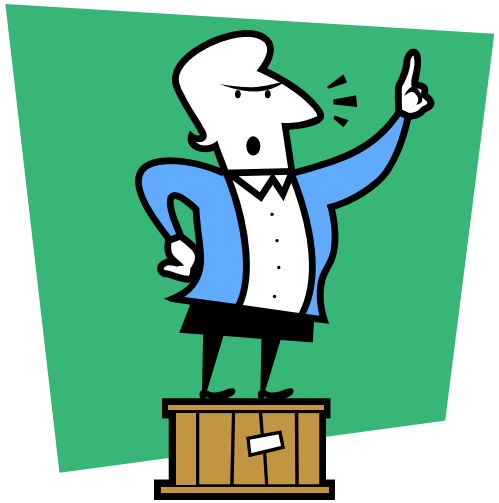
Transparent GFP

- 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
  $\Rightarrow$ 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

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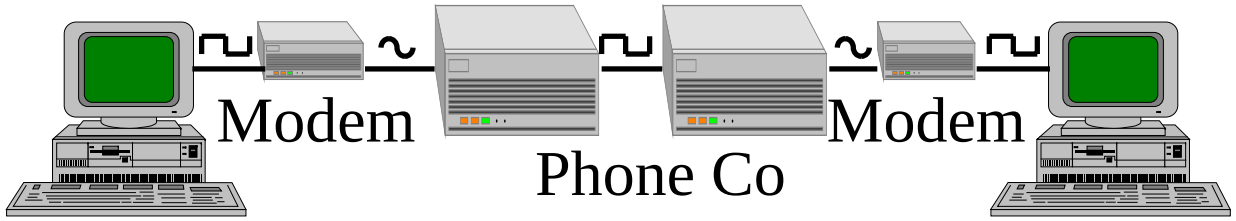
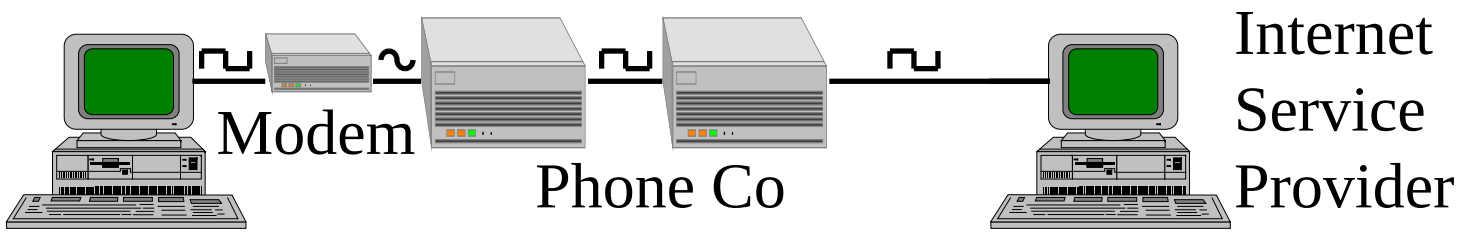
- xDSL
- Cable Modems and Hybrid Fiber Coax (HFC)
- Fiber To The X (FTTx)
- Bi-Directional Satellite
- Broadband Wireless Access (BWA) and WiMAX
- Mobile Broadband Wireless Access (MBWA)
- Optical Wireless Access
- Passive Optical Network (PON)

56 kbps Modems

- Past:

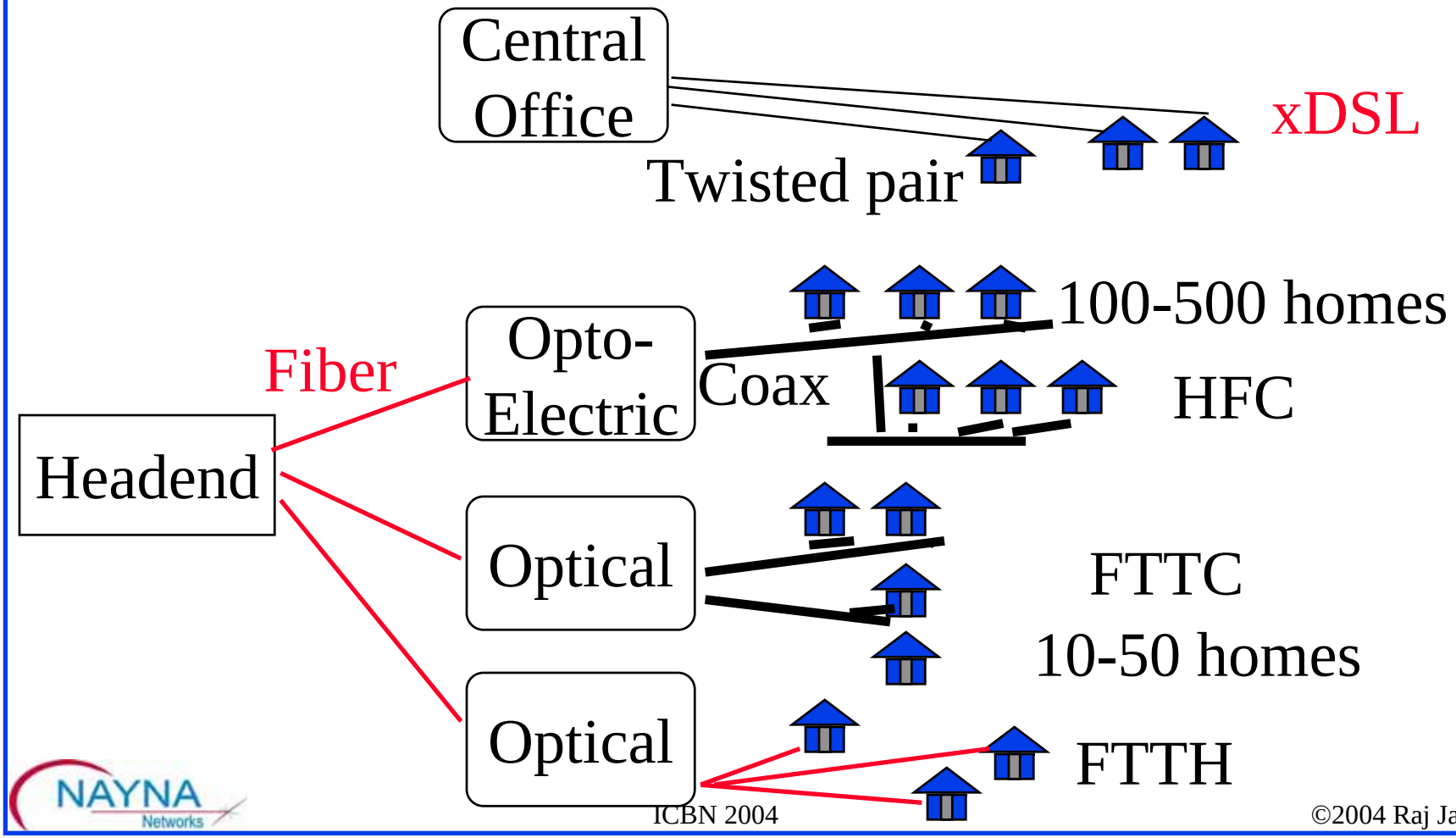


- Current:



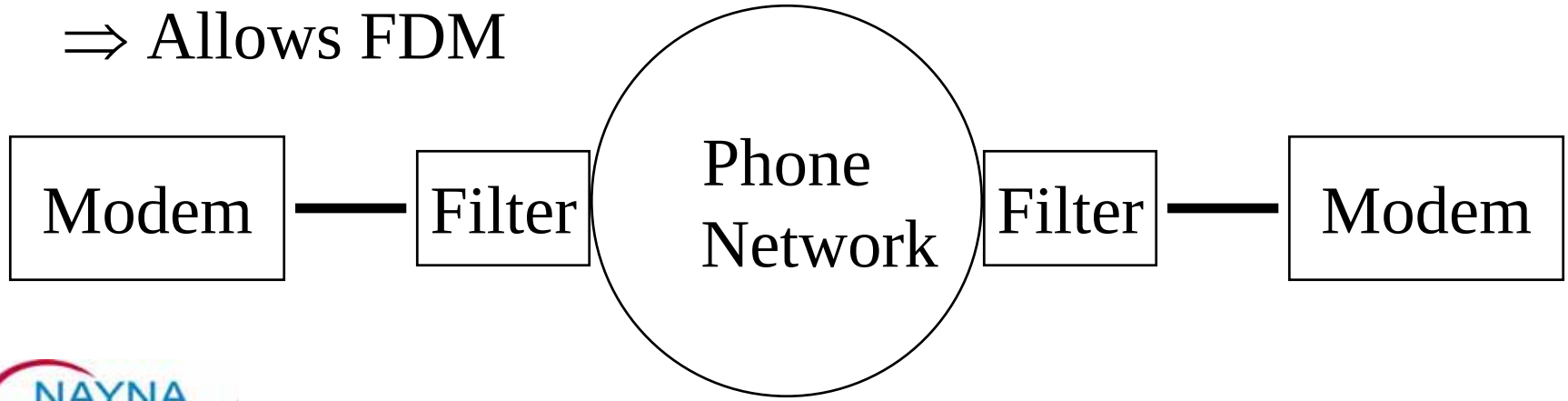
- ISP's have direct digital link (T1 or T3)
- Only one D/A/D conversion ⇒ Higher speed possible

Residential Access Networks (RANs)



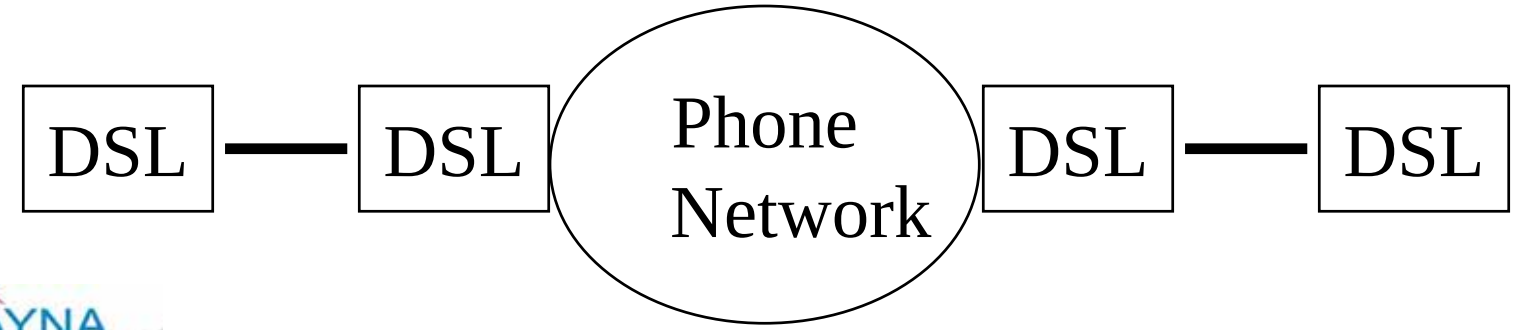
Why Modems are Low Speed?

- 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



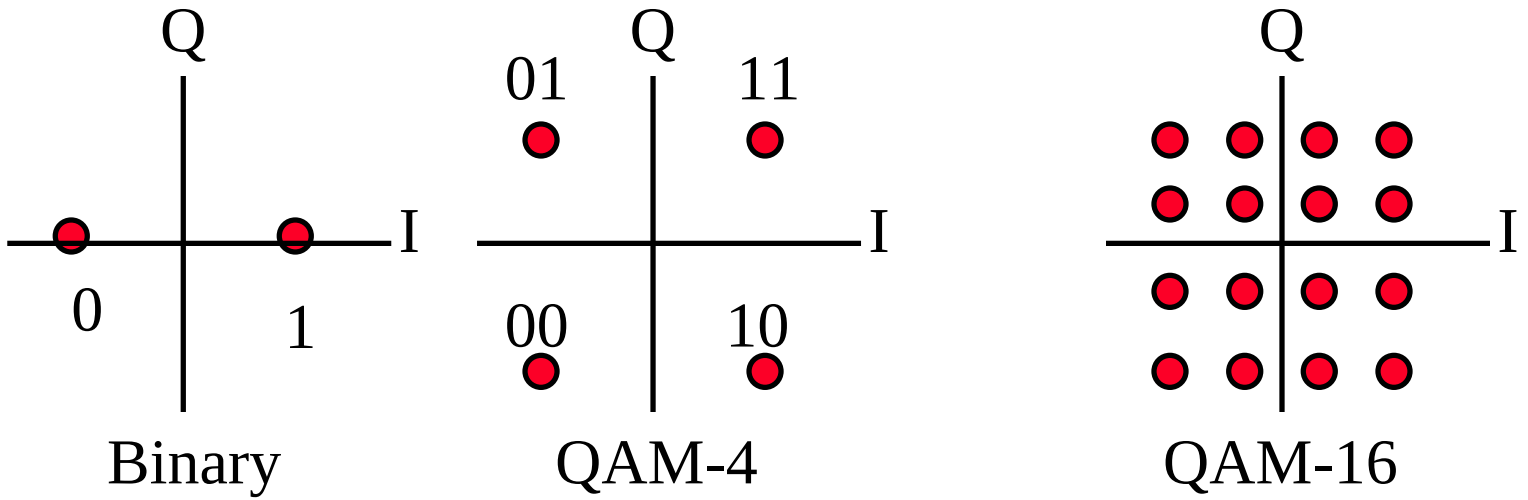
DSL

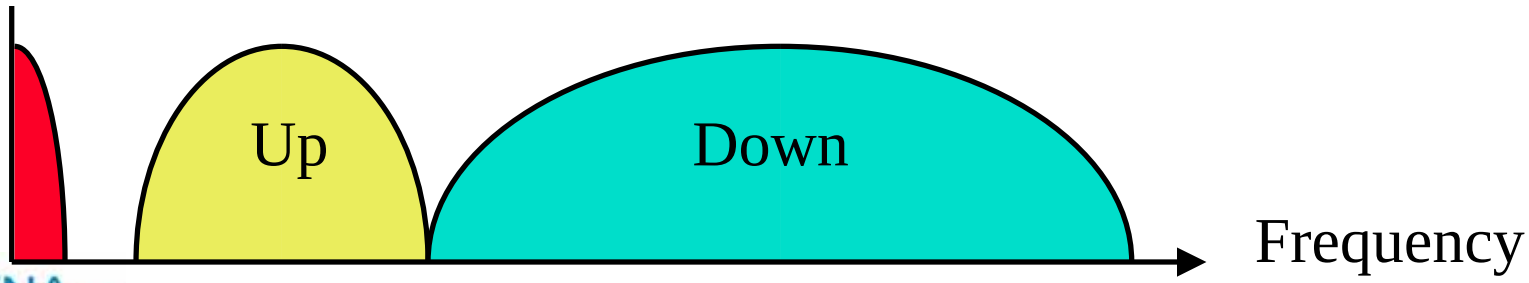
- Digital Subscriber Line = ISDN
- 64×2 + 16 + overhead
  = 160 kbps up to 18,000 ft
- DSL requires two modems (both ends of line)
- Symmetric rates ⇒ transmission and reception on same wire
  ⇒ Echo cancellation
- ISDN uses 0 to 80 kHz ⇒ Can't use POTS simultaneously



QAM

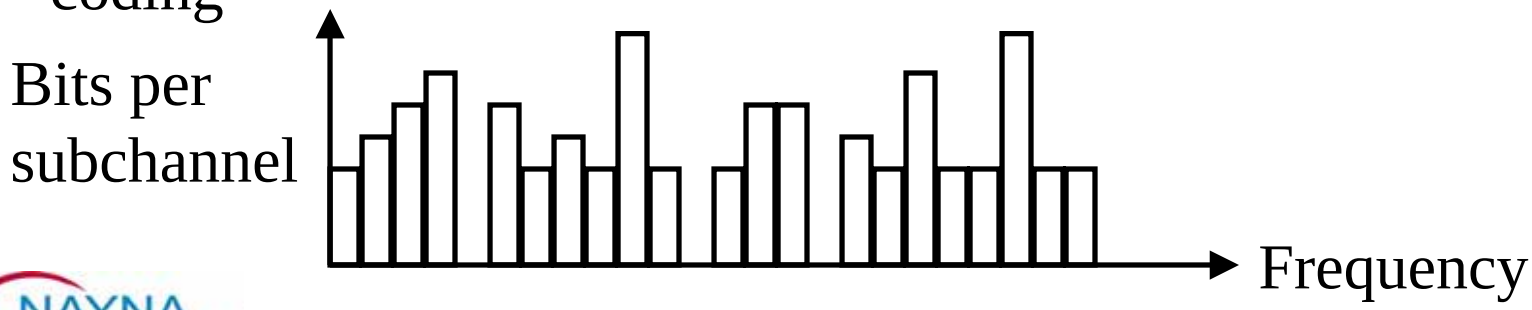
- Quadrature Amplitude and Phase Modulation
- I = In phase, Q=Quadrature signal
- Symbols occupy entire available bandwidth





Discrete Multi-Tone (DMT)

- Multicarrier modulation
- Inverse Discrete Fourier Transform (IDFT) to partition bandwidth into subchannels or tones
  E.g., 256/32 tones 4.3125 kHz apart = 1104/138 kHz Down/up
- Each tone is QAM modulated. 4kBaud symbols=250us frame
  Each tone carries 2 to 15 bits (Rate adaptive)
- Measure SNR of each subchannel
  Avoid severely degraded channels
  Lower data rate on degraded channels
- Built-in Reed-Solomon FEC with interleaving and Trellis coding



DMT vs QAM

- First linc-code war: ANSI T1E1.4 ADSL olympics in 1993

DMT	QAM
Multi-carrier Modulation	Single-Carrier Modulation
Used in wireless, ADSL, ADSL2, ADSL2+. Allows migration. Implementation in the same chipset.	Used in Modems, Satellite, HPNA, DOCSYS, HDSL, SDSL, SHDSL, IDSL, RADSL, 5-level PAM used in 100BT2 and 1000BT
Requires digital signal processing due to FFT and iFFT	No DSP
DSP firmware download	Hardwired
Needs training sequence and initialization	No training sequence or handshake
Dynamic Spectrum Management:on-the-fly PSD change. Line bonding.	SNR averaging improves effective bandwidth
Erasure of a part of a symbol kills the whole symbol	Short symbols not affected by impulse noise
VDSL Alliance: Ikanos, Stmicro, Alcatel	VDSL Coalition: Infineon
Requires licensing	Public domain

- Final Decision: ANSI T1E1.4 June 2003: DMT Std, QAM in TRQ

Copper Broadband Systems I

Acronym	Description	Standards	Year	Modu-lation	# of Pairs	Up Mbps	Down Mbps	Spectrum in kHz
ADSL	Asymmetric DSL	T1.413 G.992.1	1995	DMT	1	1	8	25-138 U 25-1104 D
G.Lite	Splitterless ADSL	G.992.2 T1.419	1999	DMT	1	1	1.5	25-138 U 25-552 D
RADSL	Rate Adaptive DSL	T1.TR.59		CAP	1	1	8	25-138 U 25-1104 D
ADSL2	ADSL 2nd Gen	G.992.3	2003	DMT	1	1	12	0-276 U 0-1104 D
G.Lite.bis	ADSL2 Lite	G.992.4	2003	DMT	1	1		
ADSL2+	Double Rate ADSL2	G.992.5	2003	DMT	1	1	24	0-276 U 0-2208 D
VDSL	Very high bit rate DSL	T1.424 G.vdsl	2002	DMT or QAM	1	13	22	25-12000
EFM	Ethernet in the First Mile	10PASS-TS 2BASE-TL	2004	DMT DMT	1 1	10 2	10 2	25-12000 25-138

Copper Broadband Systems II

Acronym	Description	Standards	Year	Modu-lation	# of Pairs	Up Mbps	Down Mbps	Spectrum in kHz
ISDN BRI	Basic Rate ISDN	T1.601 G.961	1986	2B1Q	1	0.160	0.160	0-80
IDSL	ISDN over DSL				1	0.144	0.144	
T1	T1	T1.403		AMI	2	1.544	1.544	0-1544
E1	E1	G.703		HDB3	2	2.048	2.048	0-2048
HDSL	High Bit-Rate DSL	G.991.1 T1.TR.28	1992	2B1Q	2	1.544	1.544	0-370
HDSL2	HDSL 2nd Gen	T1.418 G.991.2		TC-PAM	1	1.544	1.544	0-300 U 0-440 D
HDSL4	4-wire HDSL 2nd Gen	T1.418 G.991.2		TC-PAM	2	1.544	1.544	0-130 U 0-400 D
SDSL	Symmetric DSL	TS 101 524	1998	2B1Q	1	2.312	2.312	0-700
G.shdsl	Single pair HDSL	G.991.2 T1.422	2000	TC-PAM	1	2.312	2.312	0-400

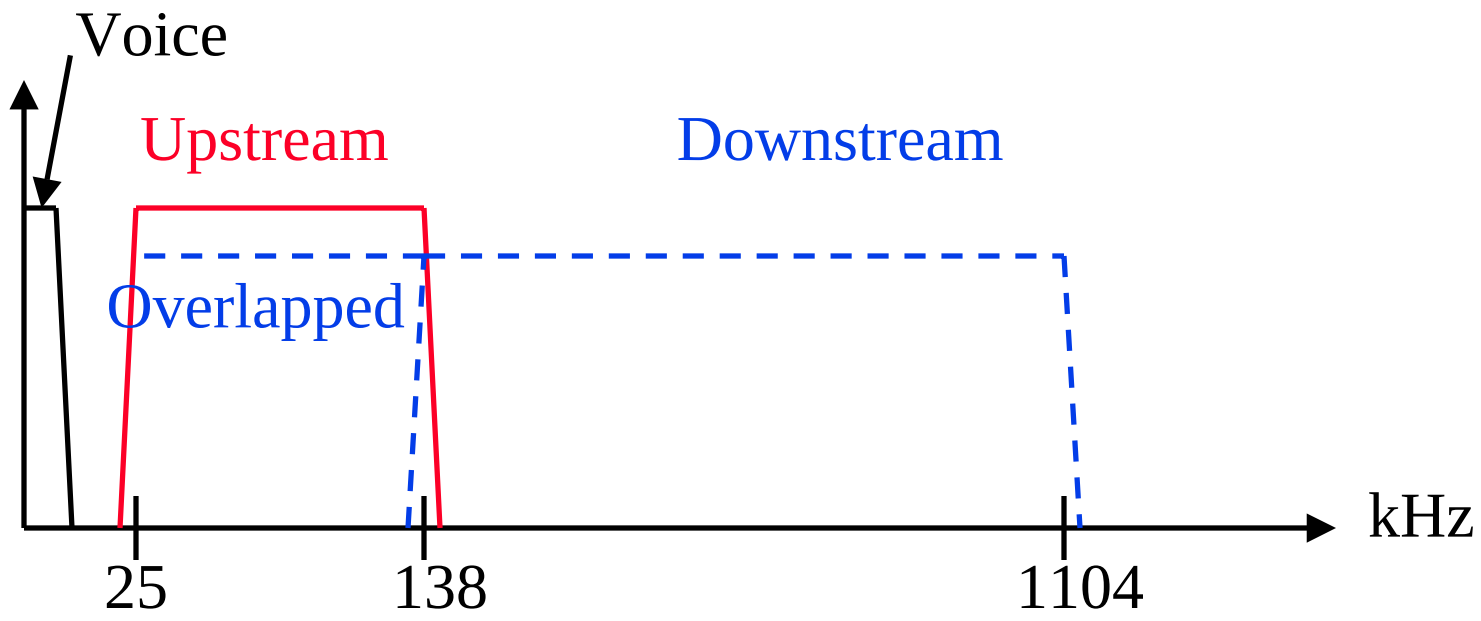
ADSL

- Asymmetric Digital Subscriber Line
- Asymmetric ⇒ upstream << Downstream
- Symmetric ⇒ Significant decrease in rate
- Originally, 6 Mbps downstream, 640 kbps upstream
  Now up to 25 Mbps downstream
- Up to 7500 m
- Using existing twisted pair lines
- No interference with phone service (0-3 kHz)
  ⇒ Your phone isn't busy while netsurfing
- ANSI T1.413 Standard
- Quickest alternative for Telcos. Low cost winner.

Why Asymmetric?

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

ADSL Spectrum



- G.992.1 Annex A: ADSL over POTS (25-138 kHz up)
- G.992.1 Annex B: ADSL over ISDN (120-276 kHz up)
- G. 992.1 Annex C: ADSL over Time-Compression Multiplex ISDN

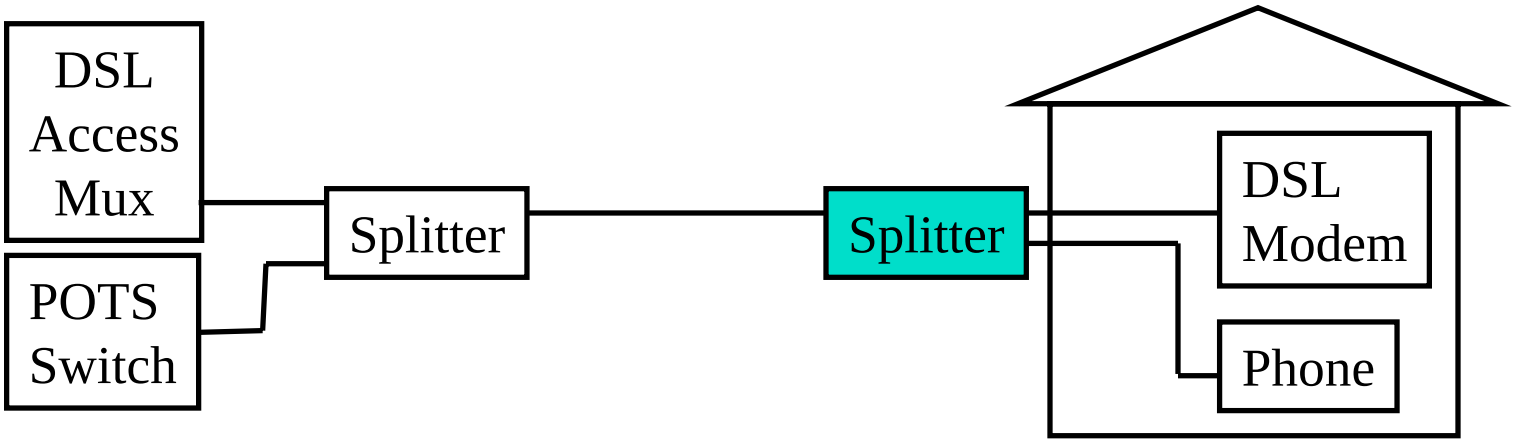
ADSL Lite (G.Lite)

- Designed for easy installation and lower cost
- Lower data rate and longer reach

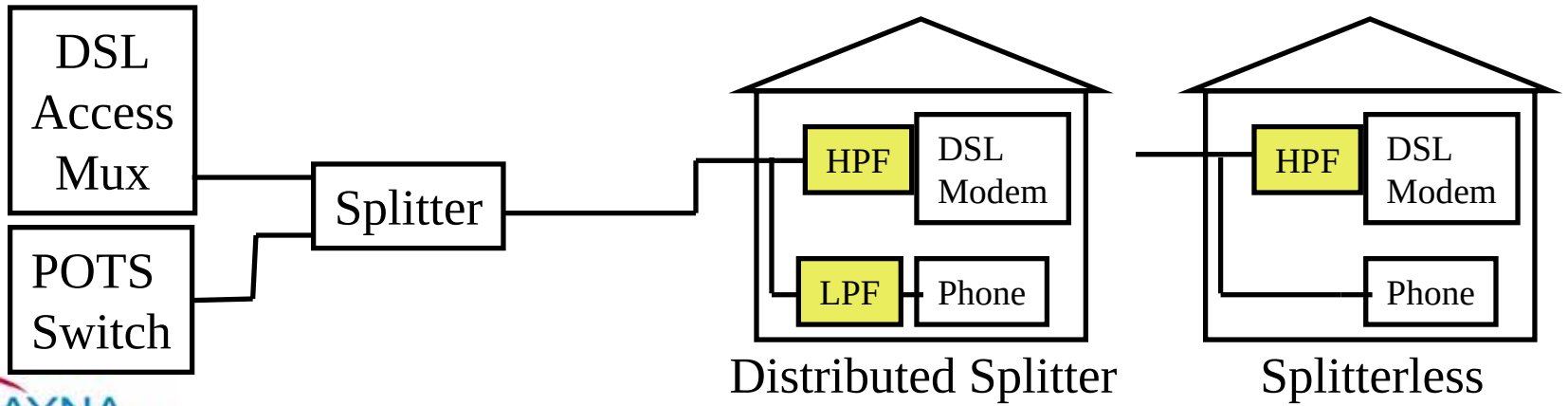
Full Rate ADSL (G.992.1)	Universal ADSL (G.992.2)
Optimized for data rate	Optimized for cost
8Mbps up, 800 kbps down	1.5 Mbps up, 512 kbps down
256 tones	128 tones
15 bits/tone	8 bits/tone
Echo canceled	FDM with EC option
Full initialization	Fast retrain
No power management	Power management

G.Lite Installation

- ADSL: Splitter outside the house⇒Truck Roll.



- ADSL Lite: No splitter outside the house

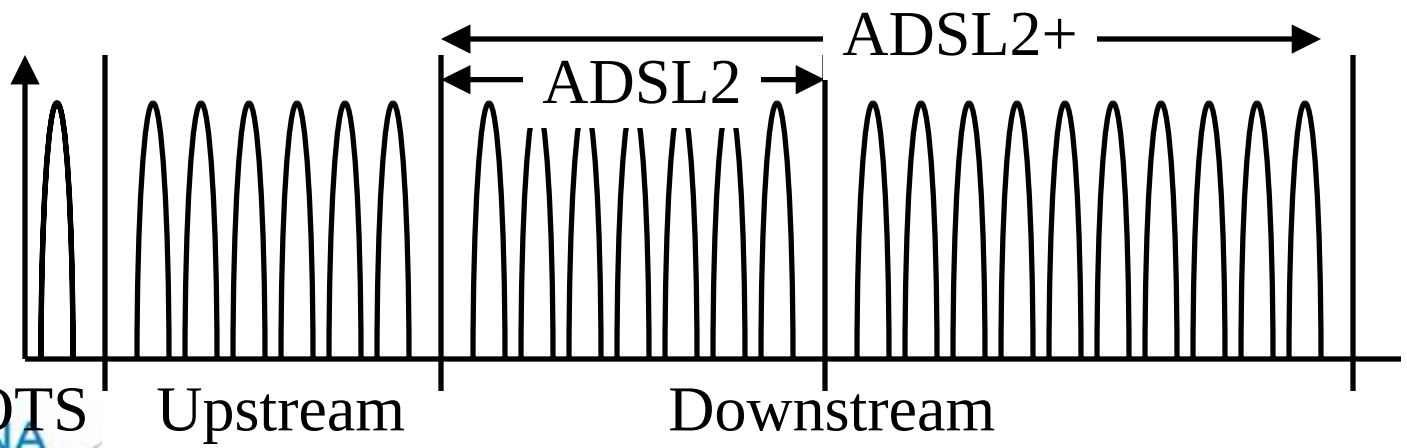


ADSL2

- G.992.3 also known as G.dmt.bis
  G.992.4 is G.lite.bis
  Completed in July 2002
- 0-276 kHz up, 0-1104 kHz down.
  Subset within these masks can be used.
  E.g., 25-276 kHz up, 25-1104 kHz down with POTS.
- 12 Mbps down, 1 Mbps up
  50 kbps more than ADSL on long lines
  600 feet more reach for the same data rate
- Programmable Framing Overhead, Improved Performance, Power Management, Diagnostics, Seamless Rate Adaptation (SRA), Multipair bonding, Dynamic Rate Partitioning, Fast Startup, All-digital mode, Multi-vendor Interoperability, Customer installable

ADSL2+

- G.992.5 (January 2003)
- Downstream frequency up to 2.2 MHz
- ADSL2 with double bandwidth downstream
  $\Rightarrow$ **double data rate** (24 Mbps) on lines shorter than 5000 ft.
- Can use only 1.1MHz to 2.2MHz (mask frequency below 1.1MHz) Reduced cross-talk in a binder

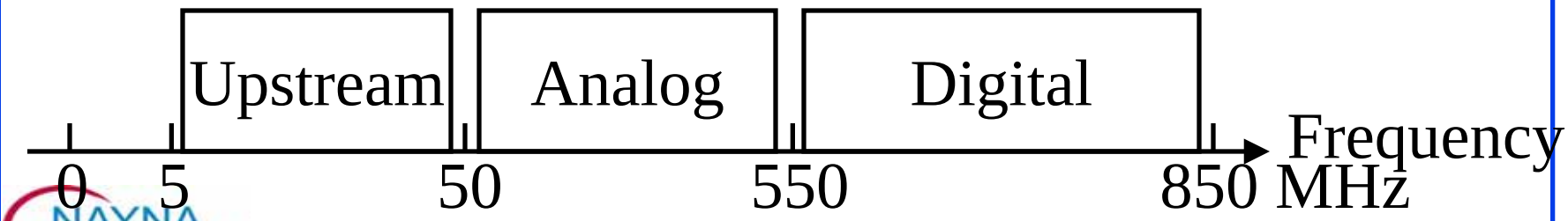


VDSL

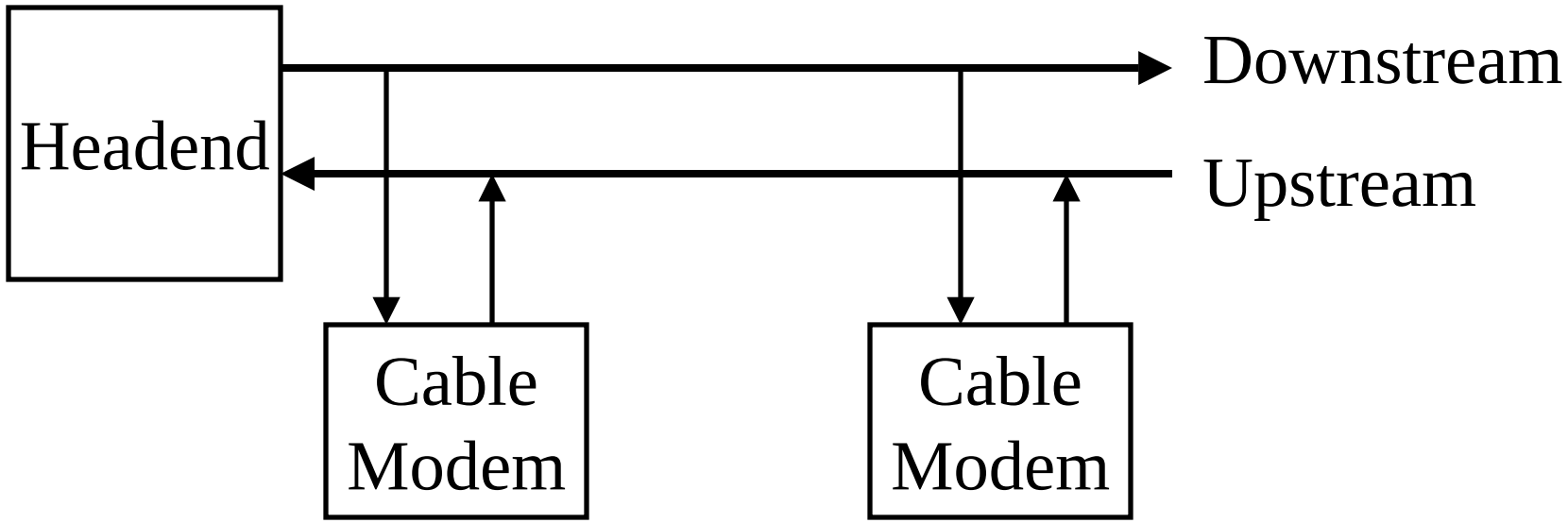
- Supports both symmetric and asymmetric bit rates:
  - Symmetric: 26 Mbps, 13 Mbps, 8 Mbps
  - Asymmetric: 52/6.4, 26/3.2, 12/2, 6/2 Mbps
    Ratios: 8:1, 6:1, 4:1, 3:1, 2:1
- Higher speed using higher bandwidth
  50 Mbps down and 30 Mbps up in Japan
  120 Mbps full-duplex touted by some vendors
- Need to overcome: bridged taps, crosstalk, impulse noise, RF ingress, RF egress (less than –80 dBm/Hz in amateur radio band)
- Band below 1.104 MHz may not be used to avoid interference with ADSL lines in the same bundle
- Dynamic Spectrum Management (DSM): Limit power. Increase cooperation between pairs.

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.

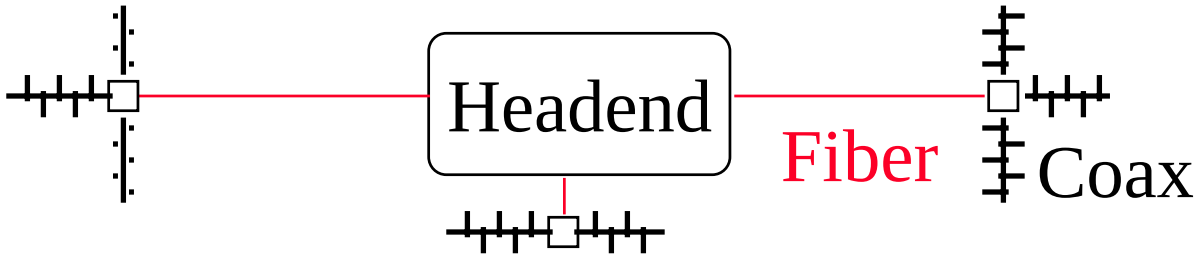


Media Sharing



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

Hybrid Fiber Coax (HFC)

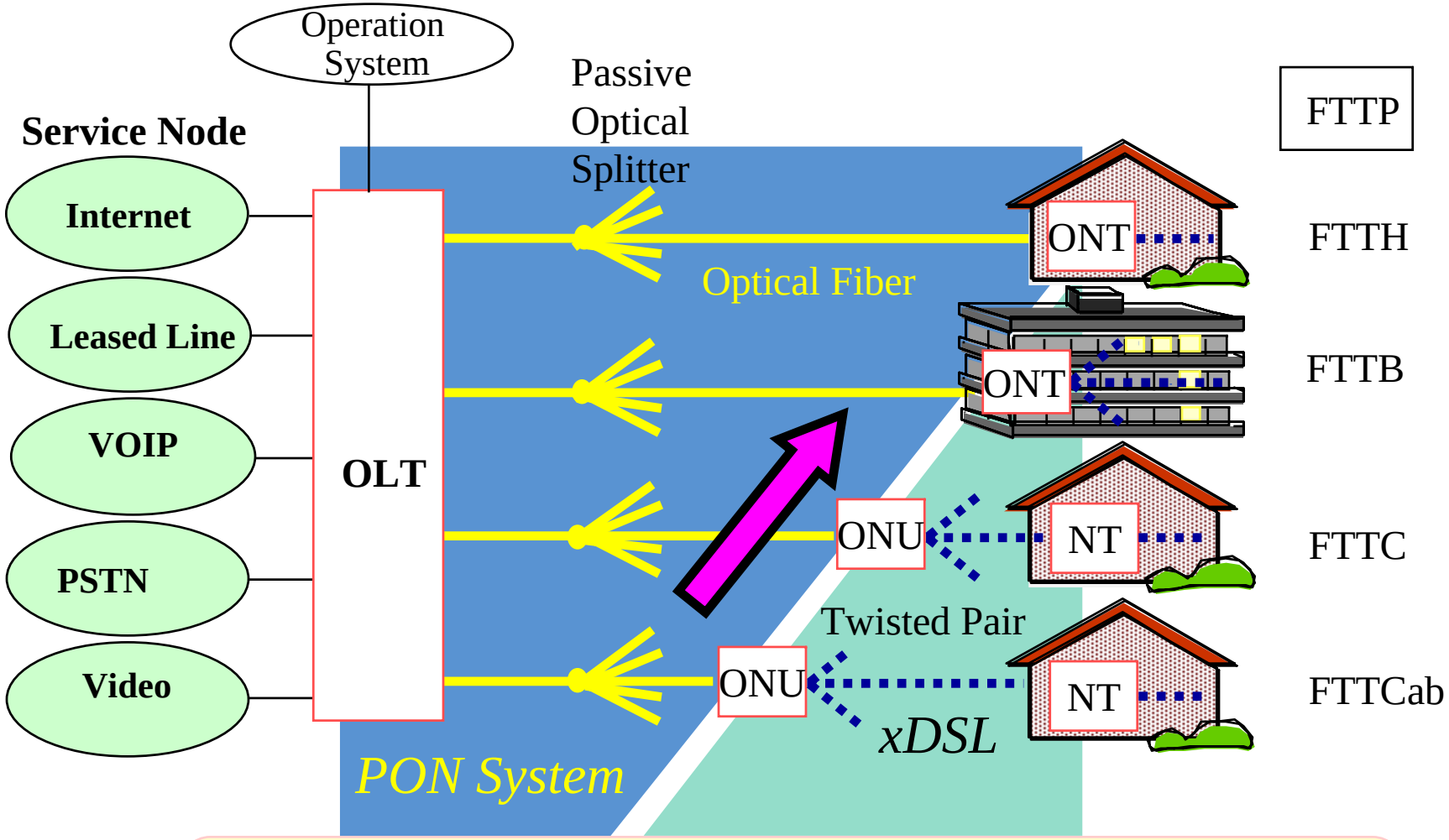


- Reuse existing cable TV coax
- Replace trunks to neighborhoods by fibers
- 45 Mbps downstream, 1.5 Mbps upstream
- MAC protocol required to share upstream bandwidth
- 500 to 1200 homes per HFC link
- Sharing ⇒ Security issues
- IEEE 802.14 standard for MAC and PHY

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)



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

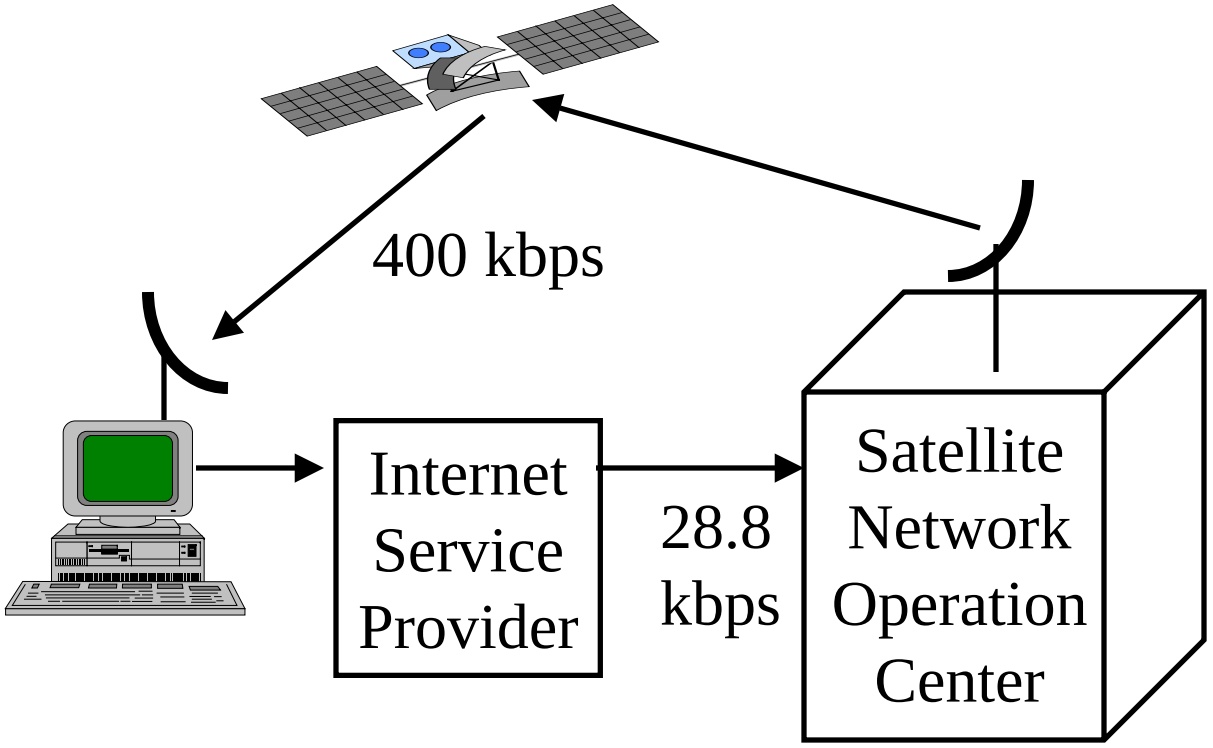
Comparison of RANs

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

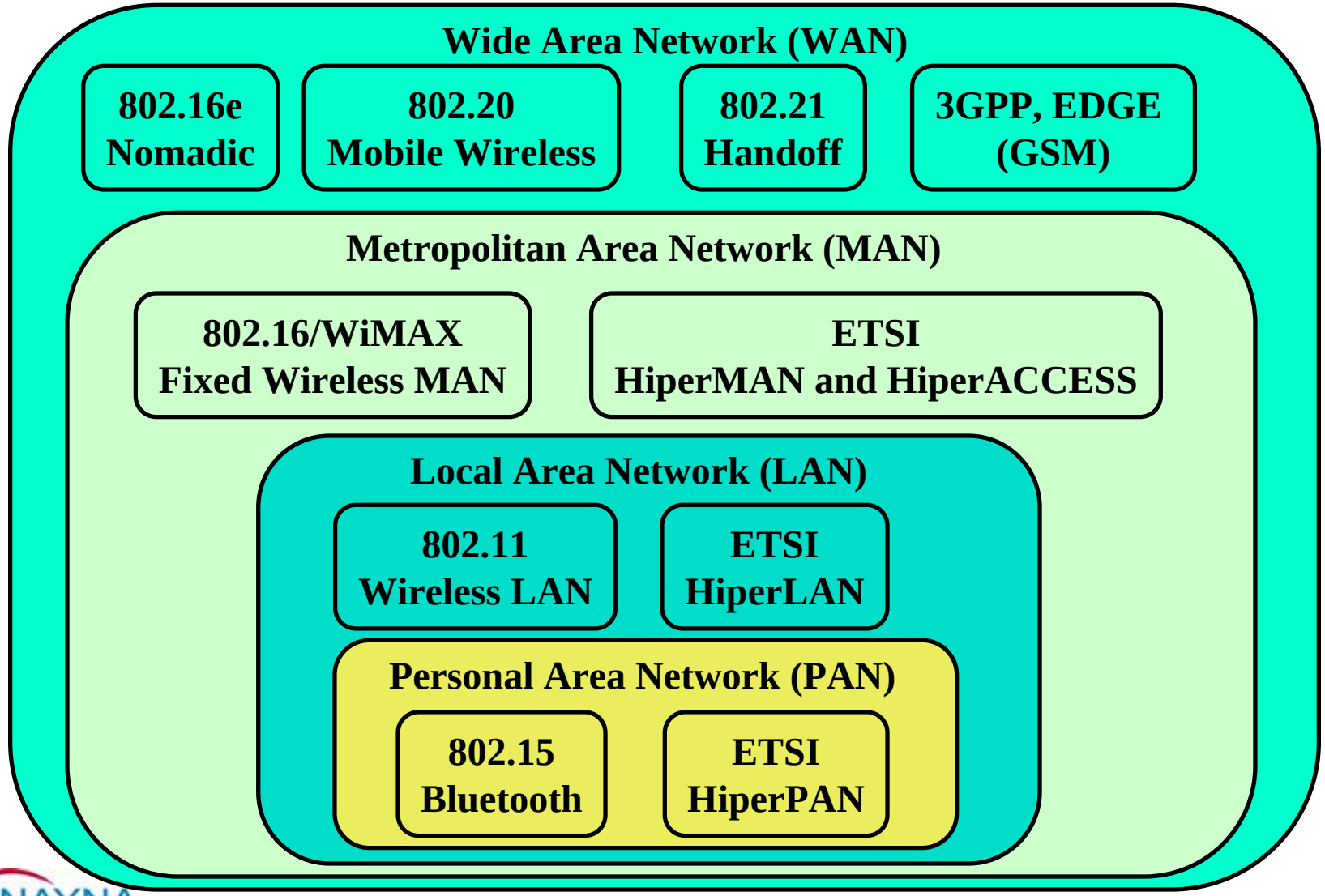


- DirecPC from Hughes
- One-way high-speed connection

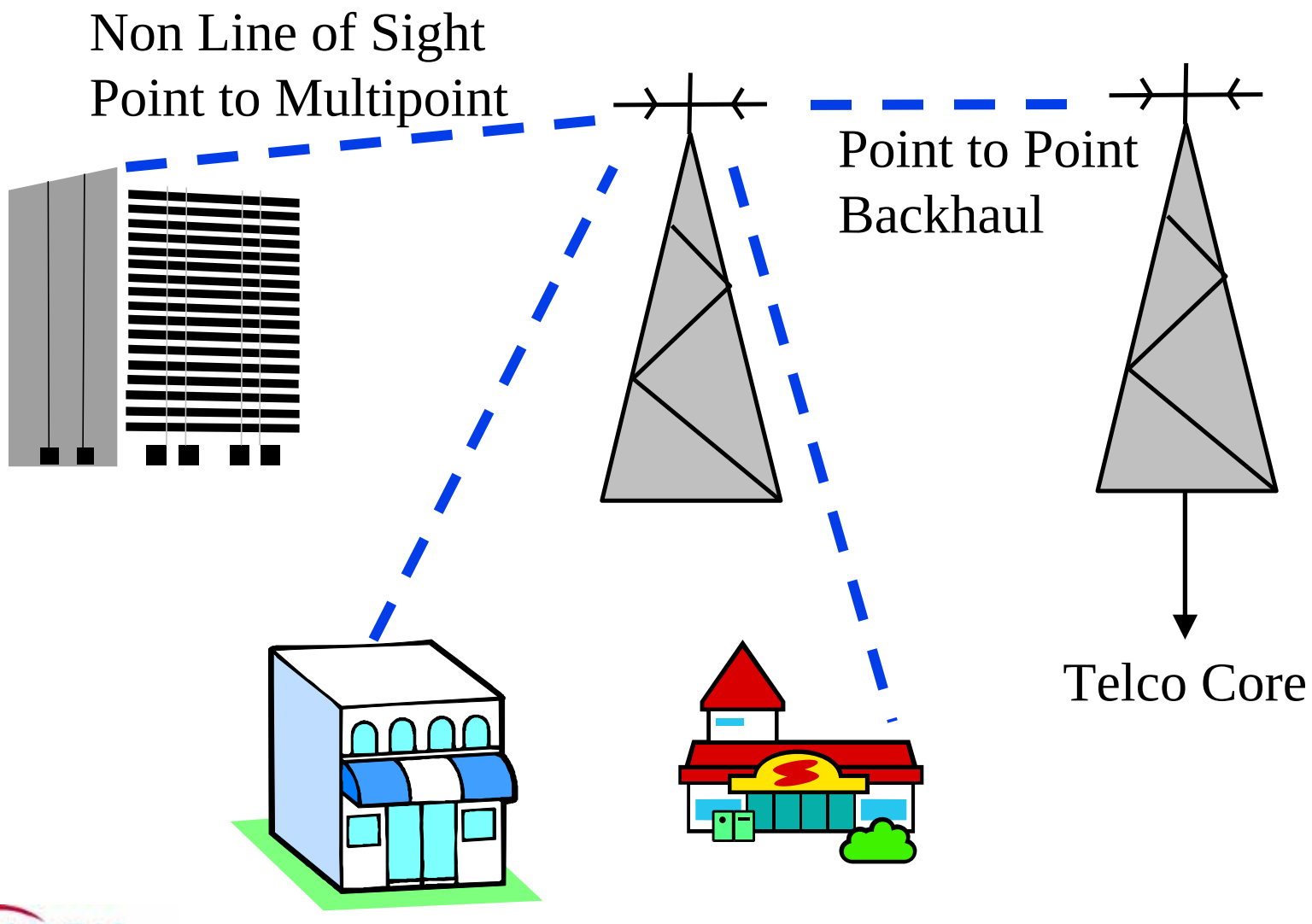
Bi-Directional Satellite

- 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 100m	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)

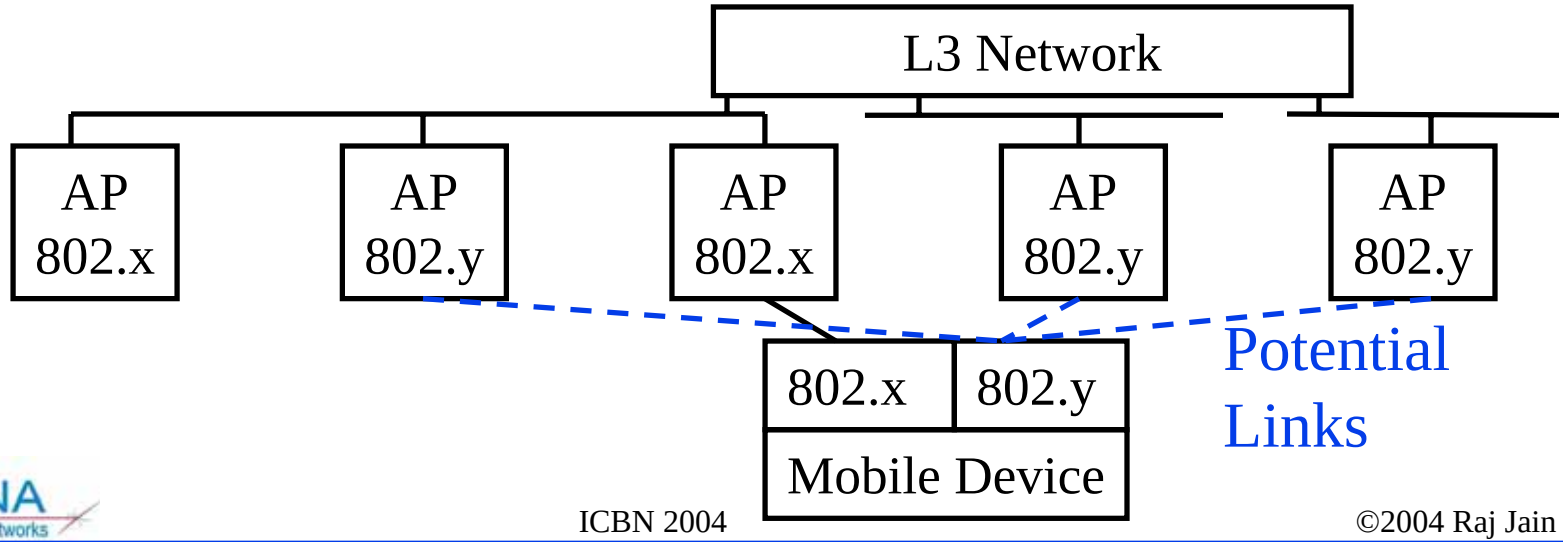
- IEEE 802.20 working group
- Optimized for IP data transport
- Licensed band below 3.5 GHz
- >1 Mbps data rate
- Vehicular mobility up to 250 Km/h
- Designed for green field wireless data providers
- Incumbent cellular providers with voice services may prefer 3G

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

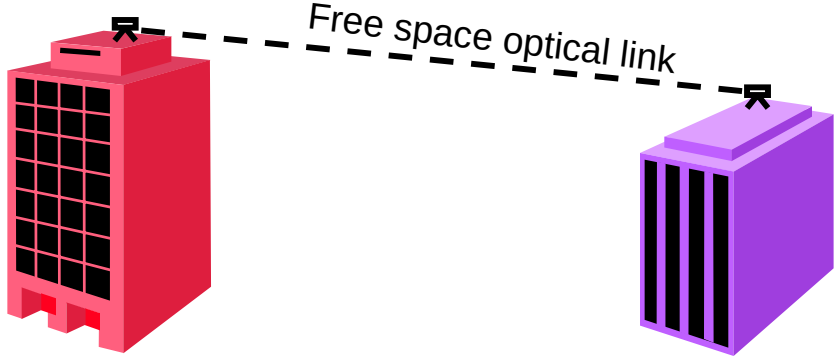
Handoff

- 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)

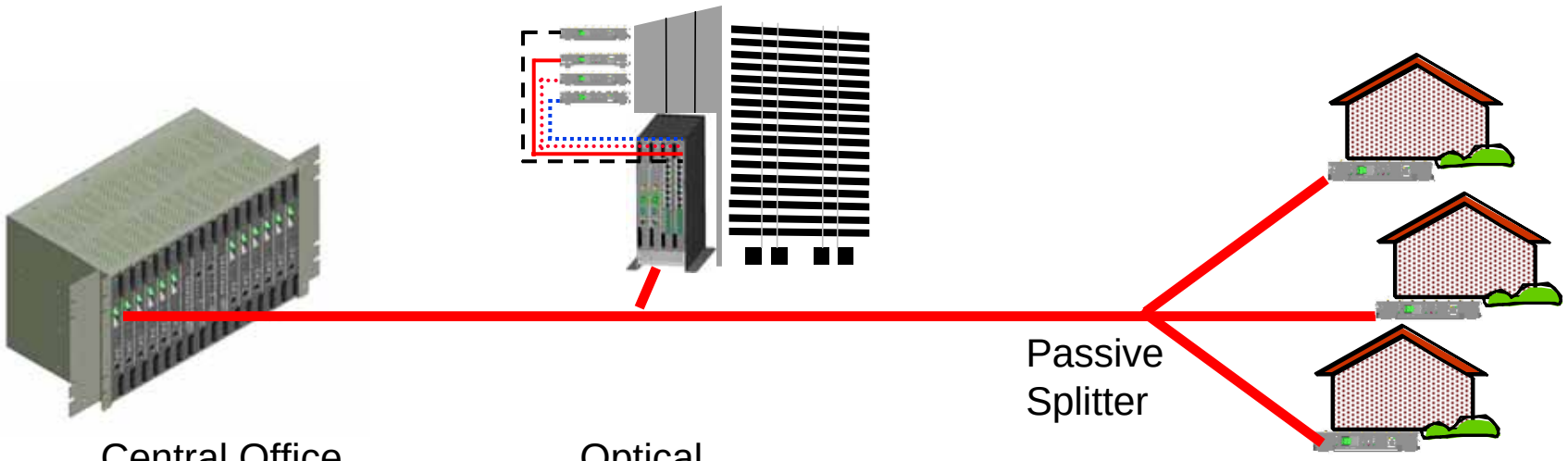


Optical Wireless (Cont)

- Immunity from interference
- Easy installation
  $\Rightarrow$ Unlimited bandwidth, Easy Upgrade
- Transportable upon service termination or move
- Affected by weather (fog, rain, sun)
  $\Rightarrow$ 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



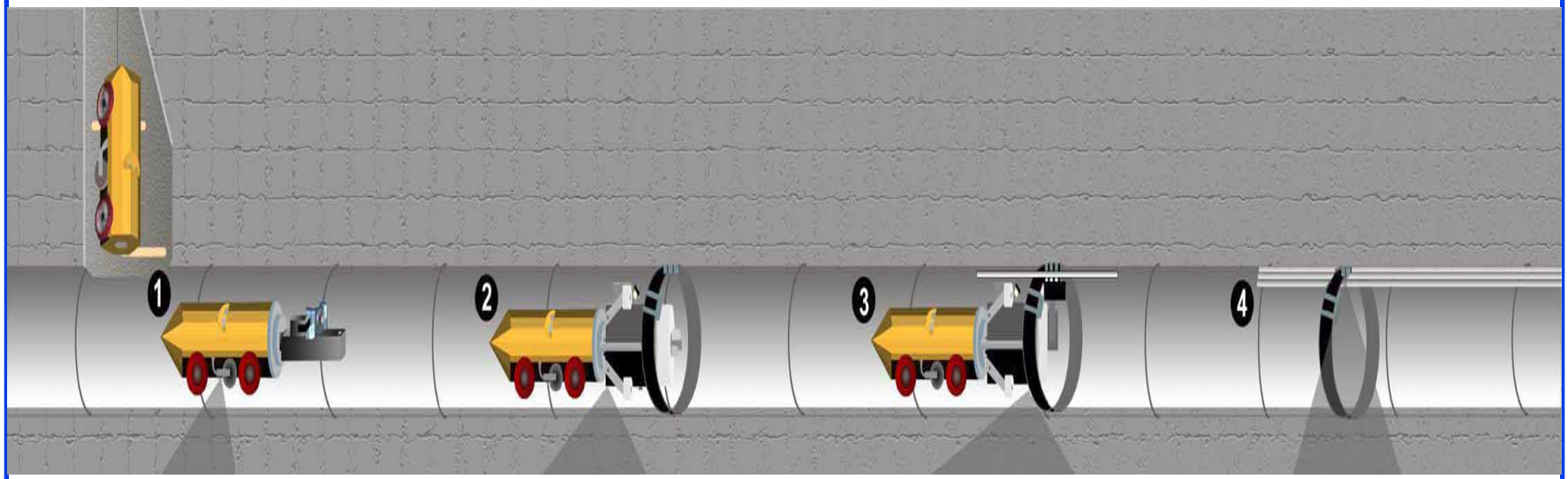
Types of PONs

- **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

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

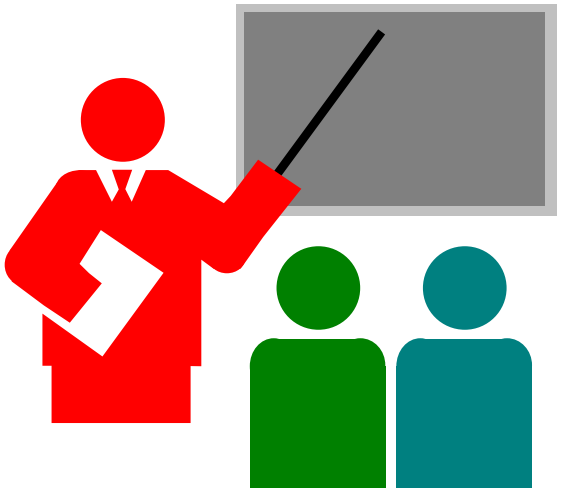
FAST Installation



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