Physical Layer
(part 3)
Transmission Media
Transmission Media Choices

- Twisted Pair
  - Dial-Up
  - ADSL
- Coaxial Cable
  - Baseband
  - Broadband
- Optical Fiber
  - Multimode step-index
  - Multimode graded-index
  - Single-mode step-index
- Wireless Communications
Transmission medium: the physical path between transmitter and receiver.

- Repeaters or amplifiers may be used to extend the length of the medium.
- Communication of electromagnetic waves is **guided** or **unguided**.

**Guided media:** waves are guided along a physical path (e.g., twisted pair, coaxial cable and optical fiber).

**Unguided media:** means for transmitting but not guiding electromagnetic waves (e.g., the atmosphere and outer space).
Figure 4.1 Electromagnetic Spectrum for Telecommunications
### Table 4.1 Point-to-Point Transmission Characteristics of Guided Media [GLOV98]

<table>
<thead>
<tr>
<th>Guided Media</th>
<th>Frequency Range</th>
<th>Typical Attenuation</th>
<th>Typical Delay</th>
<th>Repeater Spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Twisted pair (with loading)</td>
<td>0 to 3.5 kHz</td>
<td>0.2 dB/km @ 1 kHz</td>
<td>50 µs/km</td>
<td>2 km</td>
</tr>
<tr>
<td>Twisted pairs (multipair cables)</td>
<td>0 to 1 MHz</td>
<td>0.7 dB/km @ 1 kHz</td>
<td>5 µs/km</td>
<td>2 km</td>
</tr>
<tr>
<td>Coaxial cable</td>
<td>0 to 500 MHz</td>
<td>7 dB/km @ 10 MHz</td>
<td>4 µs/km</td>
<td>1 to 9 km</td>
</tr>
<tr>
<td>Optical fiber</td>
<td>186 to 370 THz</td>
<td>0.2 to 0.5 dB/km</td>
<td>5 µs/km</td>
<td>40 km</td>
</tr>
</tbody>
</table>

THz = TeraHertz = $10^{12}$ Hz
Twisted Pair

- Two insulated wires arranged in a spiral pattern.
- Copper or steel coated with copper.
- The signal is transmitted through one wire and a ground reference is transmitted in the other wire.
- Typically twisted pair is installed in building telephone wiring.
- Local loop connection to central telephone exchange was twisted pair.
Twisted Pair

- Limited in distance, bandwidth and data rate due to problems with attenuation, interference and noise.
  - Issue: *cross-talk* due to interference from other signals.
  - “shielding” wire (shielded twisted pair (STP)) with metallic braid or sheathing reduces interference.
  - “twisting” reduces low-frequency interference and crosstalk.
Twisted Pair

Fig 2-3. (a) Category 3 UTP  
(b) Category 5 UTP

Obsolete
Twisted Pair Transmission Characteristics

**analog**
- needs amplifiers every 5km to 6km

**digital**
- can use either analog or digital signals
  - needs a repeater every 2km to 3km

**limited:**
- distance
- Bandwidth ???
- data rate ???

susceptible to interference and noise
10 Mbps baseband transmission over **twisted pair**. Two Cat 3 cables, Manchester encoding, Maximum distance - 100 meters
### Table 4.2 Twisted Pair Categories and Classes

<table>
<thead>
<tr>
<th></th>
<th>Category 5e Class D</th>
<th>Category 6 Class E</th>
<th>Category 6A Class E&lt;sub&gt;A&lt;/sub&gt;</th>
<th>Category 7 Class F</th>
<th>Category 7&lt;sub&gt;A&lt;/sub&gt; Class F&lt;sub&gt;A&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bandwidth</strong></td>
<td>100 MHz</td>
<td>250 MHz</td>
<td>500 MHz</td>
<td>600 MHz</td>
<td>1,000 MHz</td>
</tr>
<tr>
<td><strong>Cable Type</strong></td>
<td>UTP</td>
<td>UTP/FTP</td>
<td>UTP/FTP</td>
<td>S/FTP</td>
<td>S/FTP</td>
</tr>
<tr>
<td><strong>Insertion loss</strong></td>
<td>24</td>
<td>21.3</td>
<td>20.9</td>
<td>20.8</td>
<td>20.3</td>
</tr>
<tr>
<td>(dB)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>NEXT loss</strong></td>
<td>30.1</td>
<td>39.9</td>
<td>39.9</td>
<td>62.9</td>
<td>65</td>
</tr>
<tr>
<td>(dB)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ACR (dB)</strong></td>
<td>6.1</td>
<td>18.6</td>
<td>19</td>
<td>42.1</td>
<td>44.1</td>
</tr>
</tbody>
</table>

UTP = Unshielded twisted pair  
FTP = Foil twisted pair  
S/FTP = Shielded/foil twisted pair
Grade 1 - Unshielded Untwisted wiring.
  Commonly called inside wire by the Telco community.

Grade 2 - Unshielded twisted pair (UTP) derived from IBM Type 3 spec.

Category 3 - Unshielded twisted pair with 100 ohm impedance and electrical characteristics supporting transmission at frequencies up to 16 MHz. May be used with 10Base-T, 100Base-T4, and 100Base-T2 Ethernet. (Obsolete)

Category 4 - Unshielded twisted pair with 100 ohm impedance and electrical characteristics supporting transmission at frequencies up to 20 MHz. May be used with 10Base-T, 100Base-T4, and 100Base-T2 Ethernet. (Obsolete)

Category 5 - Unshielded twisted pair with 100 ohm impedance and electrical characteristics supporting transmission at frequencies up to 100 MHz. May be used with 10Base-T, 100Base-T4, 100Base-T2, and 100Base-TX Ethernet. May support 1000Base-T, but cable should be tested. (Superceded by Cat5e)
Category 5e - "Enhanced Cat 5" exceeds Cat 5 performance. Very similar to Cat 5, it has improved specifications for NEXT (Near End Cross Talk), PSELFEXT (Power Sum Equal Level Far End Cross Talk), and attenuation. May be used for 10Base-T, 100Base-T4, 100Base-T2, 100BaseTX and 1000Base-T Ethernet. (Minimum acceptable wiring grade)

Category 6 - TIA approved Cat 6 specification in 2002 with bandwidth to 250 MHz. Backward compatible with lower Categories, Cat 6 supports the same Ethernet standards as Cat 5e and uses two pair in each direction as opposed to all four for 1000Base-T over Cat 5e. This cable standard is suitable for 10BASE-T, 100BASE-TX (Fast Ethernet), 1000BASE-T/1000BASE-TX (Gigabit Ethernet) and 10GBASE-T (10-Gigabit Ethernet).

Category 6a - Category 6a (or Augmented Category 6) The latest TIA standard from the TIA is defined at frequencies up to 500 MHz. May be used for 10/100/1000BASE-T and 10GBASE-T.

Category 7 - Proposed standard to support transmission at frequencies up to 600 MHz over 100 ohm twisted pair.
NOTES:

1) EIA 568 limits UTP copper cabling to maximum distance of 100 meters (328 feet). 90 meters of cable plus 10 meters of patch cord split between both ends.

2) The FCC recently changed the requirement for telephone inside wiring to minimum of Cat 3 due to crosstalk problems with nontwisted quad-four. Cat 3 is no longer recognized by TIA. The minimum wiring grade for structured wiring is Cat 5e.

3) For installation to meet specific Category requirements all components must meet or exceed the designated Category. Using a Cat 3 receptacle (or patch cord) on Cat 6 reduces performance to Cat 3.
Category 7/Class F

Figure-1 S/FTP Cable

Supports 10GBASE-T
Dial-up Modem

- Uses existing telephony infrastructure
  - Home is connected to central office.
- Up to 56Kbps direct access to router (often less).
- Can’t surf and phone at same time: not “always on”.

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Advanced Computer Networks  Transmission Media
Telephone companies originally transmitted within the 0 to 4K HZ range to reduce crosstalk. Loading coils (small amplifiers) were added within the subscriber loop to provide a flatter transfer function to further improve voice transmission within the 3K HZ band while increasing attenuation at the higher frequencies.

**ADSL** (Asymmetric Digital Subscriber Line)
- Uses existing twisted pair lines to provide higher bit rates that are possible with *unloaded twisted pairs* (i.e., there are no loading coils on the subscriber loop.)
ADSL

The network transmits downstream at speeds ranging from 1.536 Mbps to 9 Mbps.

Asymmetric
Bidirectional
digital
transmissions
[higher frequencies]

Users transmit upstream at speeds ranging from 16 kbps to 640 kbps.

0 to 4K Hz

Used for conventional analog telephone signals.
Figure 2-28. Operation of **ADSL** using discrete multitone modulation.
ITU-T G992.1 ADSL standard uses Discrete Multitone (DMT) that divides the bandwidth into a large number of small subchannels.

A splitter is required to separate voice signals from the data signal.

The binary information is distributed among the subchannels. Each subchannel uses QAM.

DMT adapts to line conditions by avoiding subchannels with poor SNR.
Figure 2-29. A typical ADSL equipment configuration.
Digital Subscriber Line (DSL)

- Also uses existing telephone infrastructure.
- up to 1 Mbps upstream (today typically < 256 kbps)
- up to 9 Mbps downstream (today typically < 1 Mbps)
- dedicated physical line to telephone central office.
# Comparison of xDSL Alternatives

<table>
<thead>
<tr>
<th></th>
<th>ADSL</th>
<th>HDSL</th>
<th>SDSL</th>
<th>VDSL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Data rate</strong></td>
<td>1.5 to 9 Mbps downstream</td>
<td>1.544 or 2.048 Mbps</td>
<td>1.544 or 2.048 Mbps</td>
<td>13 to 52 Mbps downstream</td>
</tr>
<tr>
<td></td>
<td>16 to 640 kbps upstream</td>
<td></td>
<td></td>
<td>1.5 to 2.3 Mbps upstream</td>
</tr>
<tr>
<td><strong>Mode</strong></td>
<td>Asymmetric</td>
<td>Symmetric</td>
<td>Symmetric</td>
<td>Asymmetric</td>
</tr>
<tr>
<td><strong>Copper pairs</strong></td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>Range (24-gauge UTP)</strong></td>
<td>3.7 to 5.5 km</td>
<td>3.7 km</td>
<td>3.0 km</td>
<td>1.4 km</td>
</tr>
<tr>
<td><strong>Signaling</strong></td>
<td>Analog</td>
<td>Digital</td>
<td>Digital</td>
<td>Analog</td>
</tr>
<tr>
<td><strong>Line code</strong></td>
<td>CAP/DMT</td>
<td>2B1Q</td>
<td>2B1Q</td>
<td>DMT</td>
</tr>
<tr>
<td><strong>Frequency</strong></td>
<td>1 to 5 MHz</td>
<td>196 kHz</td>
<td>196 kHz</td>
<td>≥ 10 MHz</td>
</tr>
<tr>
<td><strong>Bits/cycle</strong></td>
<td>Varies</td>
<td>4</td>
<td>4</td>
<td>Varies</td>
</tr>
</tbody>
</table>
VDSL

1.4 Km twisted pair limit
Coaxial Cable

- Center conductor
- Dielectric material
- Braided outer conductor
- Outer cover
Coaxial Cable

- Discussion divided into two basic categories for coax used in LANs:
  - 50-ohm cable [baseband]
  - 75-ohm cable [broadband or single channel baseband]

- In general, coaxial cable has better noise immunity for higher frequencies than twisted pair.

- Coaxial cable provides much higher bandwidth than twisted pair.

- However, the cable is ‘bulky’.
Baseband Coax

- 50-ohm cable is used exclusively for digital transmissions.
- Uses Manchester encoding, geographical limit is a few kilometers.

**10Base5 Thick Ethernet**: thick (10 mm) coax
10 Mbps, 500 m. max segment length, 100 devices/segment, awkward to handle and install.

**10Base2 Thin Ethernet**: thin (5 mm) coax
10 Mbps, 185 m. max segment length, 30 devices/segment, easier to handle, uses T-shaped connectors.
- 75-ohm cable (CATV system standard).
- Used for both analog and digital signaling.
- Analog signaling – frequencies up to 500 MHZ are possible.
- When FDM used, referred to as broadband.
- For long-distance transmission of analog signals, amplifiers are needed every few kilometers.
Residential Access: Cable Modems

- Does not use telephone infrastructure.
  - Instead uses cable TV infrastructure.

- **HFC: Hybrid Fiber Coax**
  - asymmetric: up to 30Mbps downstream, 2 Mbps upstream

- A **network** of cable and fiber attaches homes to ISP router.
  - homes **share access** to router.
  - unlike DSL, which provides **dedicated access**.
Residential Access: Cable Modems

Diagram: http://www.cabledatkomnews.com/cmic/diagram.html
Cable Network Architecture: Overview

Typically 500 to 5,000 homes

cable headend

cable distribution network (simplified)

home

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Cable Network Architecture: Overview

- Cable headend
- Server(s)
- Cable distribution network
- Home

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Cable Network Architecture: Overview

- **Cable Headend**: Sends signals to the cable distribution network.
- **Cable Distribution Network (Simplified)**: Distributes signals to homes.
- **Home Environment**: Includes a Set-Top Box, TV, Cable Modem, and PC.
- **Transmission Media**: Uses Coaxial cable and 10 Mbps Ethernet.
Cable Network Architecture: Overview

FDM

channels

1 2 3 4 5 6 7 8 9

Cable headend

Cable distribution network

Home

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Higher Cable Capacities

Cisco DOCSIS 3.0 Solution

uBR100012 CMTS

<15K Subs/Hub
RFGW 1 EQAM
Up to 48 QAM Channels

HFC

>15K Subs/Hub
RFGW 10 EQAM
> 480 QAM Channels

DPC3202 eMTA
(4 channels)

DPC3000 DOCSIS 3.0
Cable Modem
(4 channels)

Figure 4. M-CMTS and DOCSIS 3.0 Downstream Channel Bonding
Optical Fiber

- **Optical fiber**: a thin flexible medium capable of conducting optical rays. Optical fiber consists of a very fine cylinder of glass (core) surrounded by concentric layers of glass (cladding).
- A signal-encoded beam of light (a fluctuating beam) is transmitted by **total internal reflection**.
- Total internal reflection occurs in the core because it has a higher optical density (index of refraction) than the cladding.
- Attenuation in the fiber can be kept low by controlling the impurities in the glass.
Optical Fiber

(a) Geometry of optical fiber

(b) Reflection in optical fiber
Optical Fiber

- Lowest signal losses are for ultrapure fused silica—but this is hard to manufacture.

- Optical fiber acts as a wavelength guide for frequencies in the range $10^{14}$ to $10^{15}$ Hz which covers the visible and part of the infrared spectrum.

- Three standard wavelengths: 850 nanometers (nm.), 1300 nm, 1500 nm.

- First-generation optical fiber: 850 nm, 10's Mbps using LED (light-emitting diode) sources.

- Second and third generation optical fiber: 1300 and 1500 nm using ILD (injection laser diode) sources, gigabits/sec.
Optical Fiber

- Attenuation loss is **lower** at higher wavelengths and affected by **absorption** and **scattering** of light rays.

- There are two types of detectors used at the receiving end to convert light into electrical energy (photo diodes):
  - PIN detectors - less expensive, less sensitive
  - APD detectors - Avalanche PhotoDiodes (long haul fiber systems)

- ASK is commonly used to transmit digital data over optical fiber {referred to as intensity modulation}. 
Attenuation in Guided Media

(a) Twisted pair (based on [REE95])

(b) Coaxial cable (based on [BELL90])

(c) Optical fiber (based on [FREE02])

(d) Composite graph

DCC 9th Ed. Stallings
Wavelength Division Multiplexing

Figure 2-32.
Optical Fiber

- Three techniques:
  - Multimode step-index
  - Multimode graded-index
  - Single-mode step-index

- Presence of multiple paths $\Rightarrow$ differences in delay $\Rightarrow$ optical rays *interfere* with each other $\Rightarrow$ spacing needed between light pulses.

- A **narrow core** can create a single direct path which yields higher speeds.

- WDM (Wavelength Division Multiplexing) yields more available capacity.
Optical Fiber Transmission Modes

(a) Step-index multimode

(b) Graded-index multimode

(c) Single mode
## Frequency Utilization for Fiber Applications

<table>
<thead>
<tr>
<th>Wavelength (in vacuum) range (nm)</th>
<th>Frequency Range (THz)</th>
<th>Band Label</th>
<th>Fiber Type</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>820 to 900</td>
<td>366 to 333</td>
<td></td>
<td>Multimode</td>
<td>LAN</td>
</tr>
<tr>
<td>1280 to 1350</td>
<td>234 to 222</td>
<td>S</td>
<td>Single mode</td>
<td>Various</td>
</tr>
<tr>
<td>1528 to 1561</td>
<td>196 to 192</td>
<td>C</td>
<td>Single mode</td>
<td>WDM</td>
</tr>
<tr>
<td>1561 to 1620</td>
<td>192 to 185</td>
<td>L</td>
<td>Single mode</td>
<td>WDM</td>
</tr>
</tbody>
</table>
Internet

OLT

central office

optical fiber

optical splitter

ont

ont

ont

homes

optical fibers

- Optical links from central office to the home
- Two competing optical technologies:
  - Passive Optical network (PON)
  - Active Optical Network (AON)
- Much higher Internet rates. Fiber also carries television and phone services.

Verizon FIOS

K & R
• An application of omni-directional wireless communications to provide high-speed communications among a number of computers located in close proximity.

• In 1996 FCC in US announced its intentions to make 350 MHz of spectrum in the 5.15 to 5.35 GHz and 5.725 to 5.825 GHz bands available for unlicensed use in LAN applications.
Figure 4.1 Electromagnetic Spectrum for Telecommunications
Wireless Access Networks

- **shared wireless access network** connects end system to router
  - via base station aka “access point”

- **Wireless LANs:**
  - 802.11b/g/n (WiFi): 11, 54, 100’s Mbps, Bluetooth, Zigbee (802.15.4)

- **Wide Area Wireless Access:**
  - provided by telco operator
  - ~1Mbps over cellular system (EVDO, HSDPA, 4G LTE)
  - next up (?): WiMAX (10’s Mbps) over wide area
Wireless Multipath Interference

(a) Microwave line of sight

(b) Mobile radio

Figure 4.11 Examples of Multipath Interference
Typical residential network components:

- DSL or cable modem
- Router/firewall/NAT
- Ethernet
- Wireless access point (AP)
Transmission Media Summary

- **Twisted pair**
  - Noise, interference and attenuation are issues.
  - Cat5e modern required minimum (Fast Ethernet)
  - Dial-Up and DSL (ADSL) Connections

- **Coaxial cable**
  - Baseband versus Broadband
  - Cable is HFC (Hybrid Fiber-Coax)
  - FDM and asymmetric channel capacities
Transmission Media Summary

- **Optical Fiber**
  - Wavelength Division Multiplexing of light
  - Very High Capacities
  - Three standard wavelengths
  - Three standard techniques
  - Fiber to the home

- **Wireless Communications**
  - ‘crowded’ frequency spectrum
  - WLAN and Wide Area wireless
  - Common Residential ‘Last Hop’ to the Internet involves wireless AP (router, firewall, NAT).