SYSTEM ARCHITECTURES
Broadband access network options

Scope of access networks

Long Haul & Regional Network

Metropolitan Network Core

Local Access Network

Premise Network

~ 100 city to city links and regional connections

~ 1,000 core metro rings

~ 5,000 edge metro rings

~22 k Central Offices

~116 MM connections

~170 MM switched access lines

~109 MM households

~7 MM businesses

~1MM enterprises

Access Fiber

Copper / Coax

R. E. Wagner
April 22, 2003

Broadband Access Network Options

Slide 3

CORNING
POINT-TO-POINT

long haul
Public Switched Telephone Network

- Circuit switched PSTN
- Internet backbone
- MESH NETWORK REDUNDANCY

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nodes</td>
<td>100</td>
</tr>
<tr>
<td>Network capacity</td>
<td>64 Tb/s</td>
</tr>
<tr>
<td>Per-node demand</td>
<td>640 Gb/s</td>
</tr>
</tbody>
</table>
Submarine Systems
- Optical pass through or express traffic destined for another node.

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Fig. 5.1 Hypothetical national-scale, backbone long-haul network with nodes situated at major urban centers of the United States.

**EXPRESS TRAFFIC v ADD-DROP**
**REGEN = 3R**: reamp, reshape, retime

**PERFORMANCE MONITORING**

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**Figure 5.1**: Point-to-point fiber links with periodic loss compensation through (a) regenerators and (b) optical amplifiers. A regenerator consists of a receiver followed by a transmitter.

**AMP = 1R**: reamplify only

No OEO conversion
Optical Network Architectures and the Role of Large MEMS Switches

Transparent Network - Transparent Switch

Opaque Network - Opaque Switch

Opaque Network - Transparent Switch

Three Broad Visions

Source: E. Goldstein (Tellium)
Wavelength-Division Multiplexing (WDM) Meeting Network Needs: Capacity, Scalability, & Cost

**Single-wavelength TDM: OC-48 (40 Gb/s)**

**16-wavelength WDM: 40 Gb/s**

- 16 fibers vs 1 fiber
- 48 regenerators vs 1 optical amplifier
- ~80 wavelengths vs ~200 Gb/s

*60 wavelengths @ 40 Gb/s per ch ➔ 2.4 Tb/s*
Figure 5.4: Loss (solid lines) and dispersion (dashed lines) limits on transmission distance $L$ as a function of bit rate $B$ for the three wavelength windows. The dotted line corresponds to coaxial cables. Circles denote commercial lightwave systems; triangles show laboratory experiments. (After Ref. [1]; ©1988 Academic Press; reprinted with permission.)
**LOSS-LIMITED SYSTEM**

\[ L = \frac{10}{\alpha_f} \log \left( \frac{\bar{P}_{tr}}{\bar{P}_{rec}} \right) \quad (5.2.1) \]

\[ \bar{P}_{rec} = \bar{N}_p h v B \]

\[ L = \frac{10}{\alpha_f} \left[ \log \frac{\bar{P}_{tr}}{\bar{N}_p h v B} \right] \]

\[ L = \frac{10}{\alpha_f} \left[ \log \frac{\bar{P}_{tr}}{\bar{N}_p h v} - \log B \right] \]

<table>
<thead>
<tr>
<th>( \lambda )</th>
<th>( \alpha_f )</th>
<th>( N_p )</th>
<th>( P_{tr} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.85 ( \mu )m</td>
<td>2.5 dB/km</td>
<td>300</td>
<td>500</td>
</tr>
<tr>
<td>1.3</td>
<td>0.14</td>
<td></td>
<td>500</td>
</tr>
<tr>
<td>1.5</td>
<td>0.25</td>
<td></td>
<td>500</td>
</tr>
</tbody>
</table>

\[ \bar{P}_{tr} = 1 \text{ mW} \]
DISPERSION-LIMITED SYSTEM

2nd generation - \( n = 1.55 \text{ mm} \) - multimode laser
\( \sigma_n \approx 2 \text{ nm} = \text{rms width of source} \)

\[ BL \leq (4/10) \sigma_n^{-3} \quad (5.2.2) \]

\( D \sim 1 \text{ ps/km-nm} \), \( D \sigma = 2 \text{ ps/km} \)

\( BL \leq 125 \text{ Gb/s-km} \)

\[ \log L = \log (125) - \log B \]

3rd generation - \( n = 1.55 \text{ mm} \) - single mode laser
no chirp - transform limited pulse
\( \sigma_0 \text{ rms width of input} \), \( D_0 T \approx 1 \), \( \sigma_0 \sim B \)

\[ B^2 L < (16/\beta_2)^4 \quad (5.2.3) \]

\[ [B^2 \text{ in } \mu \text{-space}, D \text{ in } \mu \text{-space}] \]
\( D \sim 16 \text{ ps/(km-nm)} \)

\[ B^2 L < 4000 \text{ (Gb/s)^2-km} \]

\[ \log L = \log 4000 - 2 \log B \]
Power Budget

in dBm units

\[
\text{power in dBm} = 10 \log \left( \frac{\text{power}}{1 \text{ mW}} \right)
\]

\(0 \text{ dBm} = 1 \text{ mW}\)

\(10 \text{ dBm} = 10 \text{ mW}\)

\(-3 \text{ dBm} = 0.5 \text{ mW}\)

\[
\overline{P}_{\text{tr}} (\text{dBm}) = \overline{P}_{\text{rec}} (\text{dBm}) + C_L + M_s \quad (5.2.4)
\]

\[
C_L = a_L L + a_{on} + a_{splice}
\]

\[
a_L = \text{loss in dB/km}
\]

\[
M_s \approx 4-6 \text{ dB, system margin}
\]
Table 5.1 Power budget of a 0.85-μm lightwave system

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Laser</th>
<th>LED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitter power</td>
<td>$P_{tr}$</td>
<td>0 dBm</td>
<td>-13 dBm</td>
</tr>
<tr>
<td>Receiver sensitivity</td>
<td>$P_{rec}$</td>
<td>-42 dBm</td>
<td>-42 dBm</td>
</tr>
<tr>
<td>System margin</td>
<td>$M_s$</td>
<td>6 dB</td>
<td>6 dB</td>
</tr>
<tr>
<td>Available channel loss</td>
<td>$C_L$</td>
<td>36 dB</td>
<td>23 dB</td>
</tr>
<tr>
<td>Connector loss</td>
<td>$\alpha_{con}$</td>
<td>2 dB</td>
<td>2 dB</td>
</tr>
<tr>
<td>Fiber cable loss</td>
<td>$\alpha_f$</td>
<td>3.5 dB/km</td>
<td>3.5 dB/km</td>
</tr>
<tr>
<td>Maximum fiber length</td>
<td>$L$</td>
<td>9.7 km</td>
<td>6 km</td>
</tr>
</tbody>
</table>

When an APD is used in place of a $p-i-n$ photodiode, the transmission distance can be increased to 8 km even for an LED-based transmitter. Economic considerations would then dictate the choice between the laser-based transmitters and APD receivers.
Table 5.2 Terrestrial lightwave systems

<table>
<thead>
<tr>
<th>System</th>
<th>Year</th>
<th>$\lambda$ (\textmu m)</th>
<th>$B$ (Mb/s)</th>
<th>$L$ (km)</th>
<th>Voice Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>FT–3</td>
<td>1980</td>
<td>0.85</td>
<td>45</td>
<td>&lt; 10</td>
<td>672</td>
</tr>
<tr>
<td>FT–3C</td>
<td>1983</td>
<td>0.85</td>
<td>90</td>
<td>&lt; 15</td>
<td>1,344</td>
</tr>
<tr>
<td>FT–3X</td>
<td>1984</td>
<td>1.30</td>
<td>180</td>
<td>&lt; 25</td>
<td>2,688</td>
</tr>
<tr>
<td>FT–G</td>
<td>1985</td>
<td>1.30</td>
<td>417</td>
<td>&lt; 40</td>
<td>6,048</td>
</tr>
<tr>
<td>FT–G-1.7</td>
<td>1987</td>
<td>1.30</td>
<td>1,668</td>
<td>&lt; 46</td>
<td>24,192</td>
</tr>
<tr>
<td>STM–16</td>
<td>1991</td>
<td>1.55</td>
<td>2,488</td>
<td>&lt; 85</td>
<td>32,256</td>
</tr>
<tr>
<td>STM–64</td>
<td>1996</td>
<td>1.55</td>
<td>9,953</td>
<td>&lt; 90</td>
<td>129,024</td>
</tr>
<tr>
<td>STM–256</td>
<td>2002</td>
<td>1.55</td>
<td>39,813</td>
<td>&lt; 90</td>
<td>516,096</td>
</tr>
</tbody>
</table>
### Table 5.3 Commercial transatlantic lightwave systems

<table>
<thead>
<tr>
<th>System</th>
<th>Year</th>
<th>Capacity (Gb/s)</th>
<th>$L$ (km)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>TAT–8</td>
<td>1988</td>
<td>0.28</td>
<td>70</td>
<td>1.3 $\mu$m, multimode lasers</td>
</tr>
<tr>
<td>TAT–9</td>
<td>1991</td>
<td>0.56</td>
<td>80</td>
<td>1.55 $\mu$m, DFB lasers</td>
</tr>
<tr>
<td>TAT–10/11</td>
<td>1993</td>
<td>0.56</td>
<td>80</td>
<td>1.55 $\mu$m, DFB lasers</td>
</tr>
<tr>
<td>TAT–12/13</td>
<td>1996</td>
<td>5.00</td>
<td>50</td>
<td>1.55 $\mu$m, optical amplifiers</td>
</tr>
<tr>
<td>AC–1</td>
<td>1998</td>
<td>80.0</td>
<td>50</td>
<td>1.55 $\mu$m, WDM with amplifiers</td>
</tr>
<tr>
<td>TAT–14</td>
<td>2001</td>
<td>1280</td>
<td>50</td>
<td>1.55 $\mu$m, dense WDM</td>
</tr>
<tr>
<td>AC–2</td>
<td>2001</td>
<td>1280</td>
<td>50</td>
<td>1.55 $\mu$m, dense WDM</td>
</tr>
<tr>
<td>360 Atlantic-1</td>
<td>2001</td>
<td>1920</td>
<td>50</td>
<td>1.55 $\mu$m, dense WDM</td>
</tr>
<tr>
<td>Tycom</td>
<td>2001</td>
<td>2560</td>
<td>50</td>
<td>1.55 $\mu$m, dense WDM</td>
</tr>
<tr>
<td>FLAG Atlantic-1</td>
<td>2001</td>
<td>4800</td>
<td>50</td>
<td>1.55 $\mu$m, dense WDM</td>
</tr>
</tbody>
</table>

over 117 km at 40 Gb/s per channel while using all three bands simultaneously [50].
Optical telecom technologies of the last 1/4 Century (Desurvire)

Five generations of technology breakthroughs (3 decades)

10 Petabit.km/s = 1 Terabit/s over 10,000 km or 10 Tbit/s over 1,000 km

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METRO
Figure 5.3: (a) Ring topology and (b) star topology for local-area networks.
Figure 10.2: Schematic of a MAN with a ring topology. It is connected to a WAN at egress nodes (EN) and to multiple LANs at access nodes (AN). ADM stands for add–drop multiplexer. (After Ref. [15]; ©1999 IEEE.)
LOCAL ACCESS
Broadband access network options
Access network reference models

To metro network

Central Office

Head End

10-15 km
1-50 Mb/s down
1-5 Mb/s up

Cabinet (1x32 split)

0-5 km

Services
• Phone
• Internet
• Cable TV

Serving 1000-5000 subscribers

Economics
• $1500 cost per subscriber
• $100/month revenue

Approaches
• aDSL,
• HFC
• FTTC/vDSL
• FTTH - PON
• Free Space Optics
• 3G, Satellite, Fixed wireless

Subscribers
• Residential
• Apartments
• Business

R. E. Wegner
April 22, 2003

Broadband Access Network Options
Figure 5.2: (a) Hub topology and (b) bus topology for distribution networks.
Figure 4 – The evolution to one fiber appearance per home or business - From HFC to FTTH/B. Fiber is represented by green lines, copper by black.

Figure 5 takes a different cut at the evolution, and shows the historical and predicted percent penetration of all fiber carrying both telco and cable traffic whose ultimate terminus is at residences.
FTTH Technology Options

**ITU G.983 BPON**
- ATM Switch
  - OLT
  - 155/622 Mb/s
  - Opt power splitter
  - 155/622 Mbps / N per sub
- Passive outside plant
  - Low-volume, high-cost components
  - Low BW & SAR at each sub
  - Analog video overlay
  - BW upgrades are difficult

**ITU G.984 GPON**
- Multi-service switch
  - OLT
  - 1.2 or 2.4 Gbps down, 155 - 2488 Mbps up
  - Opt pwr splitter
  - 1.2/2.4 Gbps / N per sub
- Passive outside plant
  - High cost? multi-service, low volumes
  - Increased BW allows switched video
  - Analog video overlay
  - BW upgrades difficult

**Ethernet Pt-Pt (P2P)**
- Ethernet Switch
  - N x 1 Gbps or 10 Gbps
  - Active Switch/Mux
  - 100 Mbs / N per sub
- Active outside plant -- higher OPEX?
  - Low-cost Ethernet components
  - High BW per sub + isolation
  - Switched IP video supported
  - BW/service upgrades are simple

**Ethernet PON (P2MP)**
- Ethernet Switch
  - OLT
  - 1 Gbps
  - Opt pwr splitter
  - 1 Gbps / N per sub
- Passive outside plant
  - Low-cost Ethernet components
  - Switched IP video supported
  - Analog video overlay possible
  - BW upgrades more difficult

**WDM PON 2/16**
- WDM OLT
  - Nx100 Mbps - 1+ Gbps
  - Opt λ Split
  - 100 Mbps - 1+ GBps per sub
- Protocol independence
  - High BW per sub
  - Good subscriber isolation
  - Passive outside plant
  - Currently high cost
Power-Splitting PON: Broadband to Business, Homes and Base Stations

- All clients (ONT’s or ONU’s) receive same downstream data from OLT
  - bandwidth is shared over N clients -- N is the “split” -- typically 16:1 or 32:1
- Upstream channel is also shared using a distributed arbitration protocol
  - upstream transmission scheduling is key factor in QoS
- Power-splitting PON’s often support analog video overlay on separate wavelength
  - downstream BW for not used for broadcast video, packet-based STB’s not required
- Upgradable without changing fiber plant
FTTP Evolution: WDM PON

- Full, independent $\lambda$ to each subscriber
- WDM OLT handles all $\lambda$’s simultaneously -- $\lambda$’s are split to subs by external passive router
- Subscriber ONU’s are configured to transmit/receive on on their assigned $\lambda$
- Advantages: different bit rates/protocols/services for each sub, easy to upgrade sub without affecting others, good subscriber isolation, very high BW per sub possible

Low-cost, innovative WDM technologies are key to cost-effective unlimited broadband services to the home!
Figure 3 – A typical residential passive optical network using a single bidirectional fiber for all of the one-stop triple-play services: voice, data, and video. For businesses, bidirectional T1/E1 and T3 service for PBXs replaces the unidirectional TV service to set top boxes.
Coax to HFC
Coax to HFC

- Increase transport capability
- Improve quality and reliability

- Challenge for linear lightwave
→ DWDM transport for end-to-end transparency
→ Route diversity for service protection
→ Consolidate high-end terminals (CMTS)
Fiber Proves Deeper In The Network

Long Haul Network

Metropolitan Network

Metro Core

Metro Edge

Local Access Network

Last Mile Network

cell site

Trunk

Inter-Office

FBB

DLC

FSA

A/HFC

P/HF

C

FTTC

FTTH

Subscribers served by Optical Terminus


1 10 100 10,000 100,000

Avg. Homes

Min. Homes

Regression Line

Predicted

D. Keck

CORNING
SOURCES OF POWER

PENALTY
Figure 5.7: Dispersion-induced power penalty for a Gaussian pulse as a function of $B/LD\sigma_\lambda$. Source spectrum is also assumed to be Gaussian with an RMS width $\sigma_\lambda$. 
Figure 5.10: Chirp-induced power penalty as a function of $BLD\Delta\lambda_c$ for several values of the parameter $Bt_c$, where $\Delta\lambda_c$ is the wavelength shift occurring because of frequency chirp and $t_c$ is the duration of such a wavelength shift.
Figure 5.11: Chirp-induced power penalty as a function of $|\beta_2|B^2L$ for several values of the chirp parameter $C$. The Gaussian optical pulse is assumed to be linearly chirped over its entire width.
Figure 5.12: Power penalty as a function of the extinction ratio. (After Ref. [105]; ©1987 IEEE; reprinted with permission.)
5.4. SOURCES OF POWER PENALTY

Figure 5.13: Experimentally measured BER at 500 Mb/s for a VCSEL under optical feedback. The BER is measured at several feedback levels. (After Ref. [139]; ©1993 IEEE; reprinted with permission.)
computer-aided design
the end