Wireline Broadband Access

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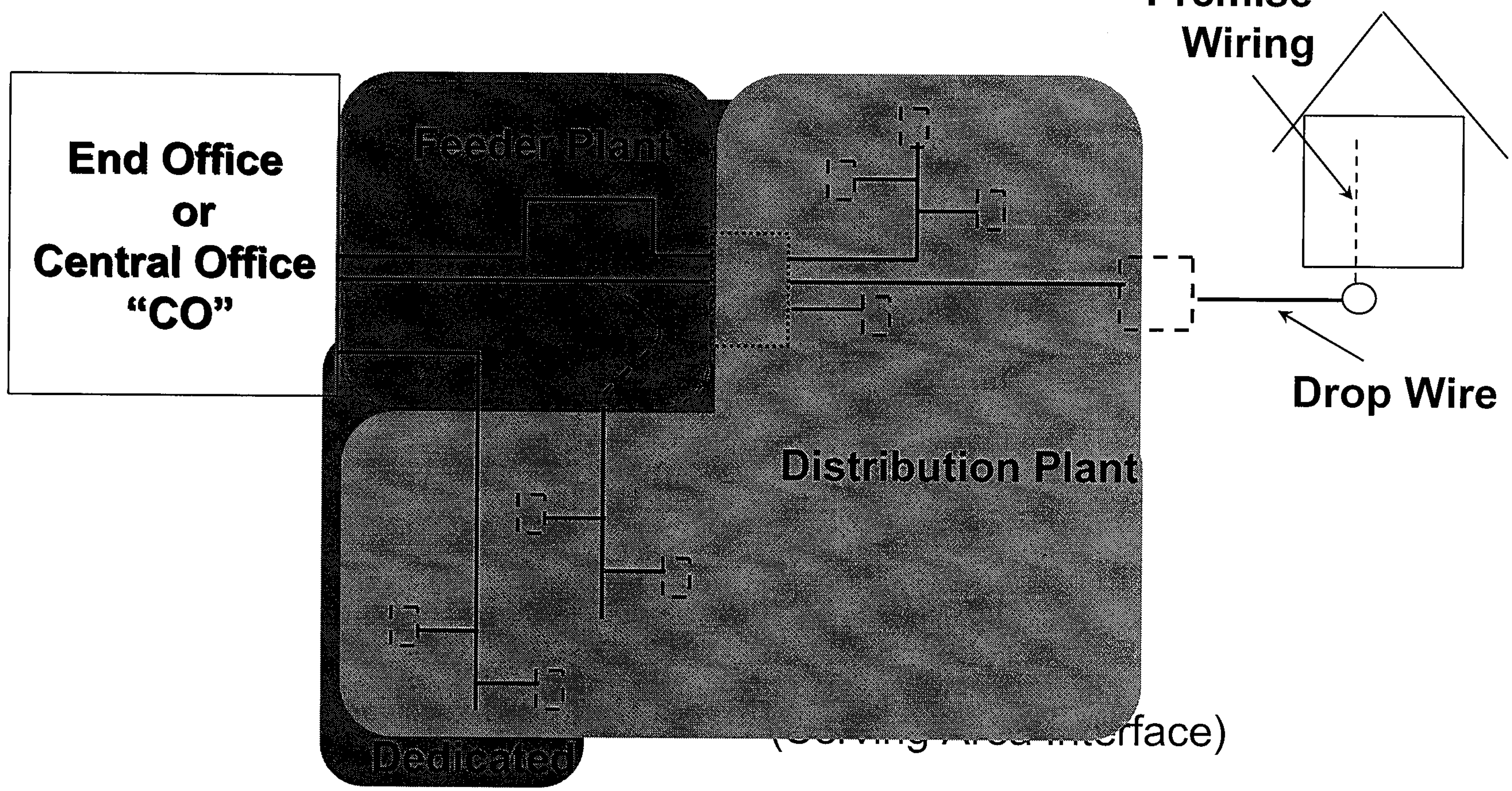
Agenda

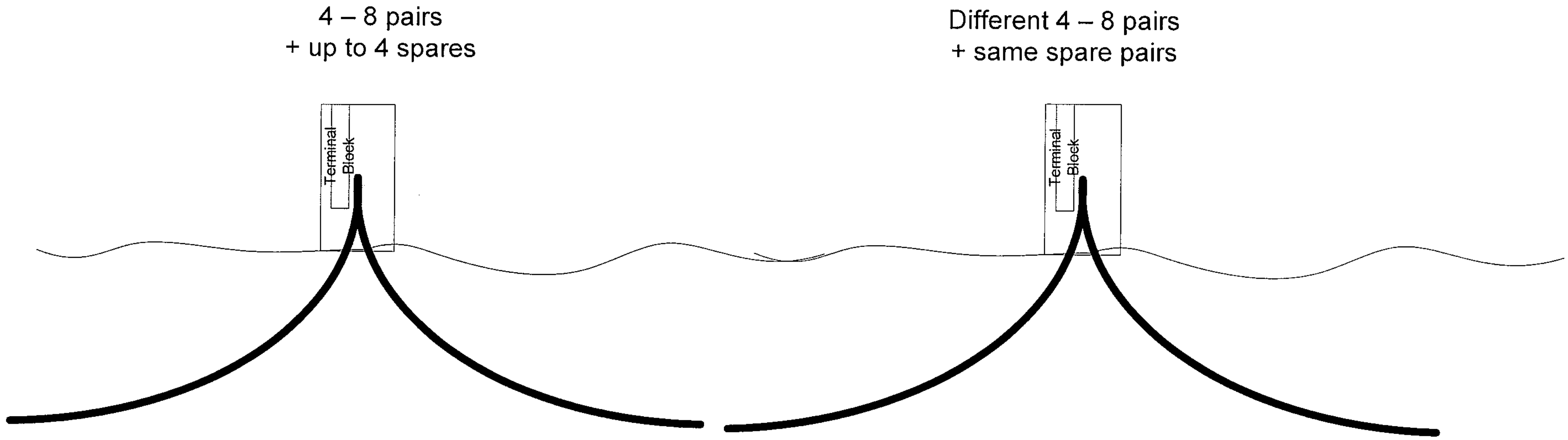
- The Wireline Resource
  - Copper
    - Part I: Copper Wireline Physical and Transmission Characteristics
    - Part II: DSL Transmission over Copper Wireline
  - Fiber
    - Part III: Fiber Optic Wireline Physical and Transmission Characteristics
      - Fiber Access Architectures
  - Access Applications

Part I: Copper Wireline Physical and Transmission Characteristics

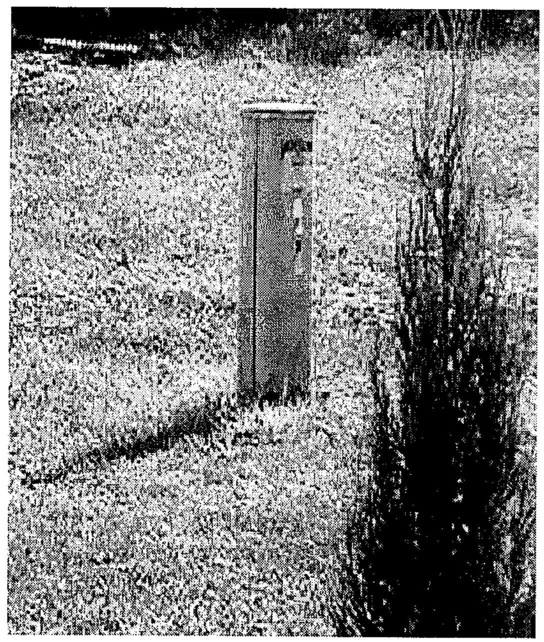
Copper Access Design Approaches

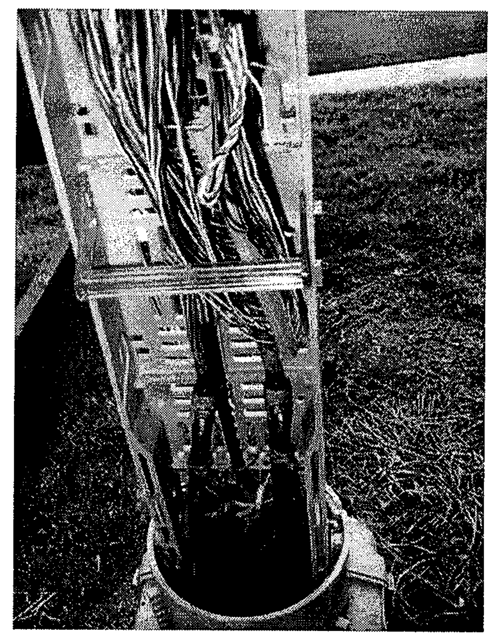


Rural Loop Plant Design

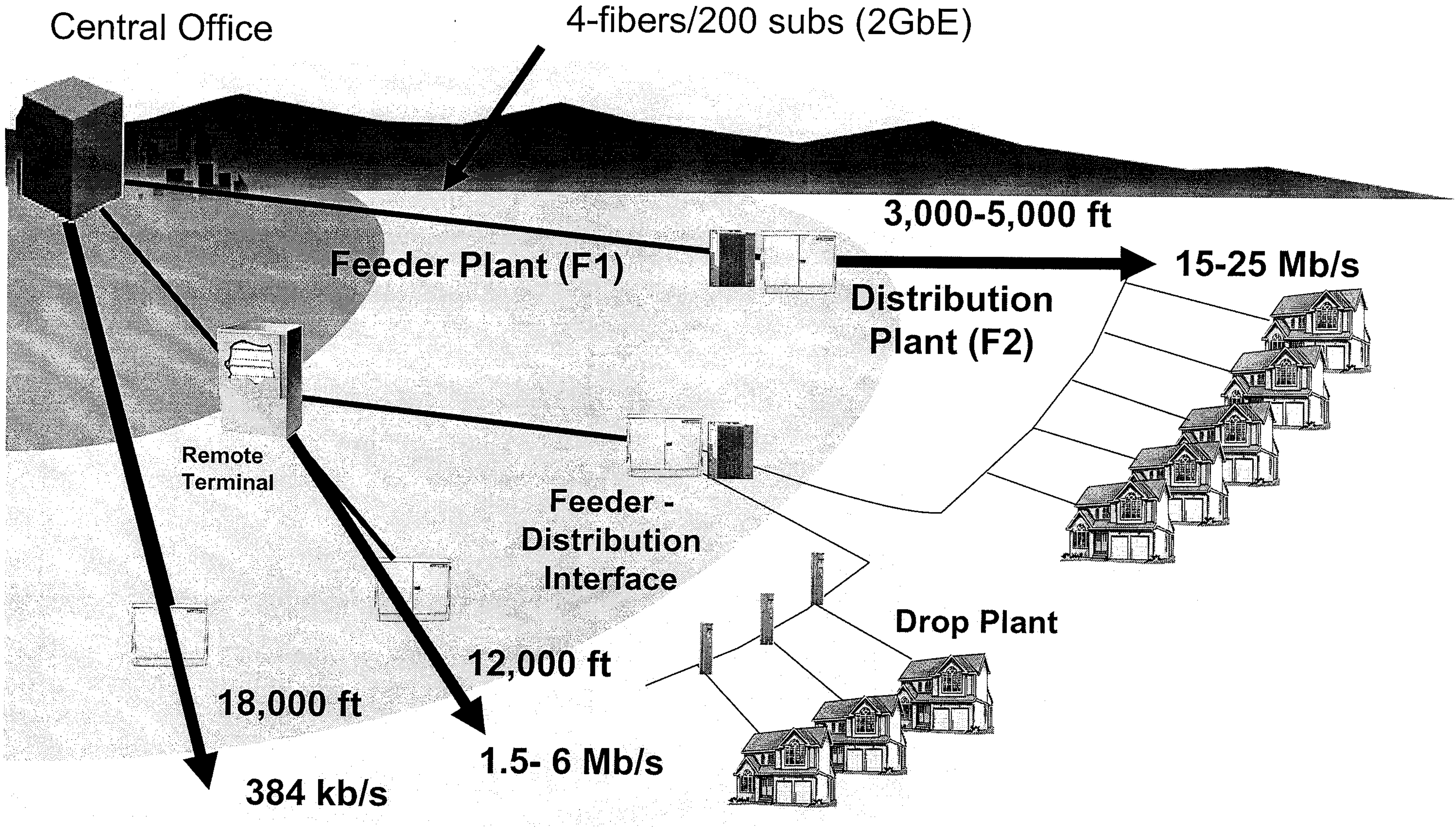


- Distribution cable is accessable at each pedestal
- Usually one or a portion of one binder group is routed to the terminal block while the other binder groups just pass through





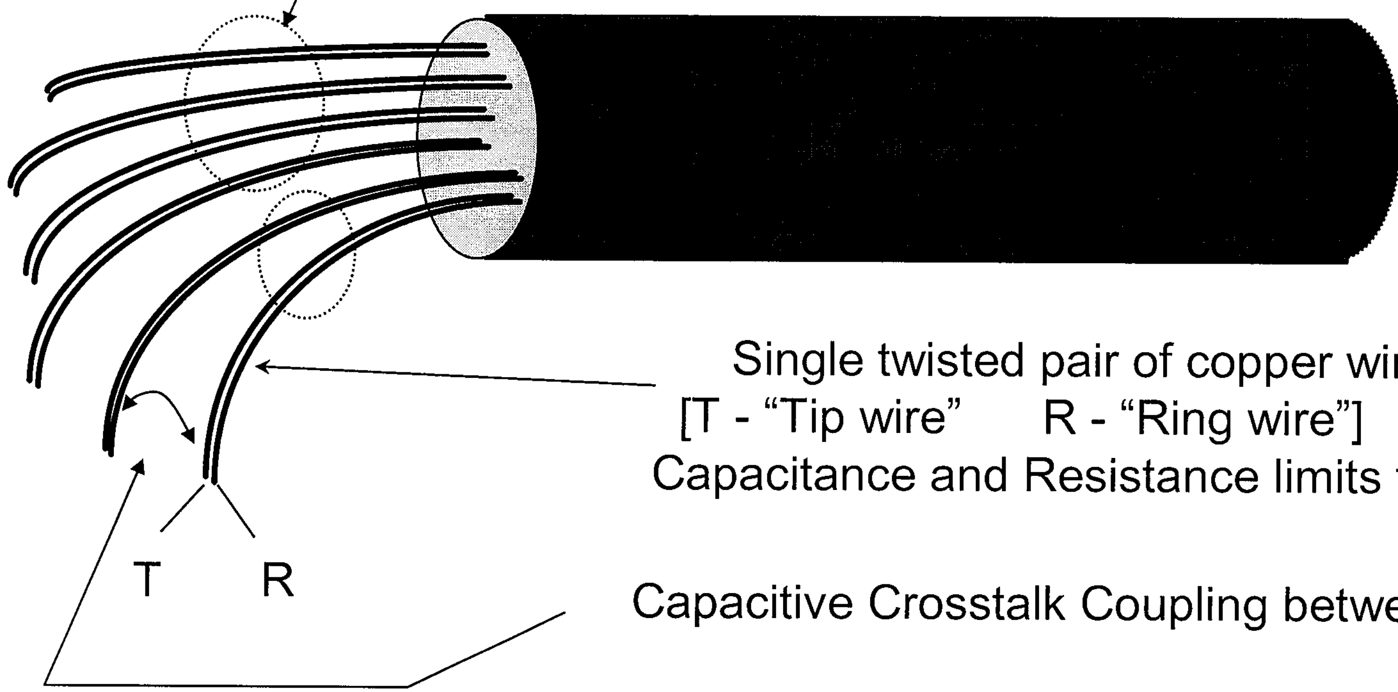
Access Network: pushing fiber deeper



Cable Composition

10-50 unshielded twisted pairs in a binder group

Multiple binder groups per shielded cable



Single twisted pair of copper wires.
[T - "Tip wire" R - "Ring wire"]
Capacitance and Resistance limits frequencies

Capacitive Crosstalk Coupling between pairs

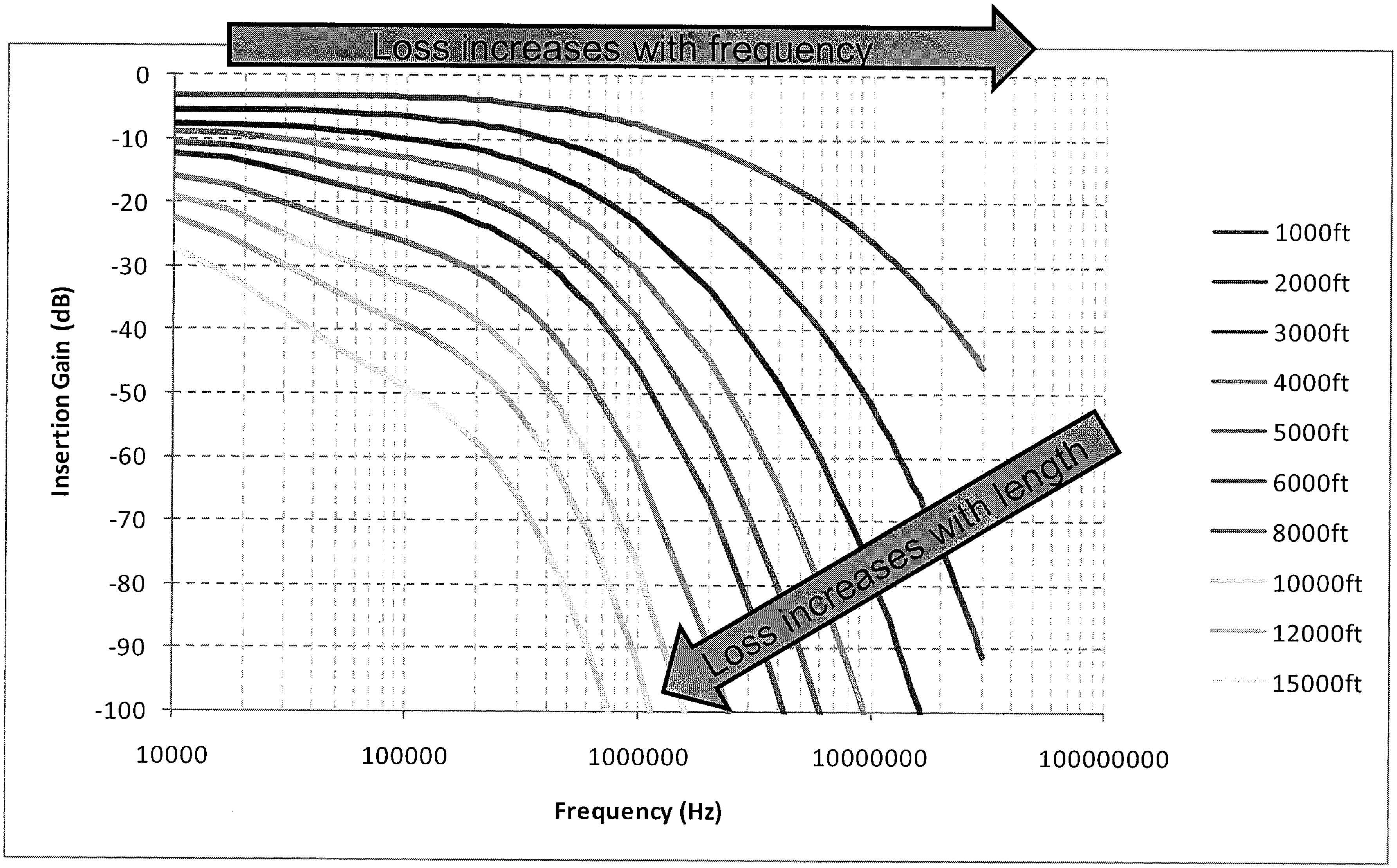
Cable Characteristics

- Wire Size
  - 26 American Wire Gauge (AWG)
    - Smallest wire, highest resistance/foot, used in large cables near the CO to keep cable size small
  - 24 AWG
    - Used extensively in distribution plant
  - 22 AWG
    - Used in many rural applications to keep loop resistance down and achieve greater distances
  - 19 AWG
    - Fairly rare; used in some rural applications

Loss/distance decreases as wire gets larger (lower AWG)

# of pairs in each cable gets smaller as cable extends from CO

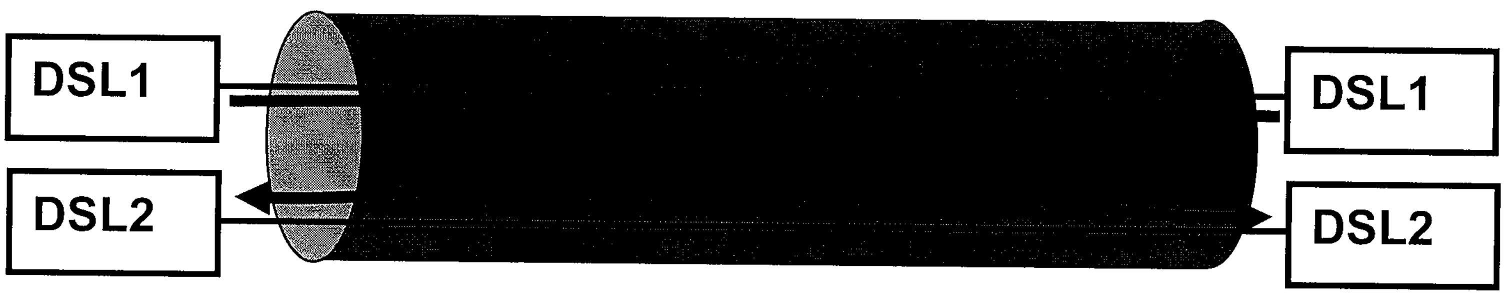
Cable Pair Channel Loss (26 AWG)



Crosstalk: NEXT and FEXT

NEXT Coupling

FEXT Coupling



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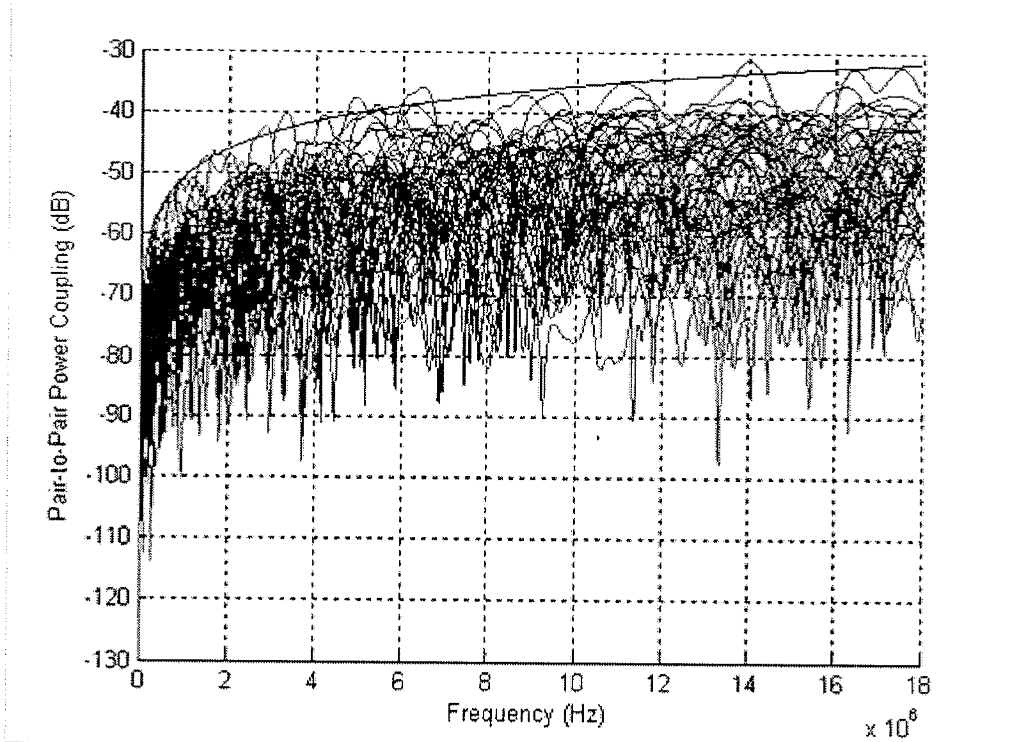
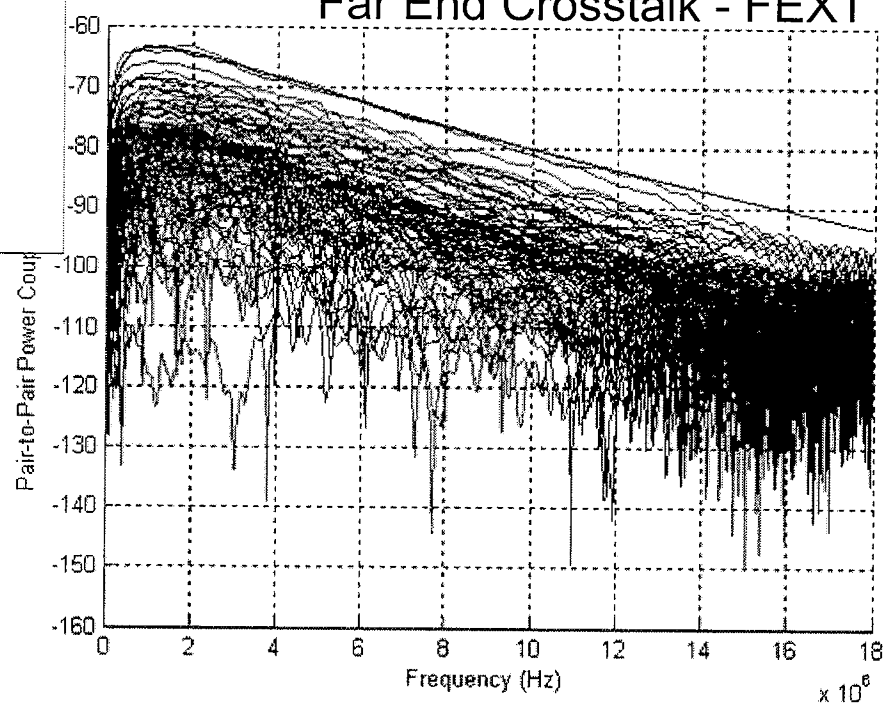
Measured Crosstalk Couplings



Far End Crosstalk - FEXT



Near End Crosstalk - NEXT

600 pair-to-pair measurements from one 25 pair binder group

Crosstalk coupling varies 20-30 dB From pair to pair

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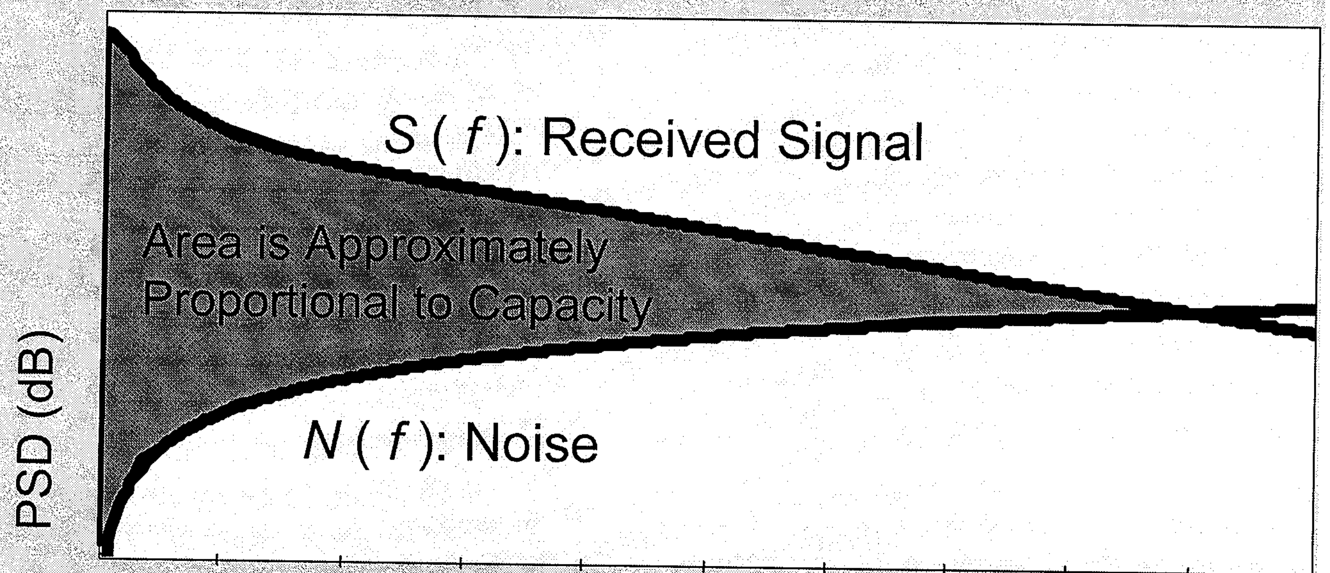
DSL Performance Limits

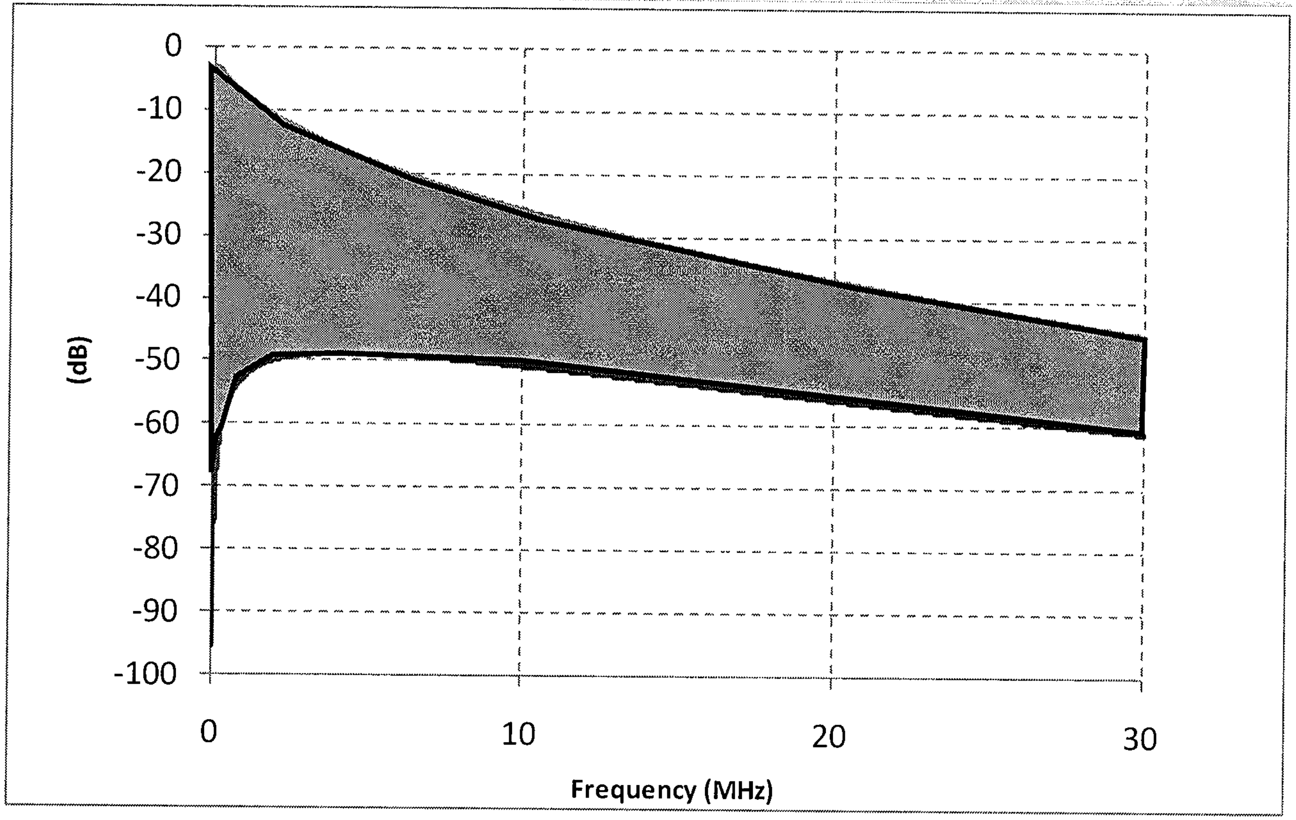
Upper Bound: Channel Capacity

$$C = \int \log_2\left(1 + \frac{S(f)}{N(f)}\right) df \quad \text{(bits/sec)}$$



Capacity Example

Loop: 1000 feet 26 AWG
Noise: 12-crosstalker FEXT



Total Capacity nearly 400 Mbps!

Capacity can be further increased by eliminating Crosstalk

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Wireline and Wireless Channel Comparison

- Wireline spectrum increases as loops shorten
  (Wireless spectrum fixed – independent of distance)
  - Enables exponentially higher rates on short loops
- Wireline copper channel has fewer short-term variations
  (Fewer variations increases reliability)
  - Loss is relative constant over time
    - Small variations due to cable temperature in aerial deployments
  - Most significant variation is crosstalkers turning on and off
- Data rates typically quoted on a per-user basis
  - Wireless tends to quote peak rate with single user in cell
- Both wireline copper and wireless have data rates that decrease with distance
  - Highest rates available only near the transmitter

Part II: Digital Subscriber Line (DSL) Transmission over Copper Wireline

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Towards realizing Capacity

- Modulation Format
  - Single Carrier (PAM, QPSK, QAM)
  - Multi-Carrier (OFDM, DMT)
- Duplexing
  - Full Duplex, Echo-cancelled
    - NEXT is limiting impairment
      - Used in HDSL, SHDSL, 1000Base-T
  - Frequency Division Duplexed (FDD)
    - Transmit in each direction using different frequencies
    - FEXT is the limiting impairment
      - Used in Mobile Wireless, ADSL, VDSL
  - Time Division Duplexing (TDD)
    - Ends take turns transmitting
    - Used in wireless (WiMAX, TD-LTE), some early DSLs

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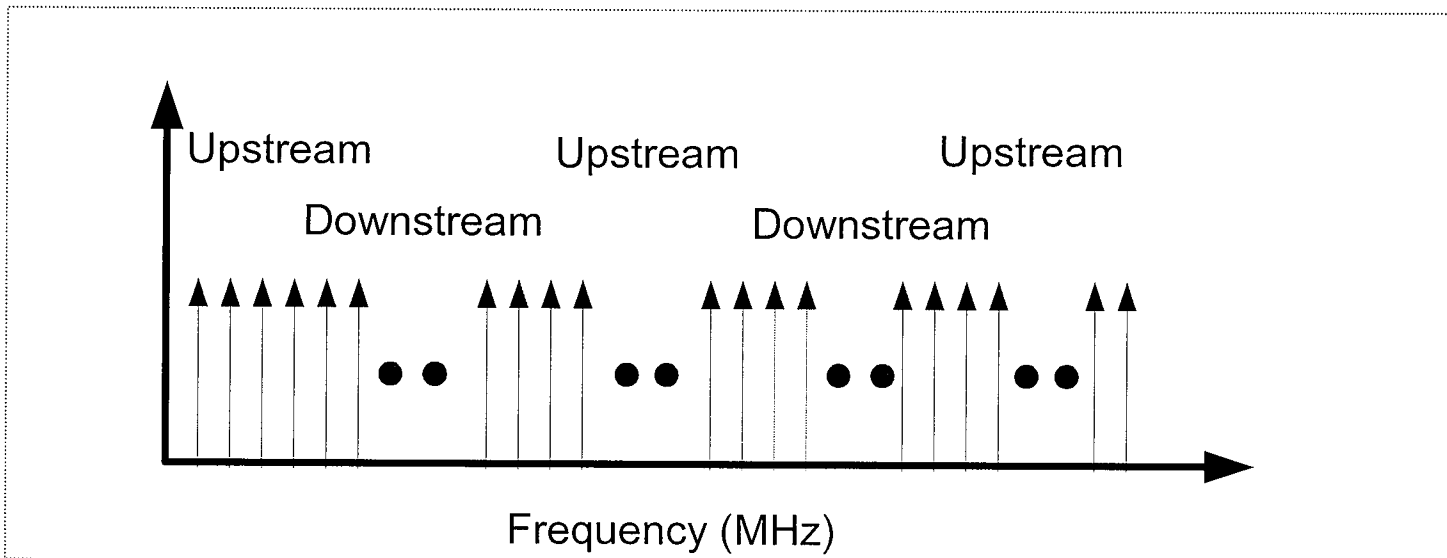
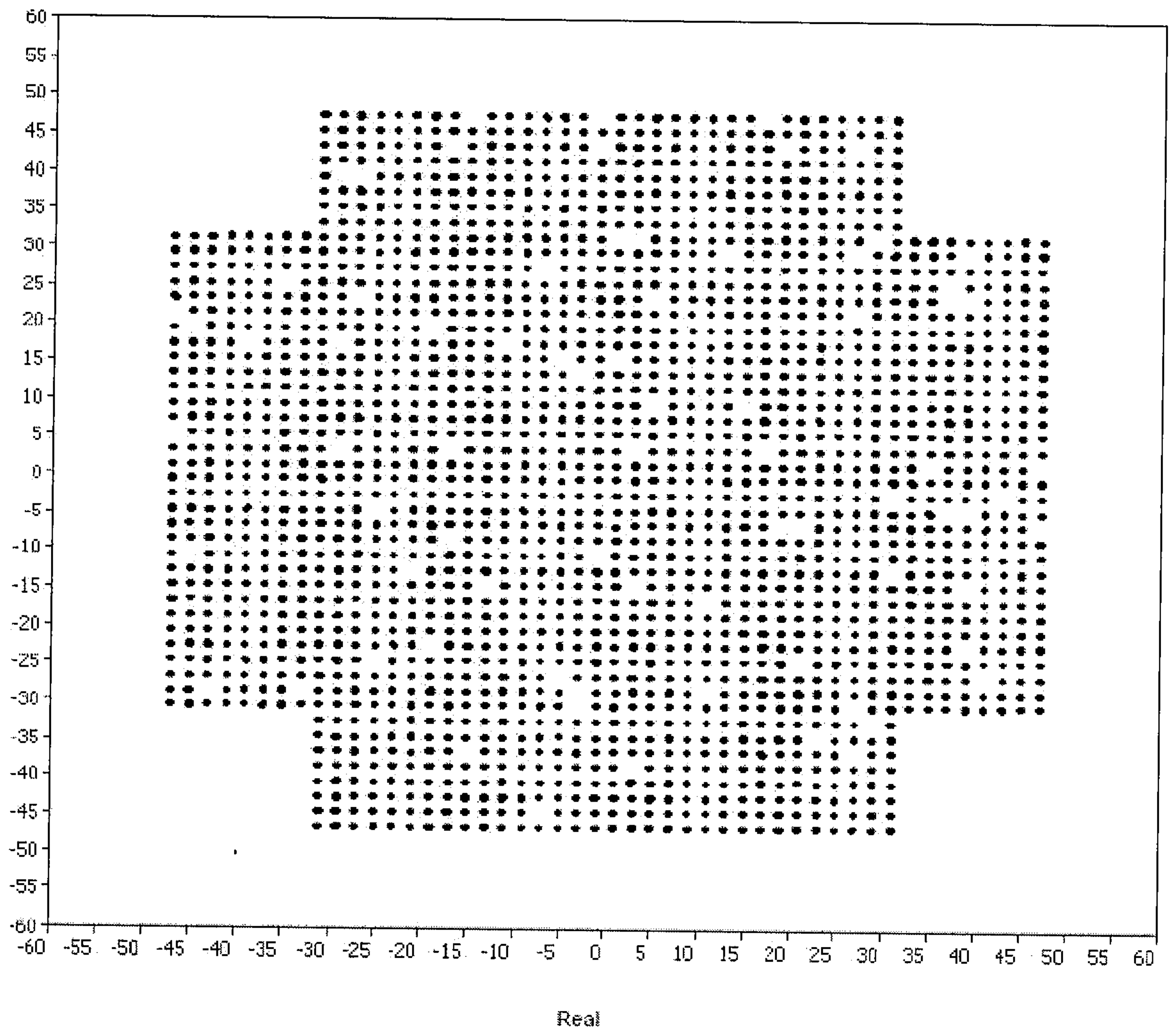
Discrete Multi-Tone

- DMT line code Is composed of individual sinusoidal carriers whose amplitude and phase change to signal the data bits
  - Similar to OFDM, but with a variable number of bits per tone/carrier
  - Up to 15 bits of information per tone/carrier (**32768 QAM**: very high spectral density)
- DMT is Frequency Division Duplexed
- DMT uses tone/carrier spacing of 4.3125 kHz
  - 8.625 kHz for VDSL2 Profile 30



Example Modulation: 2048 QAM

As defined for DMT modulation



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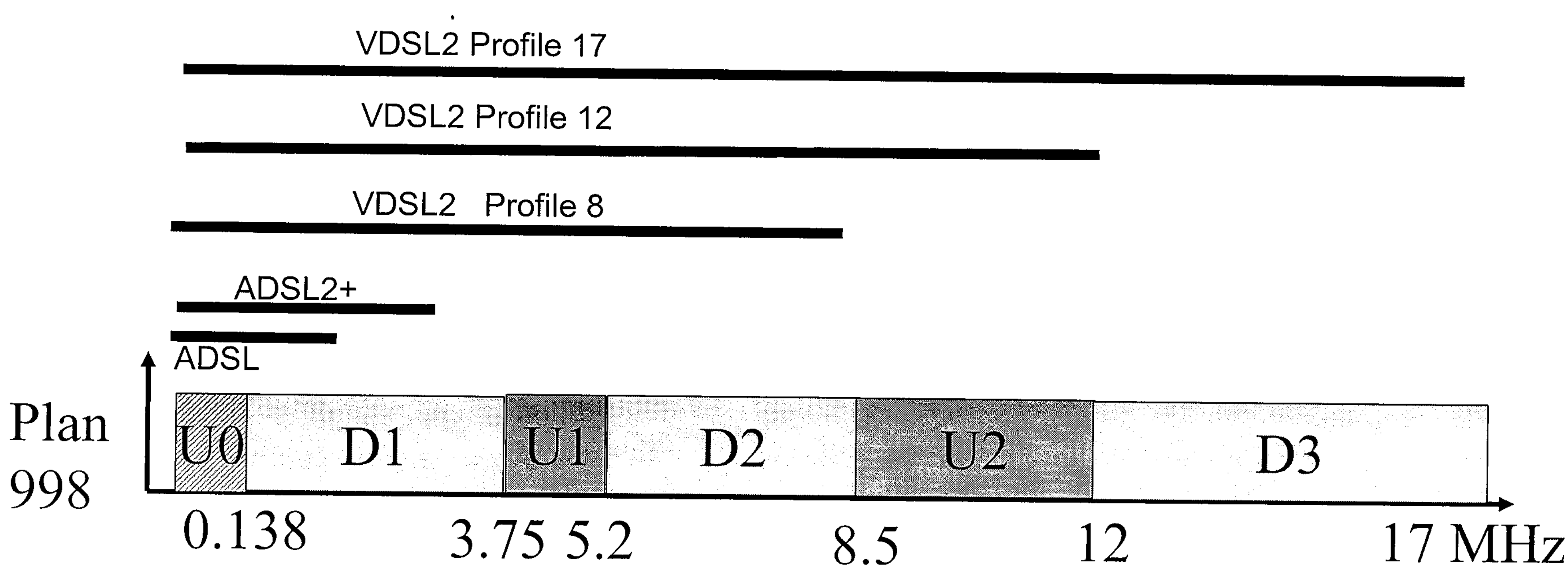
Evolution of DSL for Broadband Access

- Asymmetric DSL (ADSL)
  - First deployed in 1996
  - Frequencies up to 1.1 MHz
  - Download rate up to 8 Mbps
- ADSL2/2+
  - First Standardized in 2005
  - Frequencies up to 2.2 MHz
  - Download rate up to 24 Mbps
- Very High-Speed DSL (VDSL2)
  - First standardized in 2006
  - Frequencies up to 30 MHz
  - Data rates up to 200 Mbps

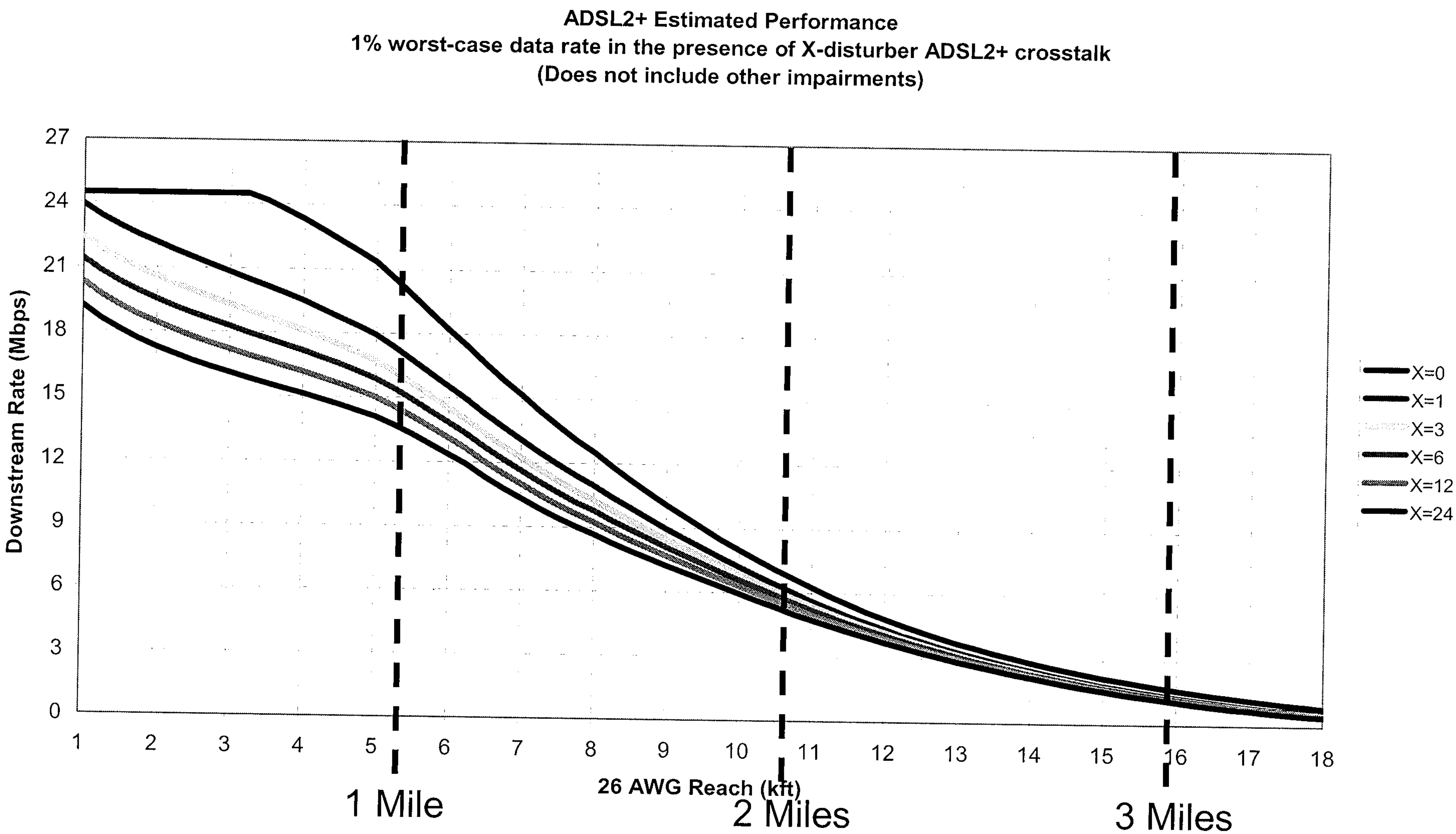
DSL FDD Band Plan (998)



Band Plan balances multiple loop lengths and desired DL/UL data rates

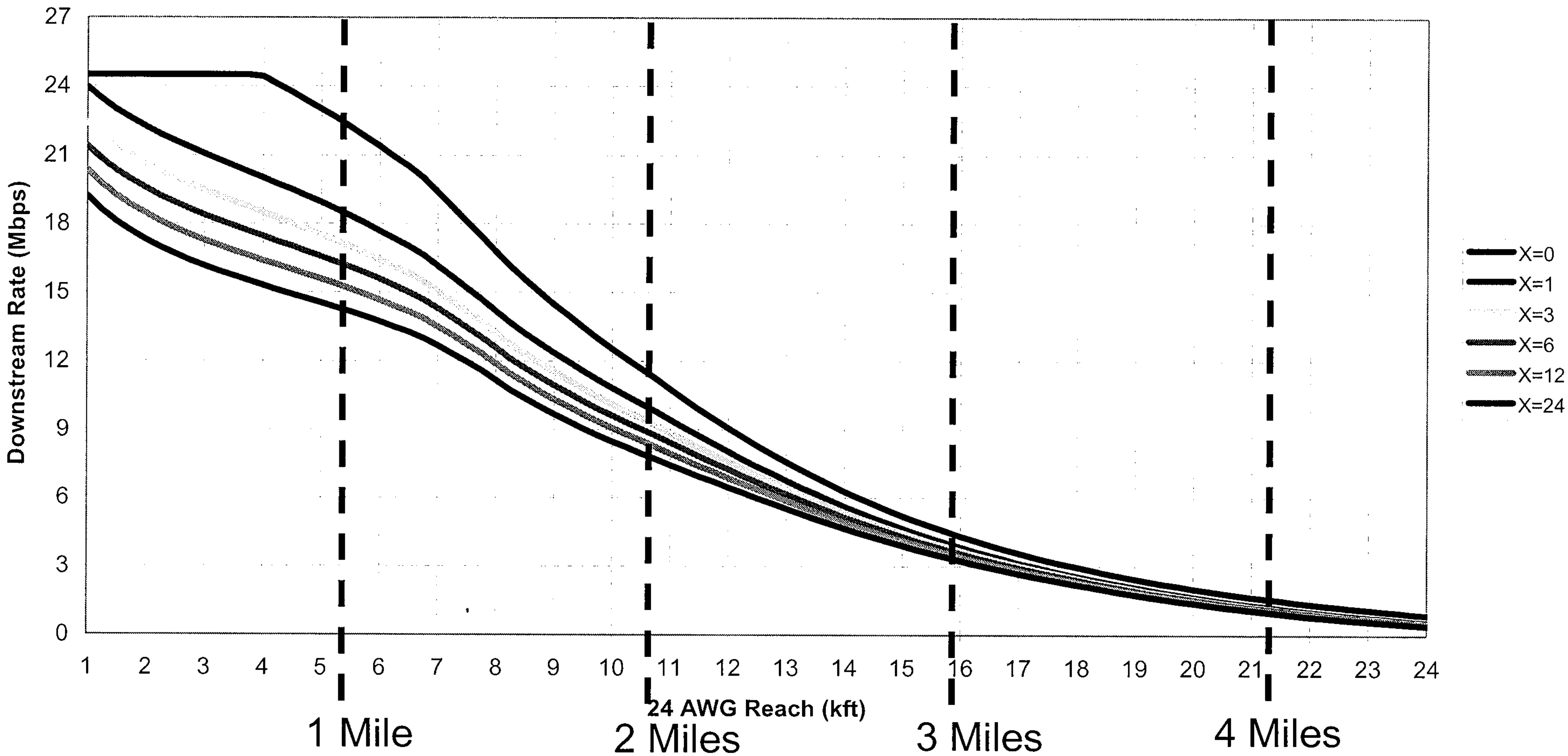
- D3 usable out to 1500 ft (450 m)
- U2 usable out to 2500 ft (760 m)
- D2 usable out to 3500 ft (1.06 km)
- U1 usable out to 4000 ft (1.22 km)
- ADSL uses D1 up to 1.1 MHz; ADSL2+ uses D1 up to 2.2 MHz
- Profile 30 extends D3 beyond 17 MHz and adds U3 out to 30

DSL Performance: ADSL2+ on 26 AWG

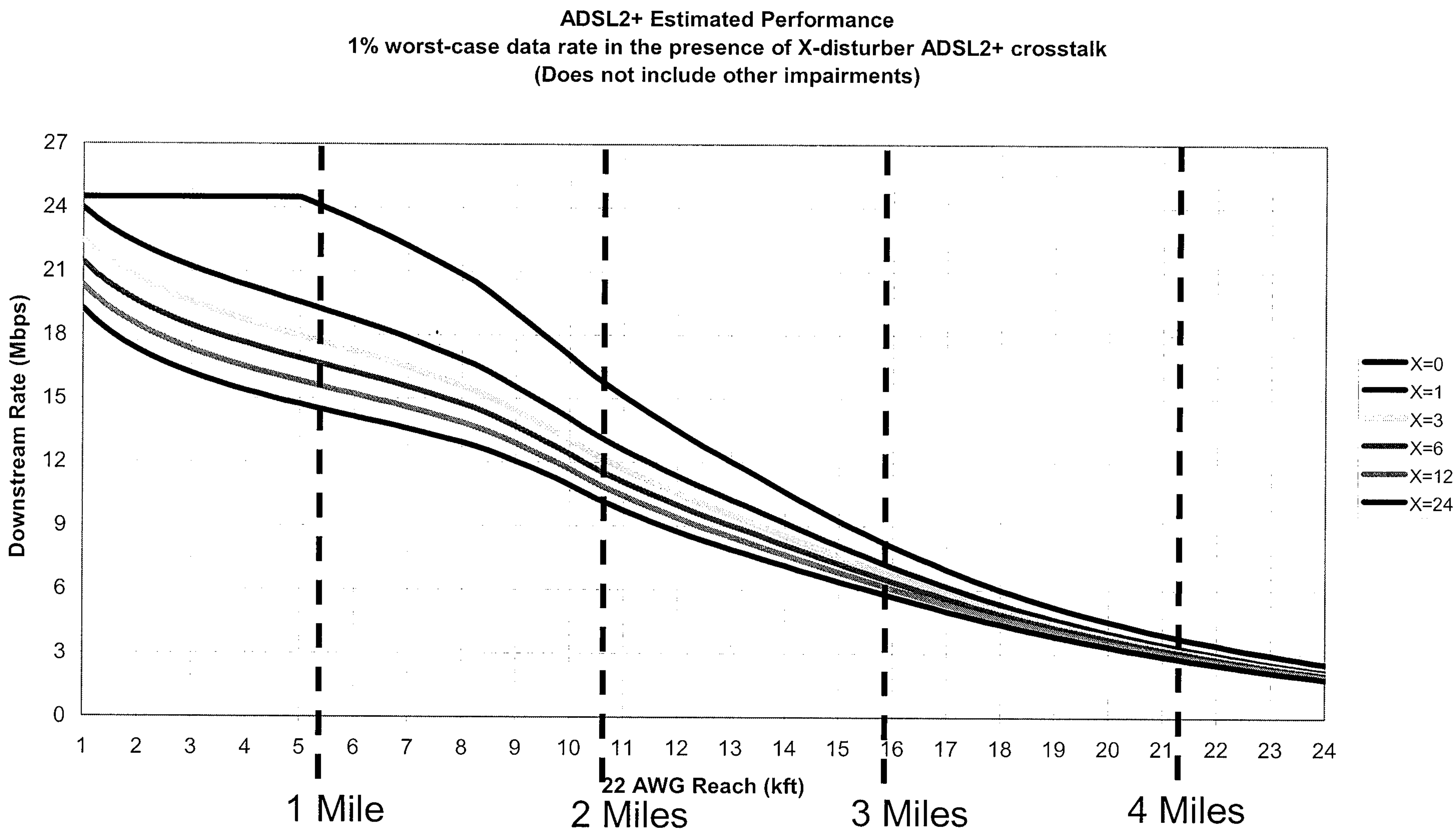


ADSL2+ on 24 AWG

ADSL2+ Estimated Performance
1% worst-case data rate in the presence of X-disturber ADSL2+ crosstalk
(Does not include other impairments)

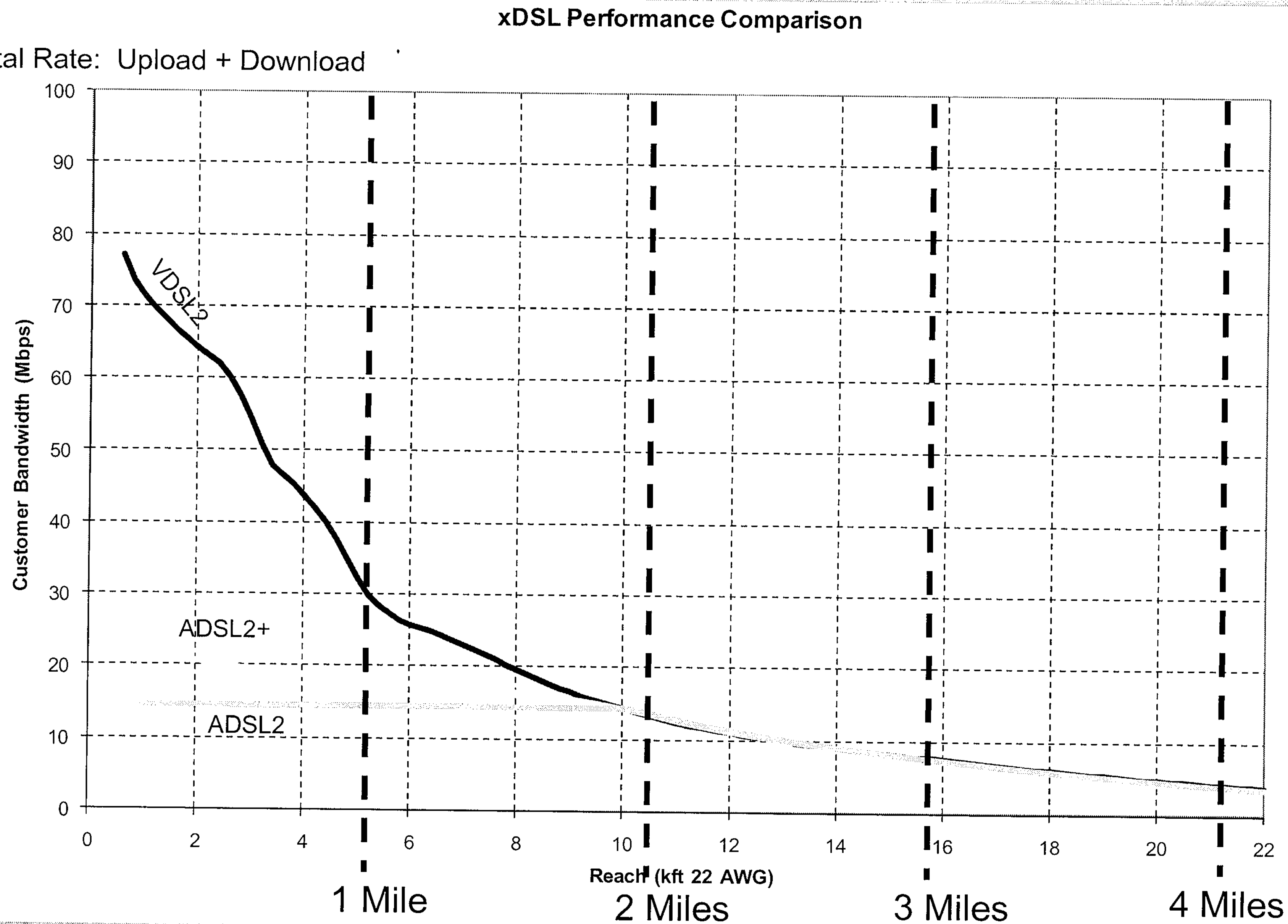


ADSL2+ on 22 AWG



ADSL2/2+ and VDSL2 Performance

Total Rate: Upload + Download



Aggregate Capacity of the Cable

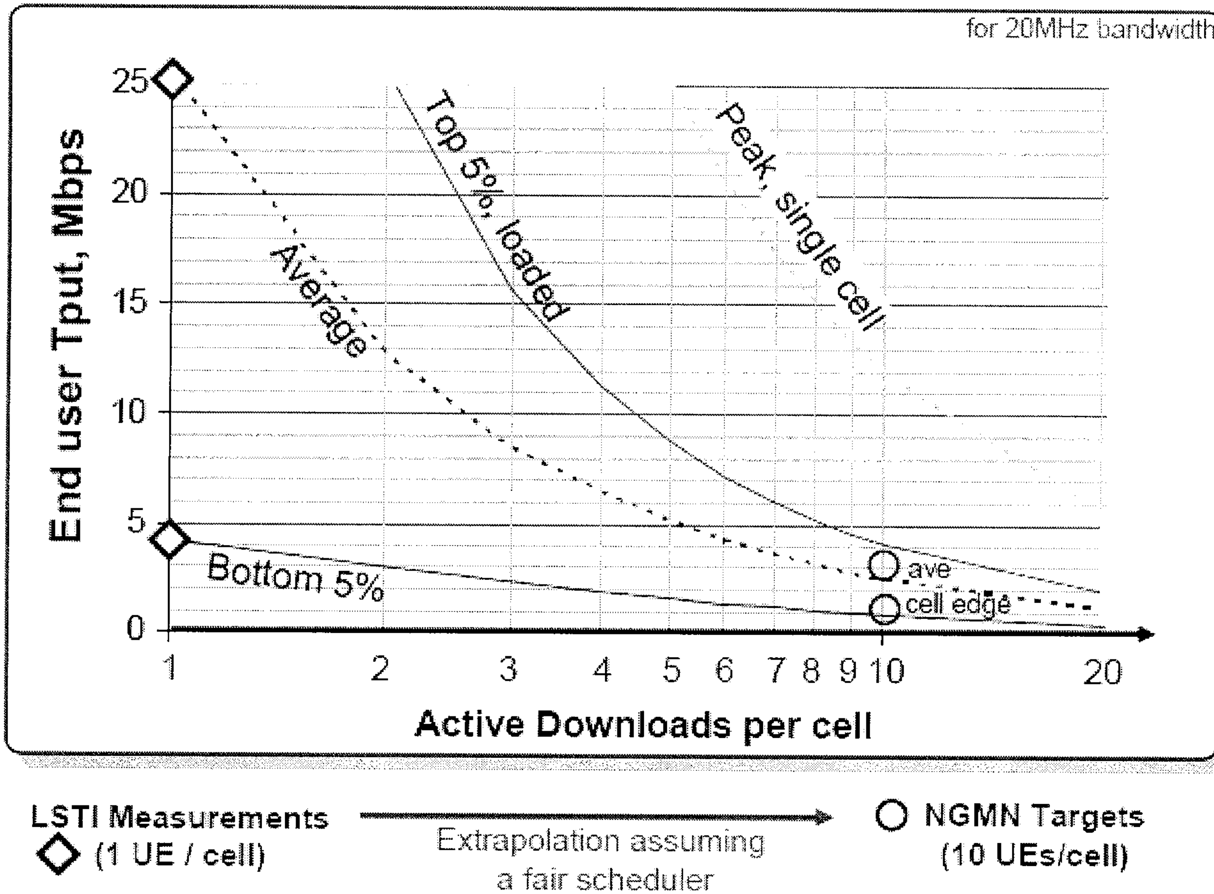
Suburban Example:

- Average Rate over 1.3 Miles: 35 Mbps
- 100 living units/200 pairs
- Total Capacity per 200 pair cable: 7 Gbps

- *Compare to up to 300 Mbps/25 Mbps average shared per 20 MHz LTE channel*

Wireless Peak vs. Average Throughput

- Average throughput is 20% of peak throughput
- End user throughput is average / # active users
- 125 Mb peak results in average of 2.5 Mb per user with 10 active users



Source: ***Latest Results from the LSTI, Feb 2009*** www.lstiforum.org

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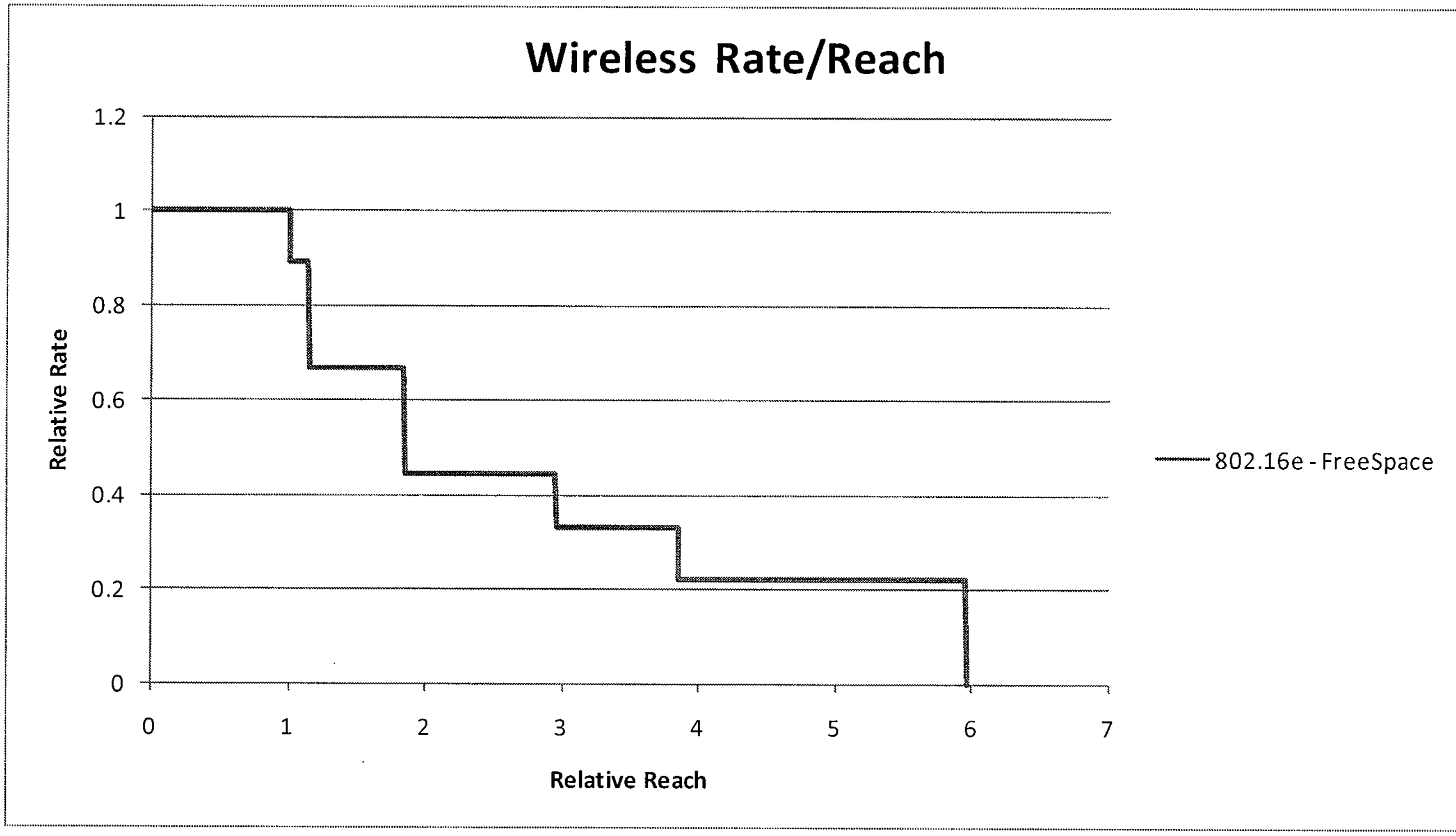
Aggregate Capacity of the Cable

Rural Example:

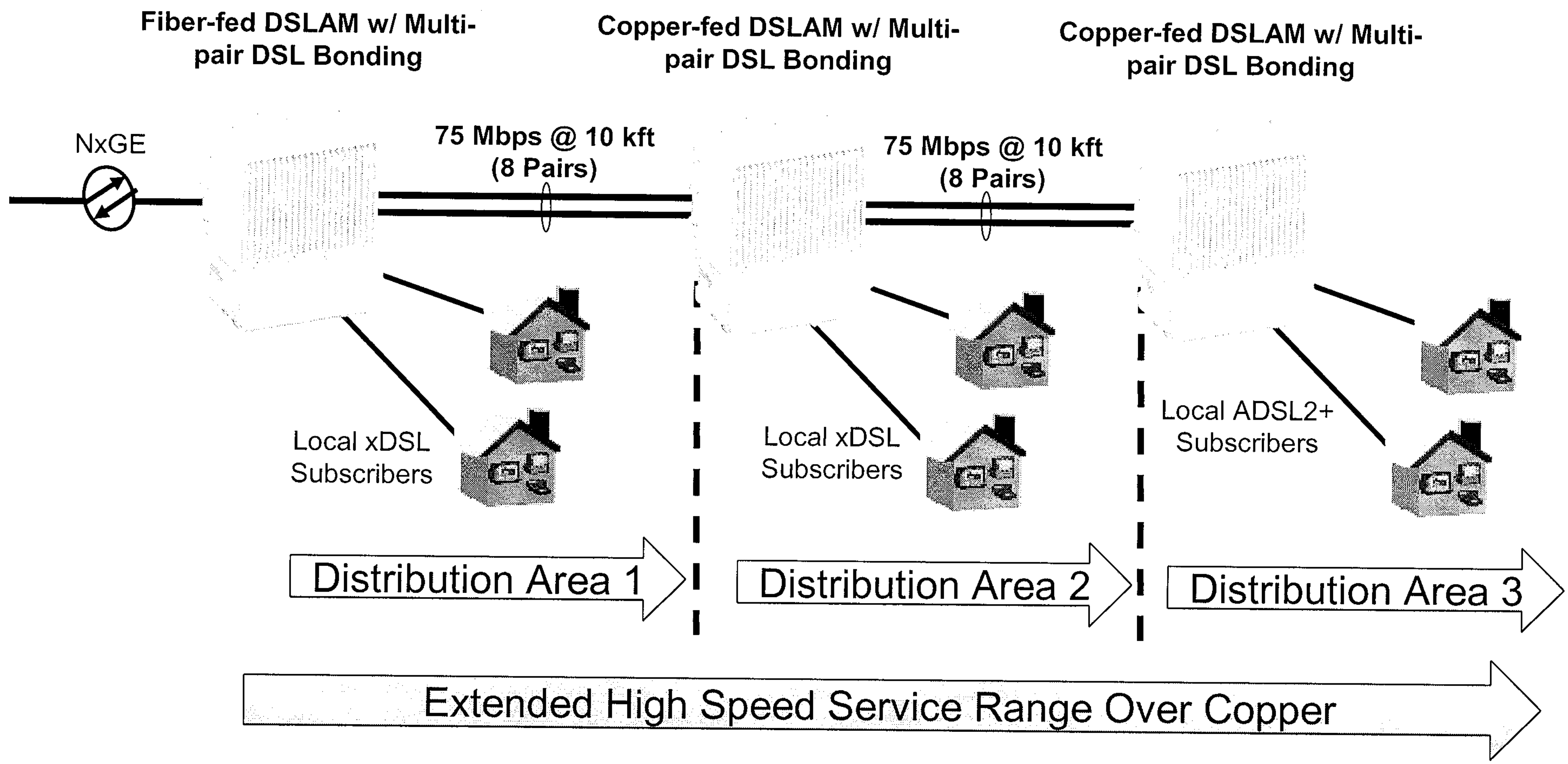
- Average rate over 4 miles 22 AWG: 12 Mbps
- At 10 subscribers per route mile, 40 subscribers/cable result in a 50 pair cable
- Total Downstream capacity per 50 pair cable: *600 Mbps*

- *Compare to 50 Mbps shared per 10 MHz WiMAX channel*

Wireless Rate/Reach



Cascading DSLAMs for Extended Range

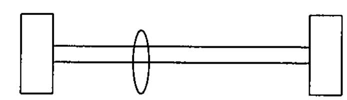


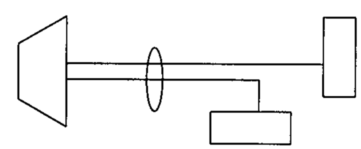
Provides 3 Mbps/sub up to 12 miles from fiber

6 Mbps/sub to 9 miles; 10 Mbps/sub to 6 miles

DSL Evolution: Beyond VDSL

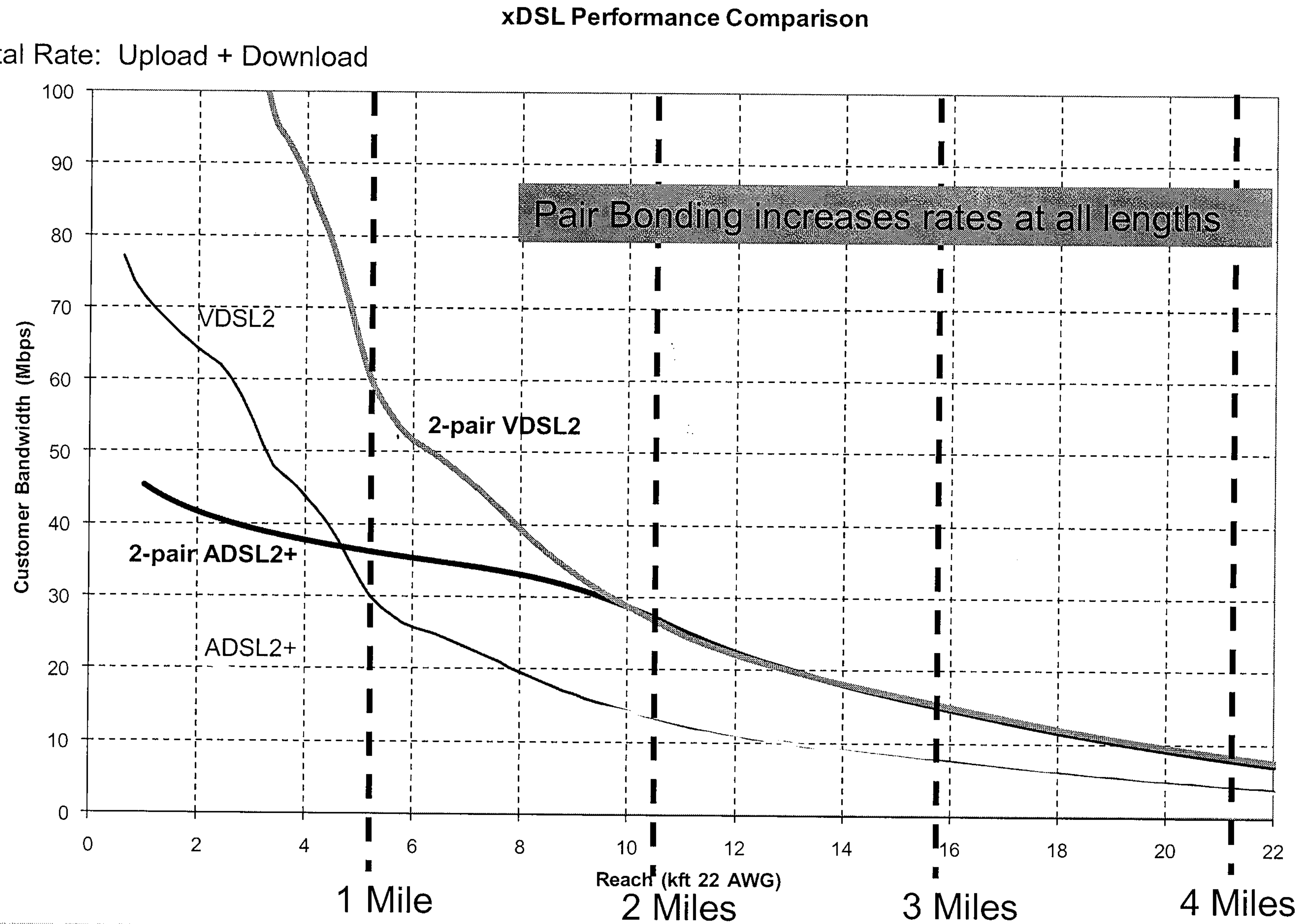
- Pair Bonding
  - Standardized in 2005, just now getting started
  - Inverse multiplex 2 or more pairs into one "super link"
  - Doubles data rate available to subscriber
  - Also can be used for backhaul
- MIMO and Vectoring (DSM Level 3)
  - Primary benefit is to reduce or eliminate crosstalk
  - Crosstalk cancellation is the simplest form
    - NEXT cancellation used with point-to-point multi-pair systems
      - 1000BASE-T
    - FEXT cancellation can be used in multi-user scenarios as well
      - Referred to as Vectoring
  - Vectoring benefit is greatest with VDSL2
    - Eliminates in-system FEXT
  - Standard in progress, expect in 2010



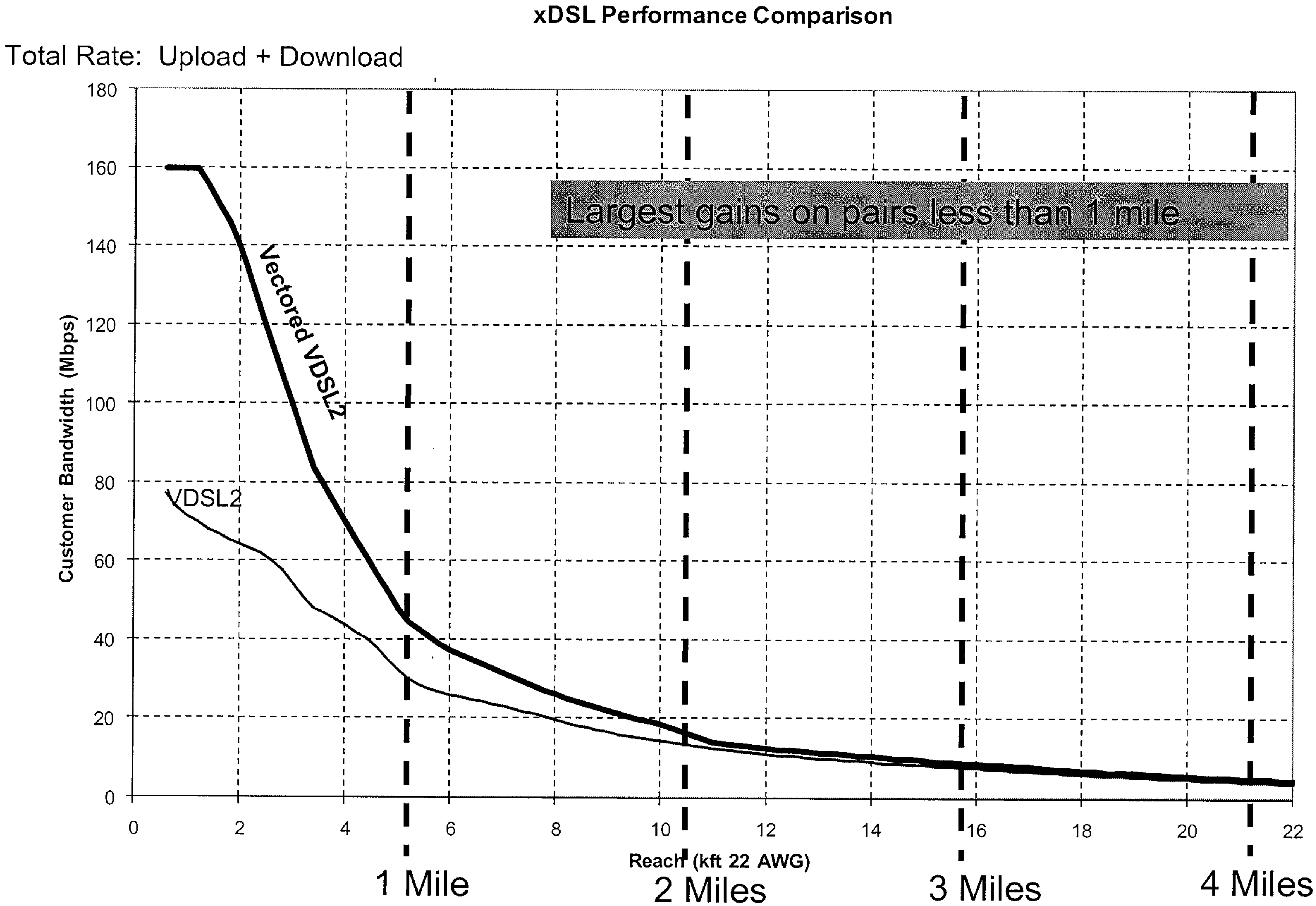


Performance Gain from Pair Bonding

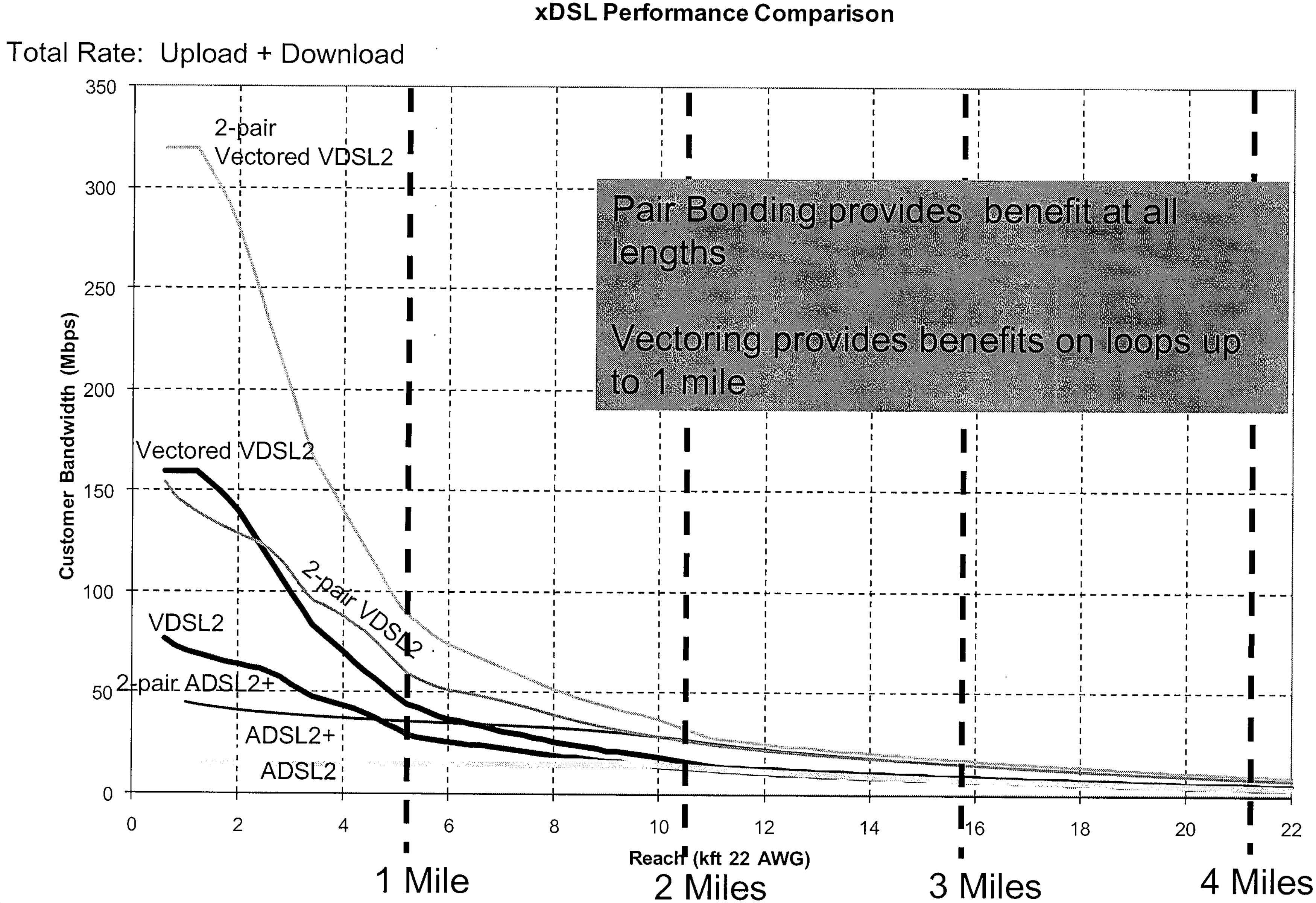
Total Rate: Upload + Download



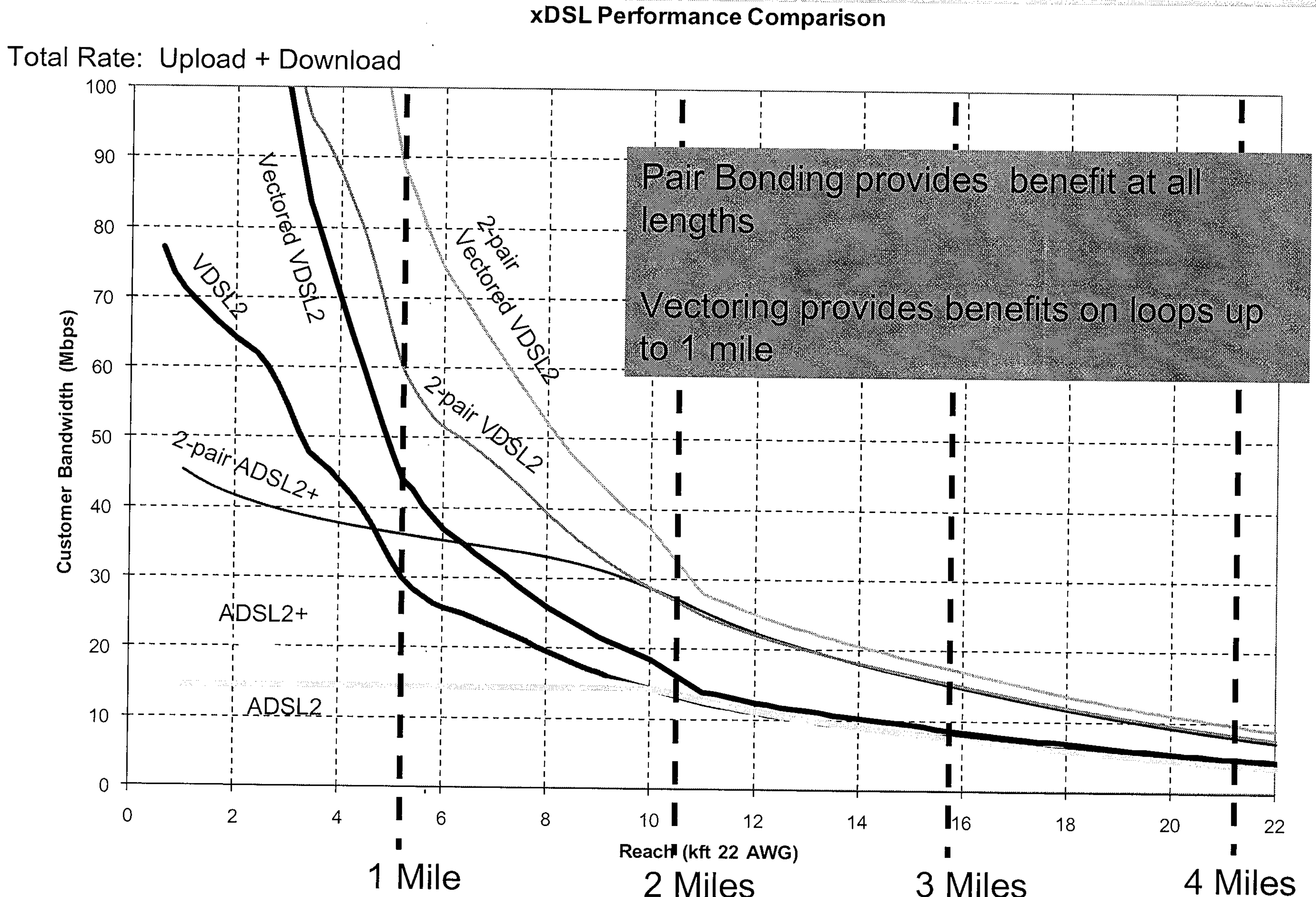
Performance Gain from Vectoring



Putting it Together: Vectoring and Bonding



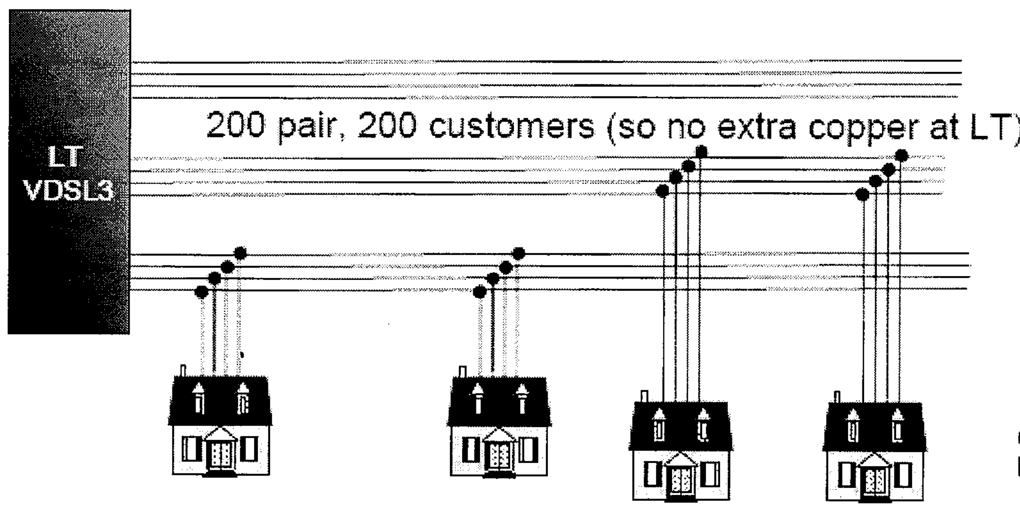
Putting it Together: Vectoring and Bonding



Beyond Mere Vectoring…

Add transmission channels by transmitting on each conductor

Ultimate in VDSL3: Copper PON? (Cu-PON)



(could also be MDU application)

- Maximizes use of all copper
  - Note receivers can cancel radio, Other lines' crosstalk, and impulse
  - So downstream now also fully improved
- Some sharing of copper (called a "tap" at "junction box")
  - Similar to PON sharing, but much easier to make the connection
  - LT DSLAM does the assignment of DSL dimensions
- Peak Customer BW (1 Gbps for 4 wires – could be up to N/4 Gbps)
- Overall BW (50 Gbps each direction)
- 3000 ft, 1 km range (no user less than 200 Mbps)
  - Typically several 100 Mbps

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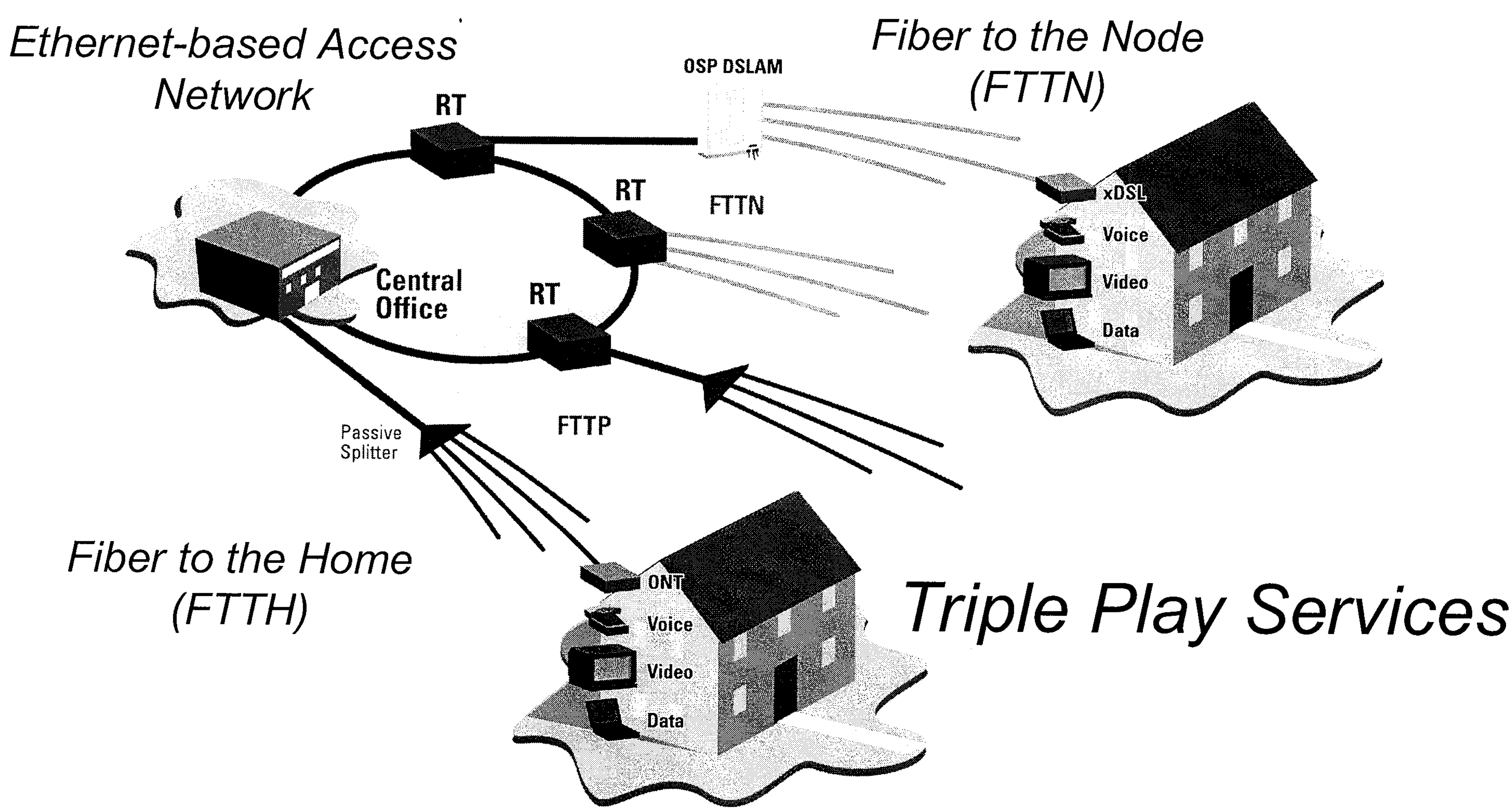
Hybrid Fiber/Copper to "shorten copper"



Part III: Fiber Wireline Physical and Transmission Characteristics

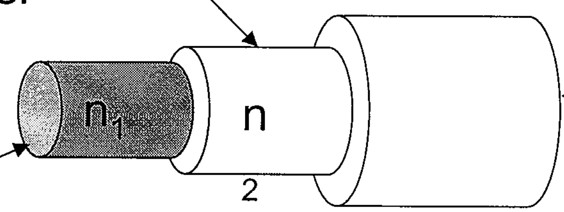
The Fiber-Optic Channel

Principle of Operation: Total Internal Reflection

- $n_1 > n_2$
- "large" angle of incidence (small numerical aperture)

Fiber Cladding: Glass with a low refractive index (n_2)to keep light from leaving the core. 125 um diameter

Fiber Core: Glass with a high refractive index (n_1). This is where the light travels. 8.5 um - 100 um diameter



Fiber Coating: Plastic to provide Strength and Flexibility.

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Two Types of Fiber

Single Mode Fiber: (SMF)

Expensive
> 1 km transmission
~8.5 um core
Typical Tx: 1310 nm - 1620 nm
Primary Impairments:
- Attenuation and Dispersion
- Non-linear effects

Primary Uses:
- **Telco networks**
- **Access (PON)**
- Core / long-distance (SONET)

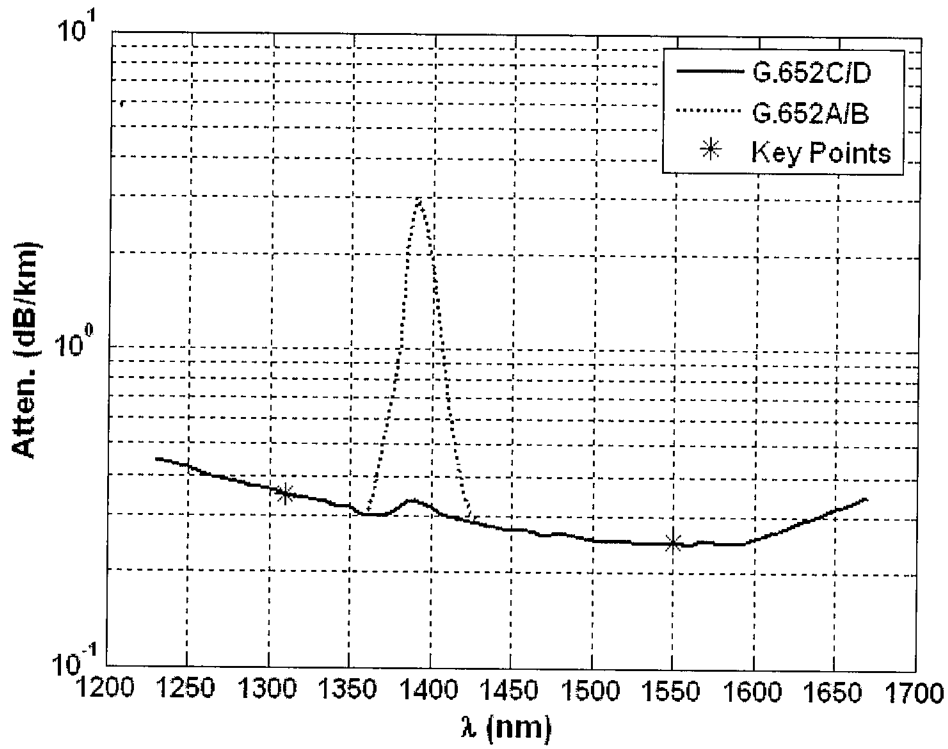
Multi-Mode Fiber: (MMF)

Cheap
< 1 km transmission
50 um and 62.5 um core
Typical Tx: 850 nm - 1310 nm
Primary Impairments:
- *Modal Distortion / Delay*
- Attenuation and Dispersion
- Non-linear effects

Primary Uses:
- Enterprise (LAN)

Long distance copper links require low frequency or large channel diamete
Long distance optical links require very small channel diameters.

Attenuation



Rule of Thumb for Attenuation:
1310nm: 0.35 dB/km
1550 nm: 0.25 dB/km

wavelength (nm)	Attenuation (dB/km)	Max Allowed Atten.	Attenuation Limited Distance (km)
1310	0.35	10	**29**
1550	0.25	10	**40**

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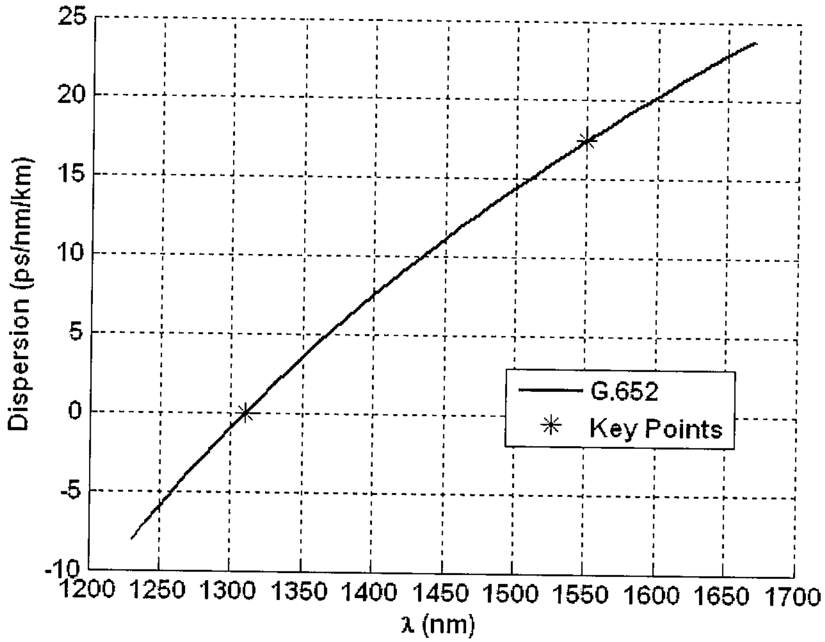
Dispersion



- Dispersion limits line width of laser
  - Increased cost to produce laser that sees less dispersion

min	nominal	max	spectral width (nm)	Dispersion (ps/nm/km)	Data Rate (Gbps)	Dispersion Limited Distance (km)
1530	1550	1570	**2**	19.3	1.25	**3.1**
1270	1310	1350	**2**	5.4	1.25	**11.2**
1530	1550	1570	**0.55**	19.3	1.25	**11.3**

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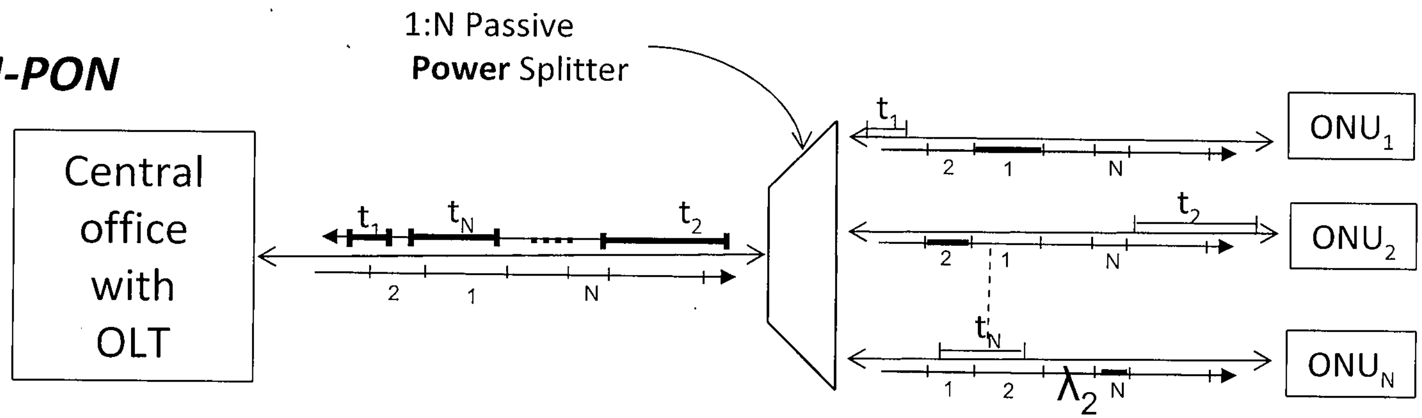
Fiber Optic Technology

- Virtually unlimited bandwidth if
  - Lasers have narrow line width
  - Receive power above receiver sensitivity threshold
- Main deterrents to deployment:
  - Cost to install fiber
    - Where copper is already installed
  - Cost of electronics/optical components
    - Remote electronics/optics needed even just for phone service
- Fiber Optics for Access has largely settled on a Passive Optical Network (PON) architecture
  - Saves costs at the Central Office
    - Fewer fibers, fewer terminations, fewer transceivers

Fiber to the Home: Passive Optical Network

TDM-PON



- Goal: Reduce cost of fiber to the premises by sharing transceiver in Central Office
- Shared bandwidth by time sharing bandwidth
  - Similar to DOCSIS and wireless
    - Broadcast downstream
    - TDMA upstream (packet/dynamic timeslot based)
- Reach from 10-20 km
  - Power limited due to power splitter (3 dB for every power of 2 split)
- Serve 32-64 subscriber per PON
- Use 2 wavelengths for data transmission: 1310 nm up / 1490 nm down
- 2 versions predominantly deployed: EPON and GPON

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PON: A tale of 2 standards

- GPON Family developed by FSAN/ITU-T
  - Pioneered PON Standards
    - APON: ATM-based TDM PON 155 Mbps (G.983.1)
    - BPON: Added RF wavelength for television (G.983.x) (1550 nm), speed up to 622/155 Mbps
    - GPON: raised data rates to 2.5 Gbps/1.25 Gbps (G.984.x)
      - Also dropped ATM and provided native support for TDM
      - GPON provides approximately 80 Mbps DL and 40 Mbps UL per subscriber (32)
- EPON Family developed by IEEE 802.3
    - Developed EPON (1 Gbps) as part of the Ethernet in the First Mile project (early 2000s)
- Primarily differ in:
  - Rate
  - Signalling for upstream scheduling
  - Overhead
  - Management
  - Network timing
  - Standardized optical options

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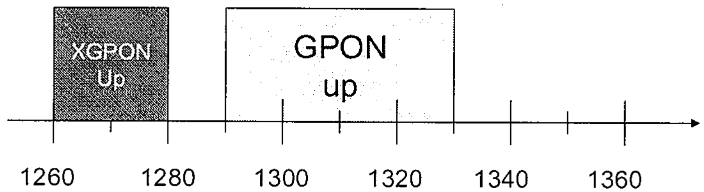
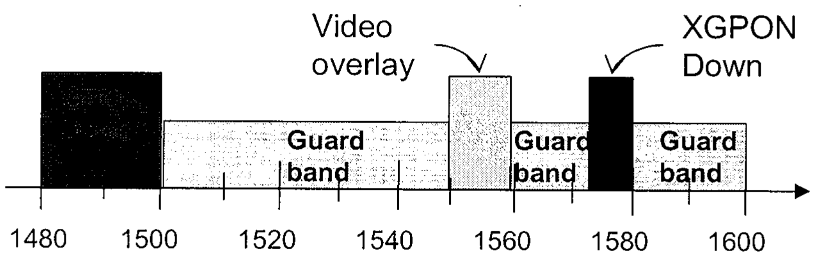
Current activities to build on TDM PON

- FSAN/ITU-T
  - Upgrade of GPON (2.5G PON) to NGPON (10G PON) (ITU-T G.987)
    - NGPON1
      - can coexist with GPON (different wavelengths)
      - XGPON1- 10Gbps down / 2.5Gbps upstream
      - XGPON2 – 10Gbps serial symmetrical
      - Wavelength plan has been decided (DS: 1577 nm, US: 1270 nm, Same as 10GEPON)
      - Link budget , TC-layer, etc. still under discussion
      - Expect XGPON1 standard completion late 2010
    - NGPON2
      - A blank slate to investigate "future PON" such as (D)WDM-PON, TDM/WDM-PON hybrid, 1:128 or higher split ratios and rates up to 40Gbps
- IEEE 802.3
  - Upgrade of GEPON (1G PON) to a 10G PON architecture
    - PRX (10 Gbps downstream and 1.25 Gbps upstream)
    - PR (10 Gbps downstream and 10 Gbps upstream)
    - Can coexist with 1 Gbps EPON (IEEE 802.3ah)
    - Same wavelength plan as XGPON1 (DS: 1577 nm, US: 1270 nm)

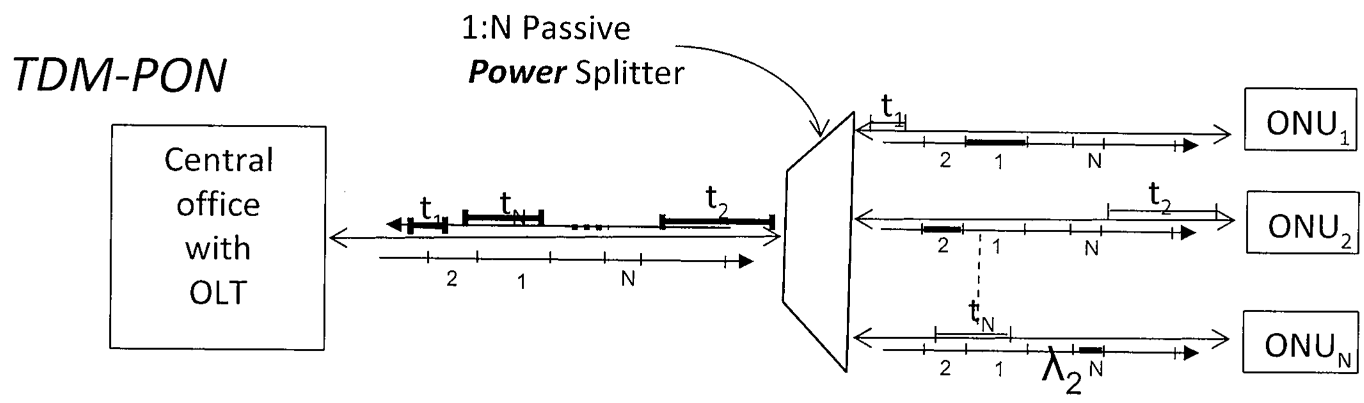
Coexistence: GPON and XGPON1

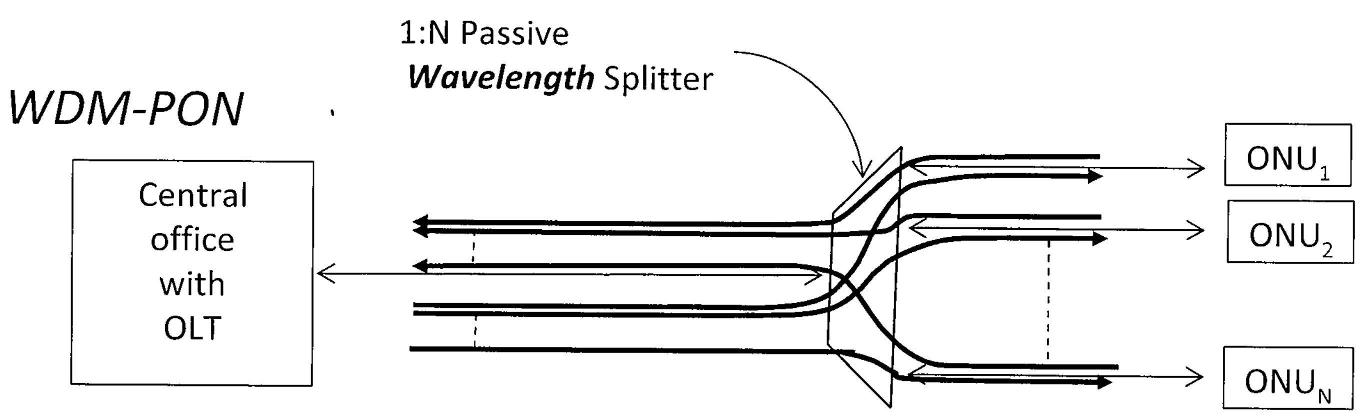




- Upstream
  - Wavelength Overlap
    - GPON: 1310 nm +/- 50 nm
    - NGPON1: 1270 nm +/- 10 nm
      - Uncooled XGPON Operation Requires Tightened GPON laser specs (+/- 20 nm)
      - Tightened OLT Filter specs
- Downstream
  - Separate Wavelengths
    - GPON: 1490 nm +/- 10 nm over temperature
    - RF-Overlay: 1555 nm +/- 5 nm and 1610
    - NGPON1: 1577 nm +3nm/-2 nm
      - cooled operation for NGPON1 DS laser
      - Tight filter specs.

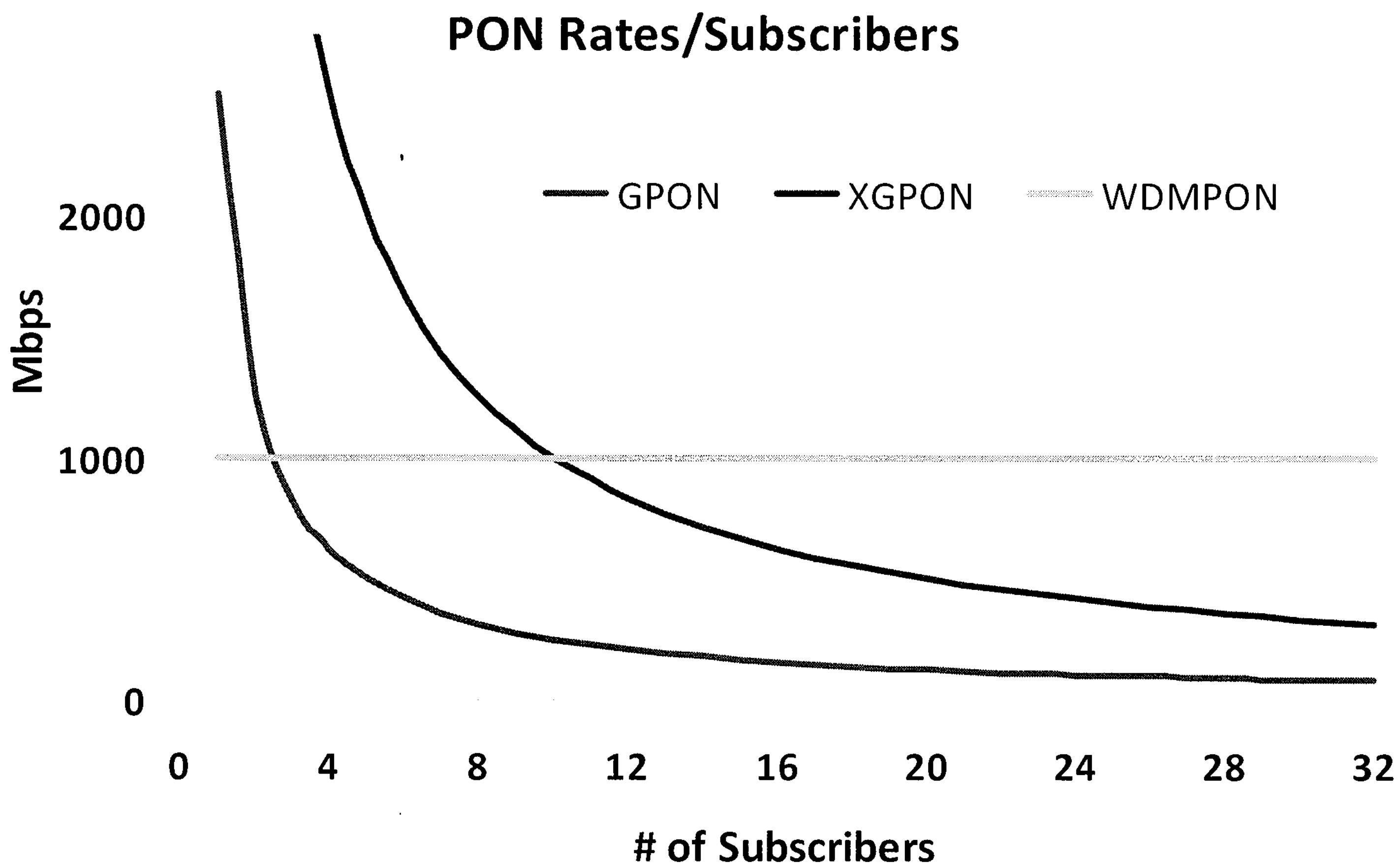
Future Fiber Access: WDM-PON

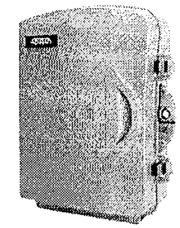




Providing a dedicated 1 Gbps per subscriber

Future of Broadband - FTTH

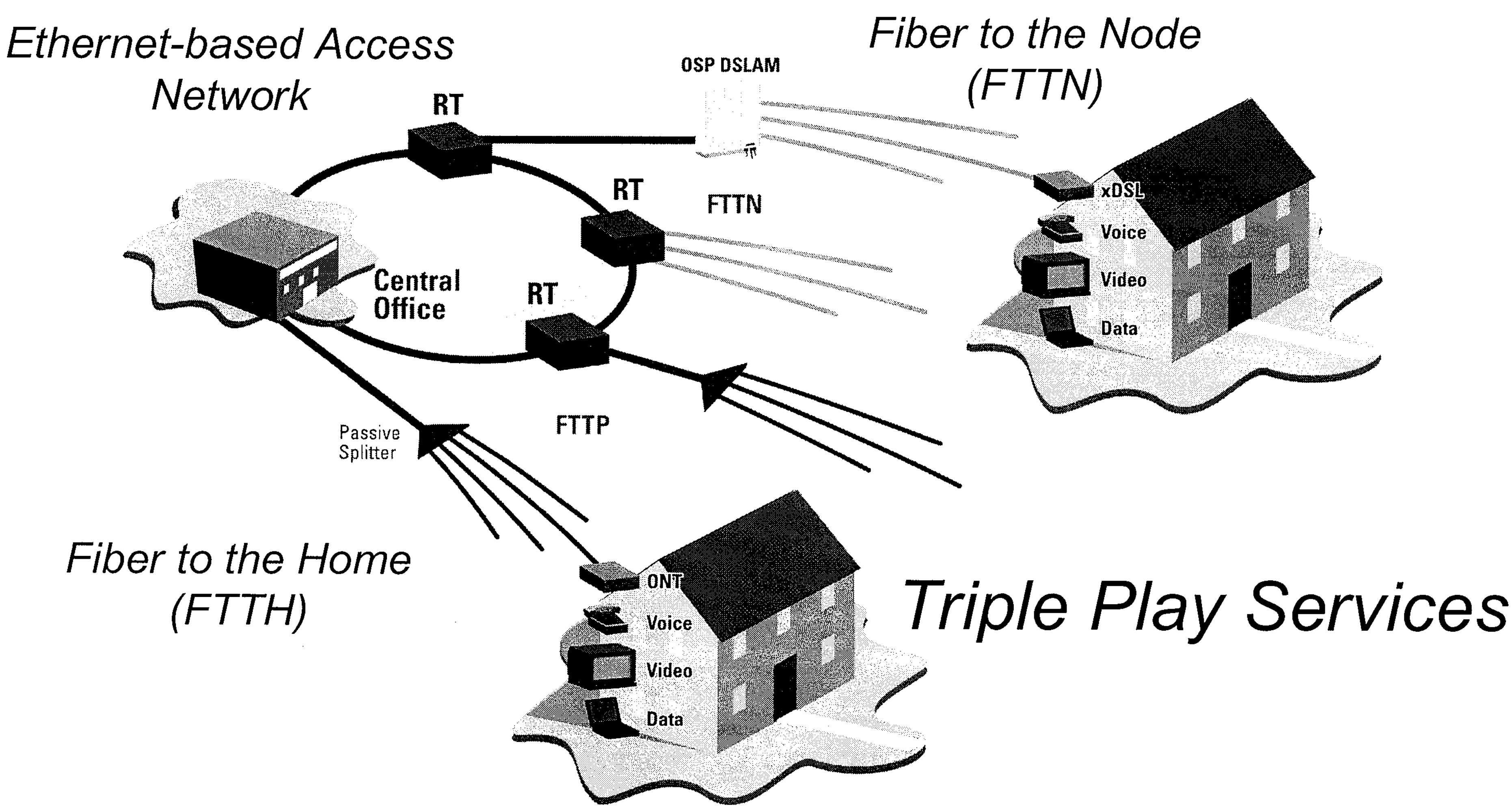




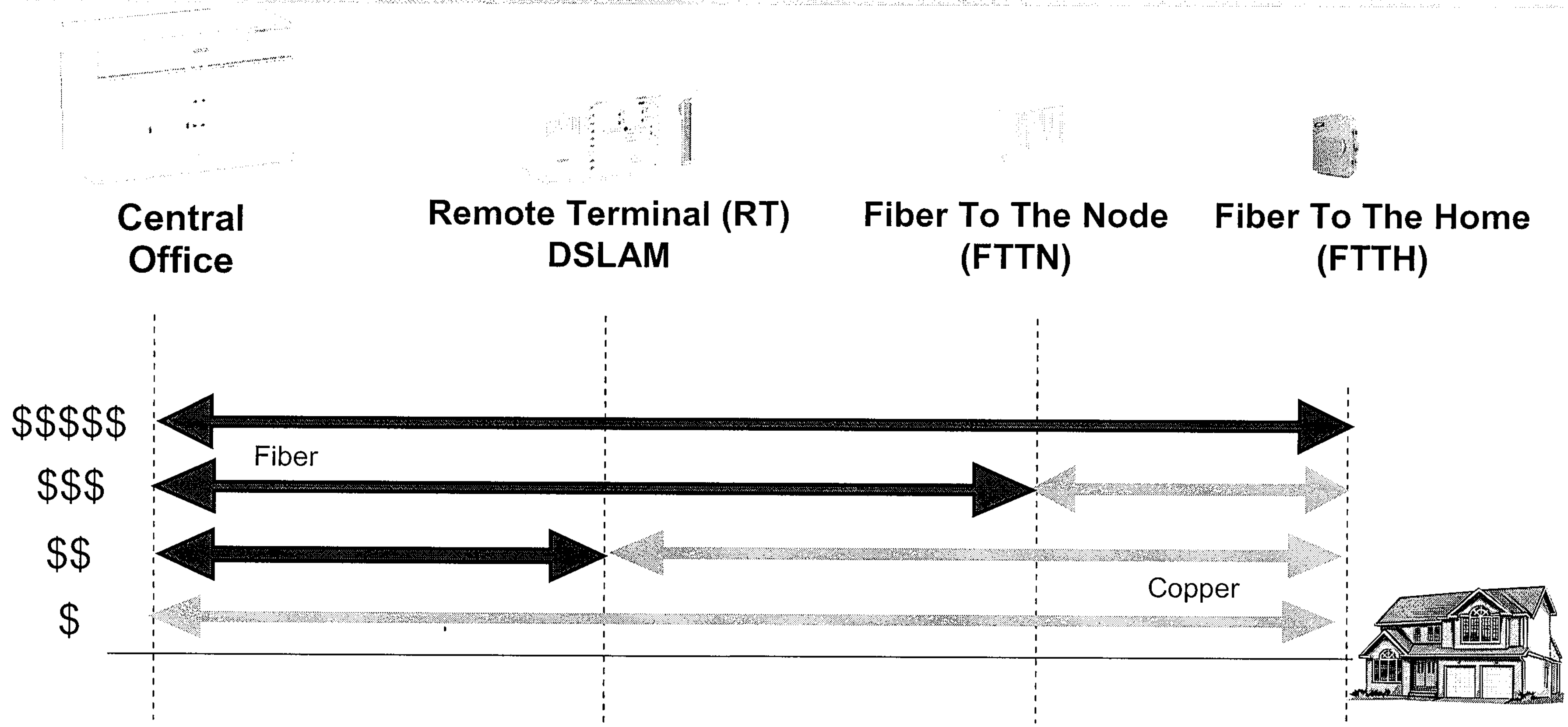
FTTH evolves from 80Mbps to 1Gbps per subscriber

Part IV: Wireline Access Applications

Next Generation Broadband



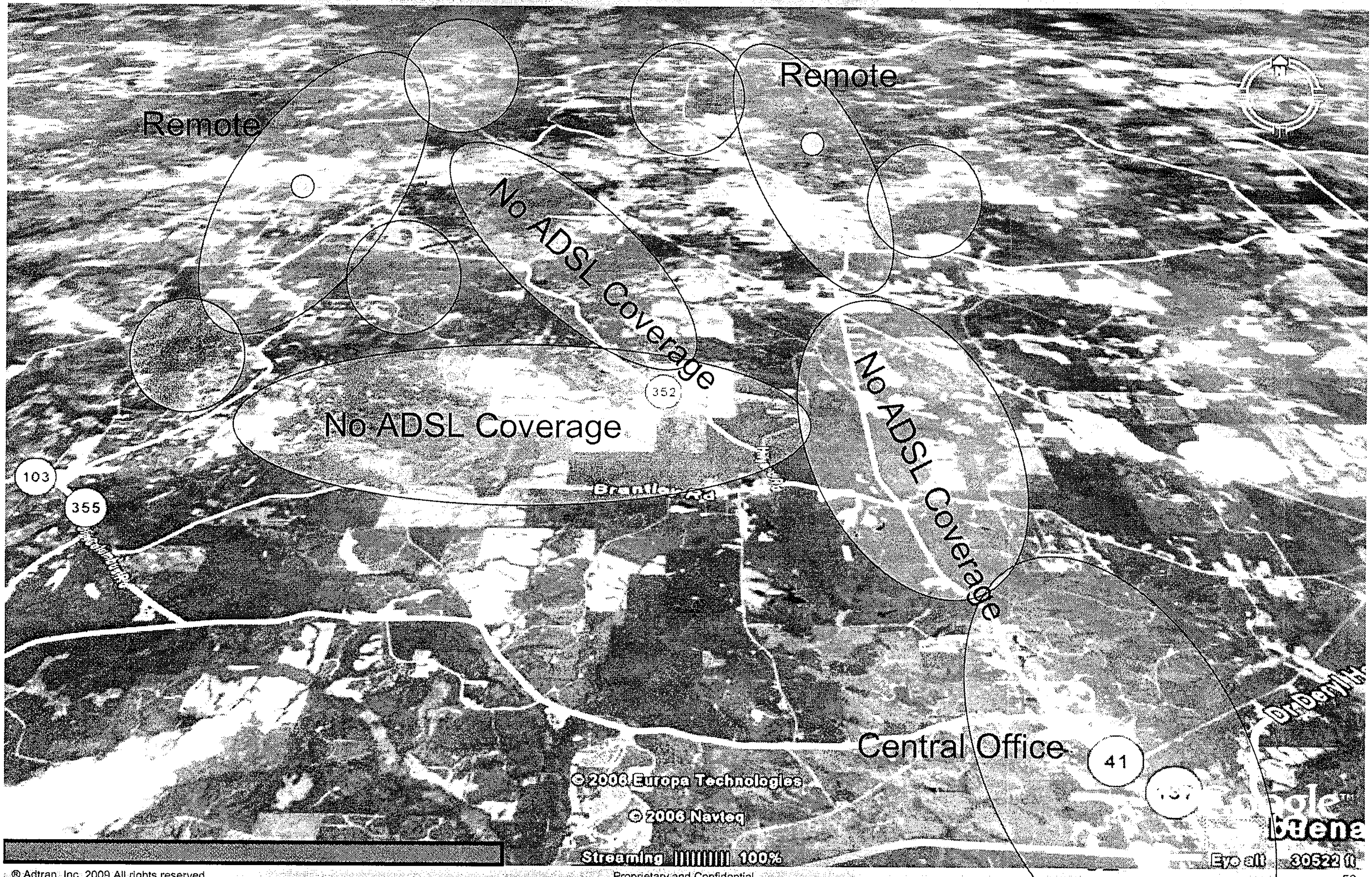
Driving Fiber Deeper



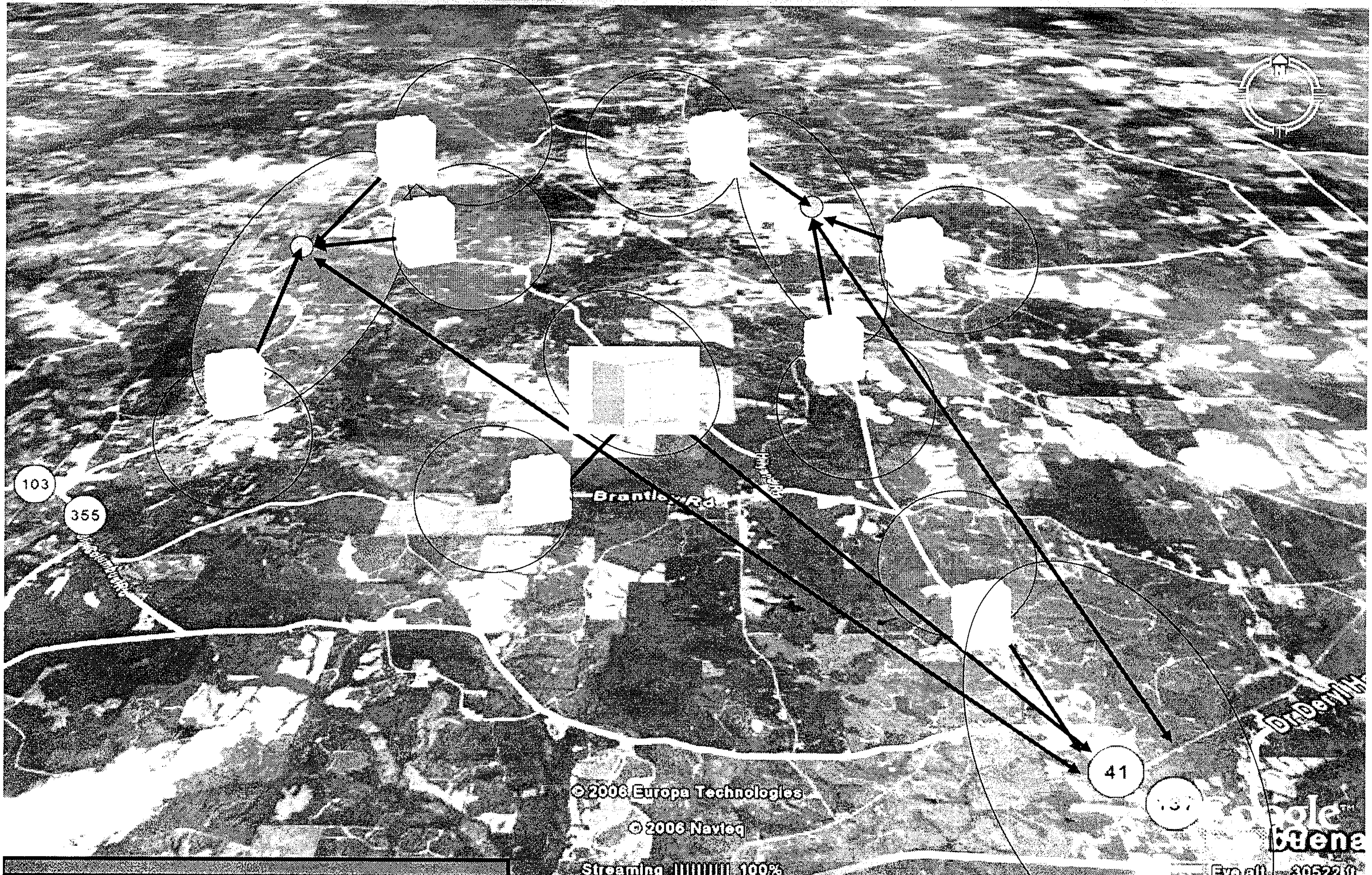
Careful Balance of Bandwidth and Economics

Note: Studies show that as much as 70% of the cost of a Brownfield conversion from copper to fiber is in last 3000’

Rural Deployment example: 234 customers w/out Broadband



100% Broadband Coverage!



Proprietary and Confidential

Subscriber Speed Forecast

Approximate required capacity/household for shared facilities in the access network

Direction	2009	2012	2015
Down (kbps per household)	350	700	1400
Up (kbps per household)	100	200	400

Affect of delay on WWW response time

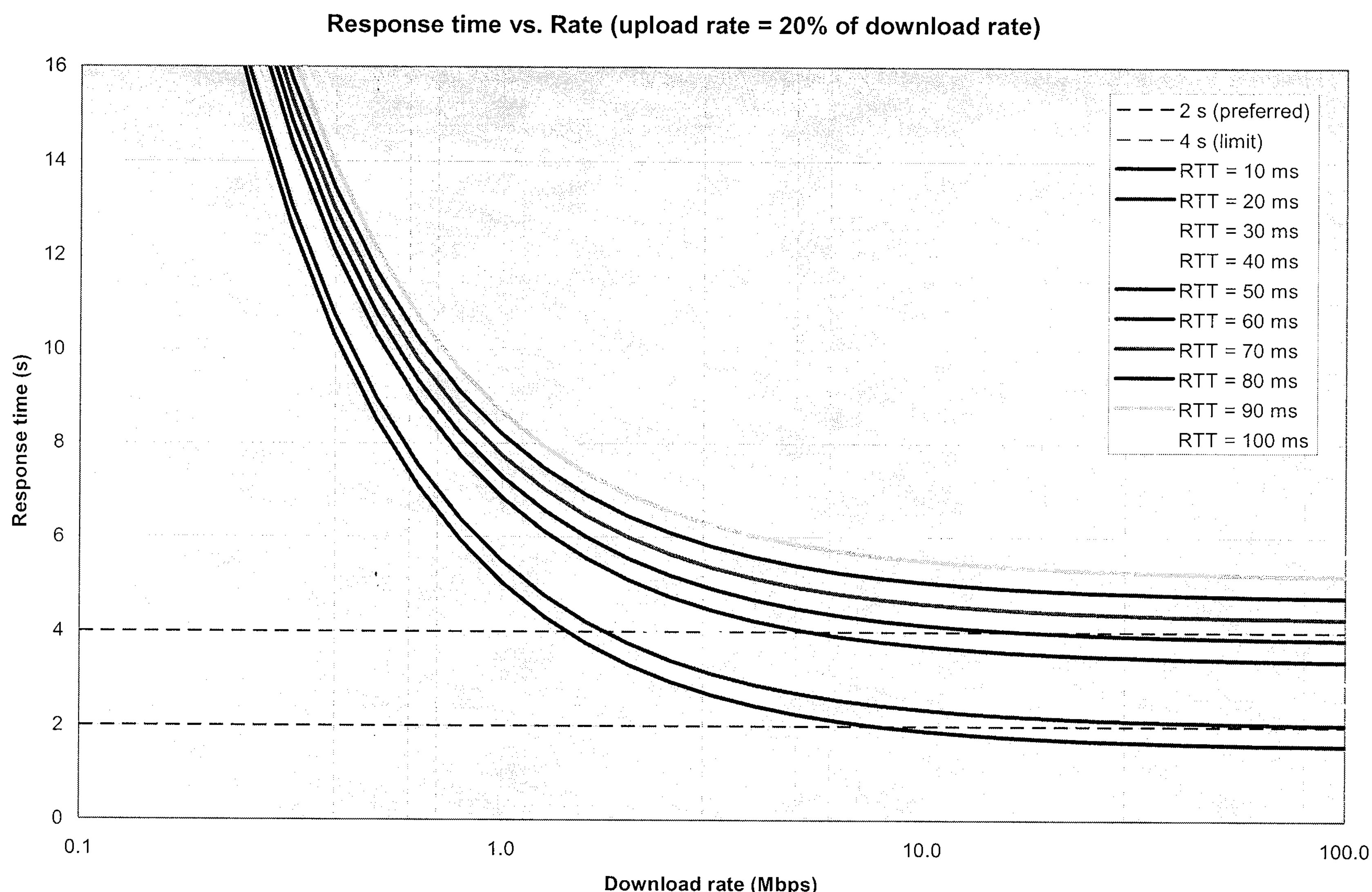


Figure 4 – Response times for average web pages

Planning for the Future

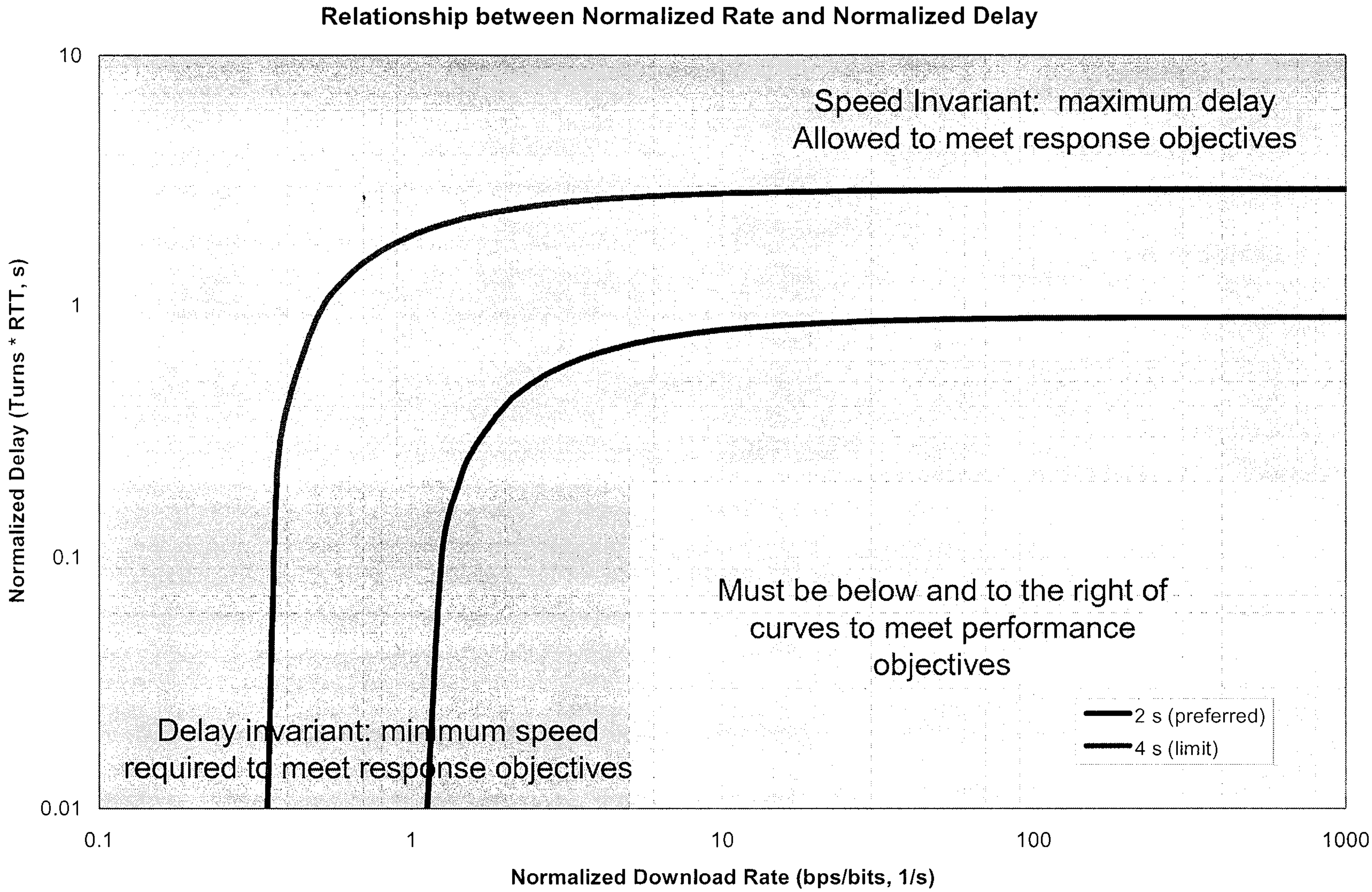
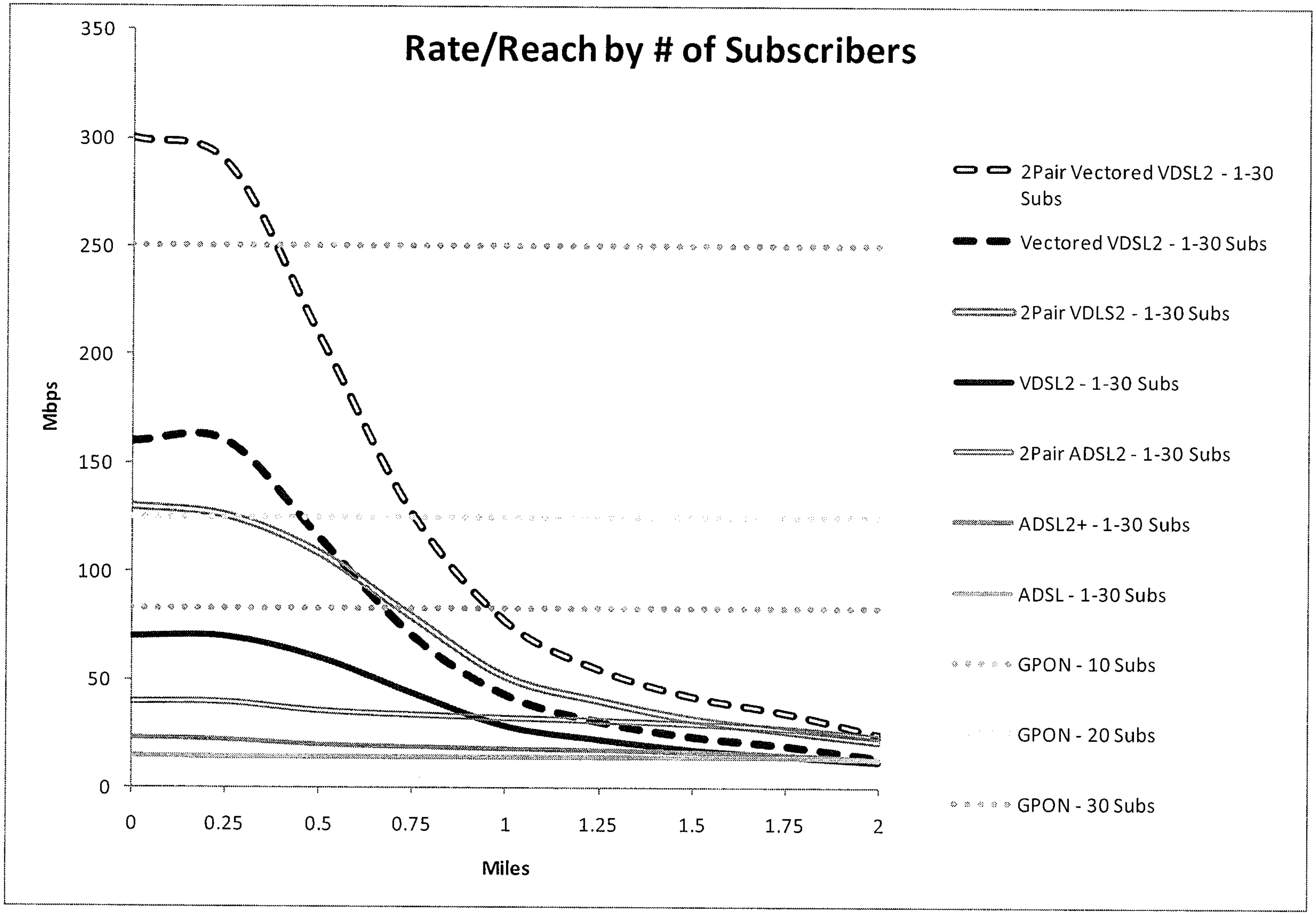


Figure 5 – Normalized rate vs. delay

Capacity of Wireline Access



DSL Summary

- Achievements to date:
  - DSL 10x increase in bandwidth capacity
    - ADSL (8), ADSL2+ (24), VDSL2 (80)
  - Accomplished through additional spectrum
- Near future:
  - Additional 3-4x increase in bandwidth capacity
  - Accomplished through noise reduction and additional channels
    - Vectoring and Pair Bonding
- Future Promise:
  - Additional 2x possible
  - Accomplished through additional channels
    - Per-conductor vectoring
- Bandwidth Capacity ***per subscriber***
  - *Sustains high broadband usage levels forecast*
    - *Streaming Video*

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Fiber Summary

- Optical Fiber provides the ultimate in broadband access
  - Nearly infinite bandwidth capacity
  - Bandwidth capacity is virtually reach independent
- Fiber in the access network enables, economic delivery of high-speed broadband using DSL
  - Access speeds over 100 Mbps per subscriber are possible with hybrid fiber/copper architectures
- Fiber to the Home offers even greater bandwidth capacities
  - Achievements to date
    - PON 16x increase in bandwidth
      - APON (155M), BPON (622M), GPON (2.5G)
  - Future Promise
    - 1 Gbps dedicated per subscriber using WDM-PON

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Conclusions

- Subscriber data usage forecast to double every three years
- Existing copper infrastructure provides the evolution path to the future broadband network
- The combination of fiber and copper enables economic deployment of broadband at speeds over 100 Mbps per subscriber.
- Fiber to the home can enable 1 Gbps per subscriber or more…
- Wireless complementary to wireline
  - Less bandwidth capacity
  - Adds mobility

