2.2 Guided Transmission Media

- Magnetic
- Twisted Pair
- Coaxial
- Power Line
- Fiber Optic
Magnetic media = tapes, HDDs

Send data on tape / disk / DVD for a high bandwidth link
- Mail one box with 1000 800GB tapes (6400 Tbit)
- Takes one day to send (86,400 secs)
- Data rate is 70 Gbps.

Have you seen this ‘network’ before? What is the problem?

Answer: bad (very long) latency!

https://aws.amazon.com/snowmobile/
A data center has a 10 Gbps fiber Internet connection (~ $900/mo) and stores 10 PB (1/10 the capacity of an Amazon Snowmobile).

How long would it take to transfer all the data?
QUIZ: Is it really worth it?

A data center has a 10 Gbps fiber Internet connection (~ $900/mo) and stores 10 PB (1/10 the capacity of an Amazon Snowmobile).

How long would it take to transfer all the data?

\[
\begin{align*}
10 \text{ PB} &= 10 \times (1024)^5 \times 8 \text{ bits} \\
10 \text{ Gbps} &= 10 \times (1000)^3 \text{ bits/s}
\end{align*}
\]

Ratio: \[8,388,608 \text{ s} = 2,330 \text{ hours} = 97 \text{ days} > 3 \text{ months}!\]
Moral of this exercise:

For all media, there are many characteristics to consider when designing a transmission system:

- Throughput
- Latency
- Noise immunity $\iff$ bit-error rate (BER)
- Cost of equipment
- Cost/ease of installation
- Cost/ease of maintenance
- Security (how easy is it to eavesdrop?)
Twisted Pair Cable

(a) Category 3 UTP.
(b) Category 5 UTP.

UTP = Unshielded Twisted Pair
## UTP Cable Today: UTP, FTP, STP, SFTP

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>UTP</strong></td>
<td>Unshielded Twisted Pair</td>
<td><img src="image1" alt="UTP Cable" /></td>
</tr>
<tr>
<td><strong>FTP</strong></td>
<td>Foiled Twisted Pair</td>
<td><img src="image2" alt="FTP Cable" /></td>
</tr>
<tr>
<td><strong>S/UTP &amp; F/UTP</strong></td>
<td>Shielded/ Screened or Foiled Unshielded Twisted Pair</td>
<td><img src="image3" alt="S/UTP Cable" /></td>
</tr>
<tr>
<td><strong>S/FTP</strong></td>
<td>Shielded and Foiled Twisted Pair</td>
<td><img src="image4" alt="S/FTP Cable" /></td>
</tr>
</tbody>
</table>

**UTP**
The UTP cable consists of pairs of wires twisted together. This is one of the most basic methods used to help prevent electromagnetic interference.

**FTP**
FTP offers an additional layer of protection with shielding (also called screening) wrapped around the individual twisted wires. This protects against EMI/FRI and crosstalk.

**S/UTP & F/UTP**
This has an overall foil or braid screen covering the 4 pairs of unshielded twisted pairs.

**S/FTP**
A combination of the two above, with foil shielding around the individual twisted wires and an overall screen which can sometimes be a flexible braid. This provides the maximum level of protection from interference and is found in the highest performance cables.

Source: [https://www.universalnetworks.co.uk/faq/copper/what-does-utp-ftp-stp-or-sftp-mean](https://www.universalnetworks.co.uk/faq/copper/what-does-utp-ftp-stp-or-sftp-mean)
“UTP” Cable Use Today

Cat 5e and Cat 6 are widely available for GE (1 Gbps Ethernet). Cat 6a and Cat 7 are being deployed for 10GE (10 Gbps Ethernet). Cat 7a can also be used for 10GE.
Cat 3 Cable – Supports 10 Base-T Standard for bandwidths up to 10 Mbps over a maximum distance of 100 meters. They can support frequencies in the range of 0-10 Mhz.

Cat 5/5E Cable – Supports 100 Base-T Standard for bandwidths up to 100 Mbps over a maximum distance of 100 meters. They can support frequencies in the range of 0-100 Mhz. Cat 5E cables can support 1000 Base-T as well.

Cat 6 Cable – Supports 1000 Base-T Standard for bandwidths up to 1000 Mbps over a maximum distance of 100 meters. Cat 6 standard can support frequencies in the range of 0-250 Mhz. They also support 10GE bandwidth over limited distances.

Cat 6A Cable – Supports 10G Base-T standard for bandwidths up to 10 Gbps over a maximum distance of 100 meters. Cat 6A standard can support frequencies in the range of 0-500 Mhz.

Cat 7 Cable – Supports 10G Base-T standard for bandwidths up to 10 Gbps over a maximum distance of 100 meters. Cat 7 standard can support frequencies in the range of 0-600 Mhz. It offers better performance and improved cross talk suppression over the Cat 6A cables.

Cat 7A Cable – Supports 10G Base-T standard for bandwidths up to 10 Gbps over a maximum distance of 100 meters. In addition to this, they can also support 40 Gbps bandwidth for around 50 meters and 100 Gbps bandwidth for around 15 meters. They support frequencies in the range of 0-1000 Mhz.

Source: http://www.excitingip.com/847/know-your-cat-5-6-7-unshielded-twisted-pair-utp-network-cables/
Cat7 cable has shielding for individual wire pairs and for the cable as a whole.

It transmits frequencies up to 600Mhz over 100m (suitable for 10Gbps Ethernet)
Coaxial Cable

Real-world applications:
- Cable TV (75-ohm) → lately Internet over cable
- Native digital MANs (50-ohm)  
  Bw: 1GHz over a few km → @8bit/Hz can transmit a few Gbps  
  Excellent noise immunity (low BER)
A network that uses household electrical wiring.

It is today possible to achieve 100 Mbps with commercial systems.
Fiber Optics

Common for high rates and long distances
- Long distance ISP links, Fiber-to-the-Home
- Light carried in very long, thin strand of glass

Never do this!
Fiber Optics

What happens when we bend a fiber too sharply?
Fiber Optics

Total internal reflection [Source: Wikipedia]
Fiber Optics

Multi-mode vs. single-mode
In single mode it is possible to transmit 100 Gbps over 100 km!

When sufficiently thin, the fiber acts as a waveguide!

The basic formula of Fiber Optics

\[ \lambda f = c \]

Speed of light in the respective medium, not necessarily vacuum!

<table>
<thead>
<tr>
<th>Material</th>
<th>Propagation velocity (fraction of speed of light in a vacuum)</th>
<th>Index of refraction</th>
<th>Velocity of signal (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical fiber</td>
<td>.68</td>
<td>1.46</td>
<td>205,000</td>
</tr>
<tr>
<td>Flint glass</td>
<td>.58</td>
<td>1.71</td>
<td>175,000</td>
</tr>
<tr>
<td>Water</td>
<td>.75</td>
<td>1.33</td>
<td>226,000</td>
</tr>
<tr>
<td>Diamond</td>
<td>.41</td>
<td>2.45</td>
<td>122,000</td>
</tr>
<tr>
<td>Air</td>
<td>.99971</td>
<td>1.00029</td>
<td>299,890</td>
</tr>
<tr>
<td>Copper wire (category 5 cable)</td>
<td>.77</td>
<td>N/A</td>
<td>231,000</td>
</tr>
</tbody>
</table>

Propagation in fiber is slower than in copper!
Transmission of Light through Fiber

Attenuation of light through fiber in the infrared region.

The three bands shown have been chosen b/c attenuation is more or less constant inside each.
Can you see it?

Never point an optic fiber at your (or anyone else’s) face!!
7. How much bandwidth is there in 0.1 microns of spectrum at a wavelength of 1 micron?

Hint: Take $\lambda_1 = 0.95 \, \mu m$, $\lambda_2 = 1.05 \, \mu m$, and calculate $f_1$, $f_2$ using eq. 2-4.
7. How much bandwidth is there in 0.1 microns of spectrum at a wavelength of 1 micron?

\[ \lambda f = c \]

\[ f_{\text{low}} = \frac{2 \times 10^8}{1.05 \times 10^{-6}} = \frac{2}{1.05 \times 10^{14}} \text{ Hz} \]

\[ = 190.476 \text{ THz} \]

Calculate \( f_{\text{high}} \) and subtract to find the bandwidth.
7. How much bandwidth is there in 0.1 microns of spectrum at a wavelength of 1 micron?

Use Eq. (2-4) to convert wavelengths of 1 micron plus/minus 0.05 microns to frequency. We have \( f_{\text{low}} = \frac{2 \times 10^8}{1.05 \times 10^{-6}} = 2/1.05 \times 10^{14} \). Similarly \( f_{\text{high}} = 2/0.95 \times 10^{14} \). Thus \( \Delta f = (2/0.95 - 2/1.05) \times 10^{14} = 2 \times 10^{13} \). This is a bandwidth of 20,000 GHz. = 20 THz
QUIZ: If the entire 0.1 micron is used as one channel, what is the Shannon limit?

Max data rate [bps] = \( B \log_2(1+S/N) \)

What else do we need to know in order to apply Shannon's eqn. ?

For optical fiber links of lengths up to 100 km (interconnecting data centers in an urban area), a SNR of 30 dB is achievable. What is the ratio S/R?
QUIZ: If the entire 0.1 micron is used as one channel, what is the Shannon limit?

$S/R = 10^3 \rightarrow 20 \cdot 10^{15} \cdot \log_2(10^3) \approx 200 \text{ Tbps}$

In contrast, the highest speeds being deployed today (2019) over 100 km are 400 Gbps.
Spectral Efficiency, the Non-linear Shannon Limit, and the coming “Capacity Crunch” for Fiber

Because of non-linear effects that are specific to fiber, the SNR cannot be increased indefinitely. There is another theoretical limit of about 10 bps/Hz (spectral efficiency), no matter how large SNR is:

For more details:


From 2019:
QUIZ: What is the attenuation of an optical signal with wavelength 1.3 micron, over a 50-km distance?

Attenuation (dB/km) = $10 \times \log_{10} \left( \frac{\text{Input intensity (W)}}{\text{Output intensity (W)}} \right)$
QUIZ: What is the attenuation of an optical signal with wavelength 1.3 micron, over a 50-km distance?

Hint: $50 \text{ km} \cdot 0.2 \text{ dB/km} = 10 \text{ dB}$

Use this to calculate the ratio of powers.
QUIZ: What is the attenuation of an optical signal with wavelength 1.3 micron, over a 50-km distance?

10 = Input/Output → Output = Input/10
The output power is 10 times smaller than the input power.
Fiber Optics

Traditional modulation method = IM (Intensity mod.)
• repeaters needed (for regeneration of signal) every 28-43 mi (45-70 km)
• compare with 3 mi (5 km) for copper

Repeater “huts” are installed and maintained by the telecomms companies that use the “right-of-way” along railway tracks

Image source: http://position-light.blogspot.com/2013/03/photos-vine-and-locust.html
Fiber Optics

Spreading of the signal is called **chromatic dispersion**, but the slight **non-linearity** of the fiber makes possible a shape of the pulse that can propagate 1000s of km w/o distortion – **soliton** (not widely deployed in the field yet).

Discovered by **John Scott Russell** in 1834 in a water channel in Scotland!

Fiber Cables

(a) Side view of a single fiber.
(b) End view of a sheath with three fibers.

Advantages over copper: lightweight (esp. bandwidth/weight), low attenuation, no leakage, difficult to tap.
Disadvantages: less familiar, harder to make connections, easily broken if bent too much.
Fiber Cables

## Transmitters and receivers for fiber

<table>
<thead>
<tr>
<th>Item</th>
<th>LED</th>
<th>Semiconductor laser</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data rate</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Fiber type</td>
<td>Multimode</td>
<td>Multimode or single mode</td>
</tr>
<tr>
<td>Distance</td>
<td>Short</td>
<td>Long</td>
</tr>
<tr>
<td>Lifetime</td>
<td>Long life</td>
<td>Short life</td>
</tr>
<tr>
<td>Temperature sensitivity</td>
<td>Minor</td>
<td>Substantial</td>
</tr>
<tr>
<td>Cost</td>
<td>Low cost</td>
<td>Expensive</td>
</tr>
</tbody>
</table>

A comparison of semiconductor diodes and LEDs as light sources.

Reception is simple: photodiode!

Image source: http://en.wikipedia.org/wiki/Photodiode
A fiber optic ring with active repeaters.
What is “OEO conversion”?
2.3 Wireless (Unguided) Transmission

Wireless digital networks started in Hawaii, due to the difficulty of installing cables among the islands → ALOHA

(more in Ch.4)
The Electromagnetic Spectrum

Very, Ultra, Super, Extremely, Tremendously 😊
Narrowband techniques

Most transmissions use a relatively narrow band of frequencies

\[ \frac{\Delta f}{f_{\text{center}}} \ll 1 \]

Example: 802.11g channels can be 20 or 40 MHz wide, with frequencies around either 2.4 or 5.7 GHz.

• Calculate the maximum \( \Delta f/f \)

The maximum of a ratio is obtained for max. numerator and min. denominator: \( \Delta f/f = 40 \text{ MHz} / 2.4 \text{ GHz} = 0.0166 \)
Wideband techniques

UWB:
• Sends a series of rapid pulses, changing their position in the frequency band to encode information.
• FCC and ITU define UWB in terms of a transmission from an antenna for which the emitted signal bandwidth exceeds the lesser of 500 MHz or 20% of the center frequency.
• It is standardized for PANs (802.15 – Bluetooth, Zigbee)
UWB definition: the emitted signal bandwidth exceeds the lesser of 500 MHz or 20% of the center frequency.

What is the minimum bandwidth needed to qualify as UWB if
• the band used is centered at 5 GHz?
• the band used is centered at 1 GHz?
UWB definition: the emitted signal bandwidth exceeds the lesser of 500 MHz or 20% of the center frequency.

What is the minimum bandwidth needed to qualify as UWB if
- the band used is centered at 5 GHz?

Applying $\Delta f/f = 0.2$ for $f = 5$ GHz, we get $\Delta f = 1$ GHz. This is greater than 500 MHz, so 500 MHz is the lesser. The Bw needs to be greater than 500 MHz, so 4.75 GHz - 5.25 GHz or wider will do.
UWB definition: the emitted signal bandwidth exceeds the lesser of 500 MHz or 20% of the center frequency.

What is the minimum bandwidth needed to qualify as UWB if

- the band used is centered at 1 GHz?

Applying $\Delta f/f = 0.2$ for $f = 1$ GHz, we get $\Delta f = 200$ MHz. This is lower than 500 MHz, so 200 MHz is the lesser. The Bw needs to be greater than 200 MHz, so 0.8 GHz - 1.2 GHz or wider will do.
Radio Transmission: VLF, LF, MF

- Main application: AM radio
- Waves follow ground (ground wave range ~ 1000 km), pass through buildings, diffract around large obstacles (e.g. hills, valleys).
- Problem: low bandwidth for transmitting data.
Radio Transmission: HF, VHF

- Applications: FM radio (65-108 MHz), ham radio, military comms., over-the-air TV channels 2-13 (54 - 216 MHz)
- Waves are absorbed by ground → no ground wave, but they still pass through buildings and diffracts around large obstacles.
- Problem: range ~ 80km (line-of-sight limited by horizon)
- Waves also bounce off the ionosphere (sky wave), but this is unreliable, so not useful for industry-strength network.
Radio Transmission: UHF

- Application: over-the-air TV channels 14 -18 (479 - 890 MHz)
- Waves do not bend around obstructions as readily as VHF. This is a particular problem for receivers located in depressions and valleys. VHF signals will be seen by antennas in the valley, whereas UHF bends about 1/10 as much, and far less signal will be received.

Diffraction depends on frequency...

A high frequency (short wavelength) microwaves -wave doesn't get diffracted much - the house won't be able to receive it...
Radio Transmission: SHF, EHF

a.k.a. microwave

At this frequency, waves travel in **straight lines**, if focused (parabolic antenna)
Microwave

- From 300 MHz (1m) to 300 GHz (1mm)
- **Pros:**
  - High SNR
  - Free-space, so no right of way needed
  - Cheaper to build towers than to dig for fiber
- **Cons:**
  - Alignment needed
  - Need line-of-sight. There are no ground waves, diffracting around obstacles, or bouncing off ionosphere.
  - Absorbed by buildings, rain (above 4GHz)
  - Multipath fading

Source: https://en.wikipedia.org/wiki/Parabolic_antenna
Microwave horn antennas

• Developed at Bell Labs in the 1950s for communications.
• In the 1960s and 1970s, this technology made possible the long-distance telephone system.

Part of the TD-2 AT&T Long Lines microwave relay system, created in 1955 to relay telephone calls, television shows, and other data from point to point in the US. The system uses C-band frequencies in two bands at 4 and 6 GHz.

Image source: https://commons.wikimedia.org/wiki/File:Hogg_horn_antennas.jpg
The max. distance (range) between repeaters (towers) is proportional with $\text{SQRT}(\text{height})$

• We know that the range is 80 km for $h = 100$ m
• What is the range for 50 m towers?
In 1965 while using this antenna, astronomers Penzias and Wilson discovered the microwave background radiation that permeates the universe.

Source: https://en.wikipedia.org/wiki/Holmdel_Horn_Antenna
Microwave history: MCI

MCI = Microwave Communications Inc.

AT&T in the 1970s had a government-supported monopoly in telephone service. MCI ordered interconnections from the local exchange carriers, which in most cases was a Bell Operating Company, owned by AT&T. The relationship between MCI and the Bell Operating companies were not that of a typical supplier and customer, as the local operating companies were generally reluctant to do business with a company that its parent was attempting to put out of business.

In a decision that became a turning point in the competitive telecommunications industry, Illinois Bell disconnected MCI circuits for what MCI believed was no other reason than to restrain trade. MCI filed an antitrust lawsuit against AT&T in 1974, and eventually changed the telecommunications industry. On June 13, 1980, a jury in Chicago awarded MCI 1.8 billion dollars in damages to be paid by AT&T. The suit, coupled with the Department of Justice antitrust suit also brought against AT&T, eventually led to the voluntary breakup of the Bell System.

[Source: Wikipedia]
Southern Pacific Communications Company (SPC) was a unit of the Southern Pacific Railroad

“The Railroad had an extensive microwave communications system along its rights of way used for internal communications; later, they expanded by laying fiber optic cables along the same rights of way. In 1972 they began selling surplus capacity on that system to corporations for use as private lines, thereby circumventing AT&T's then-monopoly on public telephony. Prior attempts at offering long distance voice services had not been approved by the Federal Communications Commission (FCC), although a fax service (called SpeedFAX) was permitted. SPC was only permitted to provide private lines, not switched services. When MCI released Execunet, SPC took the FCC to court to get the right to offer switched services, and succeeded (the "Execunet II" decision in 1978). They decided they needed a new name to differentiate the switched voice service from SpeedFAX, and ran an internal contest to select one. The winning entry was "Sprint", an acronym for Switched PRIvate Network Telecommunications.”

[Source: Wikipedia]
The ISM (Industrial, Scientific, Medical) bands in the US.

Under 1W → no license needed
Over 1W → need FCC license!

U-NII (Unlicensed National Information Infrastructure) bands

Pwr ≤ 250 mW

5.15-5.25 GHz
Pwr ≤ 50 mW
Regulated by the Office of Spectrum Management of the NTIA (National Telecomms and Information Administration)
Infrared

Limited to short distances (remotes)
Requires line-of-sight
No license required
The **Infrared Data Association** standard exists for connecting desktop devices, but it’s not very popular (Bluetooth “killed “it).
Lightwave (a.k.a. Free-space optics)

Convection currents can interfere with laser communication systems. A bidirectional system with two lasers is pictured here.
A laser beam 1 mm wide is aimed at a detector 100 mm wide, located 500 m away. What is the angular diversion (error) before the laser misses the detector completely?
Conclusion: Guided vs. unguided Tx

Wireless signals propagate much farther
interference
administration,
licensing, power limits
To do for next time for Section 2.3:

- Read **section 2.3** carefully, write down all new facts!
- Solve in notebook end-of-chapter problems 6, 7.
2.4 Communication Satellites

Read FYI (not required for exam)