Introduction to Communication Networks
The University of Kansas EECS 563
Physical Layer

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Communication Networks

Physical Layer

PL.1  Line Coding
PL.2  Signals and transmission
PL.3  Physical media
PL.4  Performance characteristics
Physical Layer

Physical Layer Communication

- Physical layer
  - is responsible for moving bits through a channel
**Physical Layer**

**Physical Layer Communication**

- Physical layer communicates digital information
  - through a communication *channel* in a *medium*
  - digital bits are *coded* as electronic or photonic *signals*
    - digital or analog coding
    - over a *link* between *nodes* (layer 2)
Physical Layer
Line Coding

PL.1 Line coding
PL.2 Signals and Transmission
PL.3 Physical media
PL.4 Performance characteristics
Physical Layer

Line Coding and Symbol Rate

- Digital Communication
  - we consider only *digital* communication for networking
    - transmission of binary data (bits) through a channel

- Line coding
  - way in which bits are encoded for transmission
  - digital codes (binary, trinary, ...)
  - analog modulation

- Symbol rate
  - baud rate [symbols/s]
    - baud = b/s only if one symbol/bit
  - clever encodings (e.g. QAM) allow high baud rates
Line Coding
Digital Code Types

• Code
  – level code
    • symbol depends on the voltage level (amplitude)
  – transition code
    • symbol depends on transition between levels
  – differential code
    • symbol depends on difference from last symbol
      – level or transition

• Polarity in electrical codes
  – unipolar: transitions between 0 and nonzero voltage
  – bipolar: transitions between a positive and negative voltage
Digital Line Coding
Binary Codes

- Binary line coding:
  - two voltage levels: high and low
  - bit rate = baud rate
- Binary amplitude code
  - 0 = low, 1 = high
  - clock rate = bit rate

Original text:

- Binary line coding:
  - two voltage levels: high and low
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Problems?
Digital Line Coding

Binary Codes

- **Binary line coding:**
  - two voltage levels: high and low
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- **Binary amplitude code**
  - 0 = low, 1 = high
  - clock rate = bit rate
  - problems: long runs of 0 or 1
    - DC bias
    - insufficient transitions for clock synchronisation
Digital Line Coding

Binary Codes

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    - DC bias
    - insufficient transitions for clock synchronisation

Alternatives?
properties?
Digital Line Coding

Binary Codes

- Binary line coding:
  - two voltage levels: high and low
  - bit rate = baud rate
- Binary amplitude code
  - 0 = low, 1 = high
- Manchester coding
  - 0 = low → high
Digital Line Coding

Binary Codes

- Binary line coding:
  - two voltage levels: high and low
  - bit rate = baud rate

- Binary amplitude code
  - 0 = low, 1 = high

- Manchester coding
  - 0 = low → high, 1 = high → low
  - clock rate = 2 × bit rate
  - no DC bias
  - ensures at least one transition per clock cycle

<table>
<thead>
<tr>
<th>0</th>
<th>0</th>
<th>1</th>
<th>0</th>
<th>0</th>
<th>1</th>
<th>0</th>
<th>1</th>
<th>1</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tr>
</tbody>
</table>
Digital Line Coding

Binary Codes

- **Binary line coding:**
  - two voltage levels: high and low
  - bit rate = baud rate

- **Binary amplitude code**
  - 0 = low, 1 = high

- **Manchester coding**
  - 0 = low → high, 1 = high → low

- **Differential Manchester coding**
  - transition=0, none=1
Line Coding
Analog Coding

- Analog line coding
  - modulate an *analog carrier* with a *digital signal*
Analog Line Coding
Amplitude Modulation

- Analog line coding
  - modulate an analog carrier

- Amplitude modulation
  - each symbol a different level of carrier
    - one may be zero voltage
  - compare to AM radio
    - modulate an analog carrier with an analog signal
Analog Line Coding

Frequency Modulation

• Analog line coding
  – modulate a *carrier*

• Amplitude modulation
  – each symbol a different level

• Frequency modulation
  – each symbol a different frequency
  – FSK (frequency shift keying)
  – compare to FM radio
    • modulate an analog carrier with an *analog* signal
Analog Line Coding

V.21 AFSK

- AFSK analog modem line coding
  - AFSK (audio frequency shift keying)
  - modem (modulate / demodulate)
- ITU V.21 300 baud = 300b/s (1964 – 1980s)
  - full duplex: one channel for each direction
  - frequencies within audio spectrum of POTS telephone line

why?
Analog Line Coding
V.21 AFSK

- AFSK analog modem line coding
  - AFSK (audio frequency shift keying)
  - modem (modulate / demodulate)
- ITU V.21 300 baud = 300b/s (1964 – 1980s)
  - full duplex: one channel for each direction
  - frequencies within audio spectrum of POTS telephone line
  - motivation: transport data over existing phone lines
  - old timers recall modem squeal

<table>
<thead>
<tr>
<th>Channel</th>
<th>Carrier</th>
<th>0 Symbol</th>
<th>1 Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1080 Hz</td>
<td>1180 Hz</td>
<td>980 Hz</td>
</tr>
<tr>
<td>2</td>
<td>1750 Hz</td>
<td>1850 Hz</td>
<td>1650 Hz</td>
</tr>
</tbody>
</table>
Analog Line Coding

DTMF

- DTMF (dual tone multi-frequency)
  - AMFSK (audio multi-frequency shift keying)
- PSTN in-band signalling
  - handset (user–network) and network–network
- Design goals
  - within PSTN audio spectrum
  - not a binary code: symbols include all decimal numbers
  - MPSK
    - multiple frequencies
    - two frequencies per symbol
    - avoid harmonics that could lead to false symbol decoding
Analog Line Coding

DTMF

- DTMF (dual tone multi-frequency)
  - AMFSK (audio multi-frequency shift keying)
- PSTN in-band signalling

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>440 Hz</th>
<th>480 Hz</th>
<th>620 Hz</th>
<th>1209 Hz</th>
<th>1336 Hz</th>
<th>1477 Hz</th>
<th>1633 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>350 Hz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>440 Hz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>480 Hz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>697 Hz</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>A</td>
</tr>
<tr>
<td>770 Hz</td>
<td></td>
<td></td>
<td></td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>B</td>
</tr>
<tr>
<td>852 Hz</td>
<td></td>
<td></td>
<td></td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>C</td>
</tr>
<tr>
<td>941 Hz</td>
<td></td>
<td></td>
<td></td>
<td>*</td>
<td>0</td>
<td>#</td>
<td>D</td>
</tr>
</tbody>
</table>
Analog Line Coding

Phase Modulation

- Analog line coding
  - modulate a *carrier*
- Amplitude modulation
  - each symbol a different level
- Frequency modulation
  - each symbol a different frequency
- Phase modulation
  - each symbol a different phase
  - e.g. 0°, 180°
Analog Line Coding

Combination Codes

- Analog line coding: modulate a carrier
- Amplitude modulation: each symbol a different level
- Frequency modulation: each symbol a different frequency
- Phase modulation: each symbol a different phase
- Combinations possible: why?

0 0 1 0 0 1 0 1 1 1
Analog Line Coding
Combination Codes

- Analog line coding:
  - modulate a carrier
- Amplitude modulation
  - each symbol a different level
- Frequency modulation
  - each symbol a different frequency
- Phase modulation
  - each symbol a different phase
- Combinations possible
  - e.g. amplitude and phase
Analog Line Coding

PAM

- PAM: pulse amplitude modulation
  - $n$ bits coded in $2n$ amplitudes per symbol
  - PAM-5 in 1GBaseT for CAT-5 100MHz frequency limit

<table>
<thead>
<tr>
<th>Name</th>
<th>Amplitudes</th>
<th>Phases</th>
<th>Bits/Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAM-4</td>
<td>4</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>PAM-5</td>
<td>5</td>
<td>1</td>
<td>2 + error</td>
</tr>
<tr>
<td>PAM-8</td>
<td>8</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>PAM-16</td>
<td>16</td>
<td>1</td>
<td>5</td>
</tr>
</tbody>
</table>
Analog Line Coding
QPSK and QAM

• Combination of amplitude- and phase-modulation
  – allows more bits per symbol

• QAM: quadrature amplitude modulation
  – quadrature = 4 phases carried on two sine waves
  – PAM is case for only one phase
  – QPSK is case for only one amplitude

<table>
<thead>
<tr>
<th>Name</th>
<th>Amplitudes</th>
<th>Phases</th>
<th>Bits/Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>QPSK</td>
<td>1</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>QAM-16</td>
<td>2</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>QAM-64</td>
<td>3</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>QAM-256</td>
<td>4</td>
<td>4</td>
<td>8</td>
</tr>
</tbody>
</table>
Analog Line Coding
QPSK and QAM

- QAM: amplitude- and phase modulation
- Represented by *constellation diagram*
  - amplitude is distance from origin
  - phase is angle

### QPSK
- 90°
- 180°
- 270°
- 0°

### QAM-16
- 90°
- 180°
- 270°
- 0°

### QAM-64
- 90°
- 180°
- 270°
- 0°
# Analog Line Coding

## Modem Standards Summary

<table>
<thead>
<tr>
<th>Std.</th>
<th>Duplex</th>
<th>Echo</th>
<th>Baud</th>
<th>b/Sym</th>
<th>Data Rate</th>
<th>Modulation</th>
<th>Year Std.</th>
</tr>
</thead>
<tbody>
<tr>
<td>V.21</td>
<td>full</td>
<td>none</td>
<td>300</td>
<td>1</td>
<td>300 b/s</td>
<td>AFSK</td>
<td>1964</td>
</tr>
<tr>
<td>V.22</td>
<td>full</td>
<td>none</td>
<td>600</td>
<td>1</td>
<td>600 b/s</td>
<td>APSK</td>
<td>1980</td>
</tr>
<tr>
<td>V.22 bis</td>
<td>full</td>
<td>none</td>
<td>600</td>
<td>2</td>
<td>1200 b/s</td>
<td>APSK QAM</td>
<td>1984</td>
</tr>
<tr>
<td>V.27</td>
<td>half/full</td>
<td>none</td>
<td>1600</td>
<td>3</td>
<td>4800 b/s</td>
<td>8PSK</td>
<td>1972</td>
</tr>
<tr>
<td>V.27 ter</td>
<td>half</td>
<td>cancel</td>
<td>1200</td>
<td>2</td>
<td>2400 b/s</td>
<td>QPSK 8PSK</td>
<td>1976</td>
</tr>
<tr>
<td>V.29</td>
<td>half/full</td>
<td>none</td>
<td>4800</td>
<td>2</td>
<td>4800 b/s</td>
<td>QPSK QAM-8</td>
<td>1976</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7200</td>
<td>3</td>
<td>7200 b/s</td>
<td>QAM-16</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>9600</td>
<td>4</td>
<td>9600 b/s</td>
<td></td>
<td></td>
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</tbody>
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# Analog Line Coding

Modem Standards Summary

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<th>Modulation</th>
<th>Year Std.</th>
</tr>
</thead>
<tbody>
<tr>
<td>V32</td>
<td>full</td>
<td>cancel</td>
<td>2400</td>
<td>2,4</td>
<td>4800 b/s, 9600 b/s</td>
<td>QPSK, QAM-16, trellis-32</td>
<td>1984</td>
</tr>
<tr>
<td>V.32 bis</td>
<td>full</td>
<td>cancel</td>
<td>2400</td>
<td>2,3,4,5,6</td>
<td>4800 b/s, 7200 b/s, 9600 b/s, 12000 b/s, 14400 b/s</td>
<td>QPSK, trellis-16, trellis-32, trellis-64, trellis-128</td>
<td>1991</td>
</tr>
<tr>
<td>V.34</td>
<td>full</td>
<td>cancel</td>
<td>600</td>
<td>. . . 3429</td>
<td>2400 b/s, 33600 b/s</td>
<td>trellis</td>
<td>1998</td>
</tr>
</tbody>
</table>
Analog Line Coding
Modem Standards Summary

<table>
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<tr>
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<th>Data Rate</th>
<th>Modulation</th>
<th>Year Std.</th>
</tr>
</thead>
<tbody>
<tr>
<td>V90</td>
<td>full asym.</td>
<td>cancel</td>
<td>8000</td>
<td>7</td>
<td>28800↓b/s 4800↑b/s ... 56000↓b/s 28800↑b/s</td>
<td>PCM</td>
<td>1998</td>
</tr>
<tr>
<td>V.92</td>
<td>full asym.</td>
<td>cancel</td>
<td>8000</td>
<td>7</td>
<td>28000↓b/s 24000↑b/s ... 56000↓b/s 48000↑b/s</td>
<td>PCM</td>
<td>2000</td>
</tr>
</tbody>
</table>
Physical Layer
Signals and Transmission

PL.1 Line coding
PL.2 Signals and transmission
PL.3 Physical media
PL.4 Performance characteristics
Communication

Signal Types

- Transmission of a *signal* through a *medium*
Communication

Signal Types

• Transmission of a *signal* through a *medium*

• Analog signal: time-varying levels
  – electrical: voltage levels
  – photonic: light intensity
Communication

Signal Types

• Transmission of a *signal* through a *medium*

• Analog signal: time-varying levels
  – electrical: voltage levels
  – photonic: light intensity

• Digital signal: sequence of bits represented as levels
  – electrical: voltage pulses
  – photonic: light pulses
  – *two* levels for *binary* digital signal
    – more levels in some coding schemes
Communication

Digital vs. Analog

- Digital bits are reconstructed at the receiver
Communication
Digital vs. Analog

- Digital bits are reconstructed at the receiver
  - all transmission is *actually* analog!
  - frequency response determines
    - pulse rate that can be transmitted
    - shape of pulse → ability for receiver to recognise pulse
Communication
Digital vs. Analog

- Digital bits are reconstructed at the receiver
  - all transmission is *actually* analog!
  - frequency response determines
    - pulse rate that can be transmitted
    - shape of pulse → ability for receiver to recognise pulse
  - high-frequency attenuation reduces quality of pulse

adapted from [Tanenbaum 2003]
Communication

Medium Types

- Guided through waveguide
  - wire (generally copper)
  - fiber optic cable
Communication
Medium Types

- Guided through waveguide
  - wire (generally copper)
  - fiber optic cable
- Unguided (wireless) free space propagation
  - wireless
    (generally implying RF – radio frequency)
  - free-space optical
Communication
Medium Sharing

- Dedicated
  - single transmitter attached to medium
  - signals may be multiplexed by a *single* transmitter
    - link multiplexing

- Shared: multiple access
  - multiple transmitters transmit into a the same medium
Communication Challenges

- Goal: receiver reconstruct signal transmitter sent
Communication Challenges

- **Goal:** receiver reconstruct signal transmitter sent
- **Noise makes this difficult**
  - background noise $N_o$ interferes with the signal bit energy $E_b$
    - SNR: signal to noise ratio $= 10 \log_{10} \left( \frac{E_b}{N_o} \right)$ dB
  - interference from other signals in shared medium
    - collisions among multiple transmitters
    - jamming from adversaries
  - imperfections in the physical medium that alters the signal
    - especially in fiber optic cables
Communication
Challenges

• Goal: receiver reconstruct signal transmitter sent
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    • jamming from adversaries
  – imperfections in the physical medium that alters the signal
    • especially in fiber optic cables
• Attenuation over distance that reduces the amplitude
  – $10 \log_{10} \left( \frac{E_t}{E_r} \right)$ dB
Communication
Challenges

• Goal: receiver reconstruct signal transmitter sent

• Noise makes this difficult
  – background noise $N_0$ interferes with the signal bit energy $E_b$
    • SNR: signal to noise ratio $= 10 \log_{10} \left( \frac{E_b}{N_0} \right)$ dB
  – interference from other signals in shared medium
    • collisions among multiple transmitters
    • jamming from adversaries
  – imperfections in the physical medium that alters the signal
    • especially in fiber optic cables

• Attenuation over distance that reduces the amplitude
  – $10 \log_{10} \left( \frac{E_t}{E_r} \right)$ dB

• Frequency response of the medium
Communication Challenges

- Result: difficulty in reconstructing signal
Communication Challenges

- Result: difficulty in reconstructing signal
- Analog: distortion of received waveforms
Communication Challenges

- Result: difficulty in reconstructing signal
- Analog: distortion of received waveforms
- Digital: bit errors – an artifact of distortion
  - distance attenuation reduces level of pulse
  - frequency attenuation distorts shape of pulse
  - distortion changes shape of pulse
  - dispersion smears pulses
Communication Challenges

- Result: difficulty in reconstructing signal
- Analog: distortion of received waveforms
- Digital: bit errors – an artifact of distortion
  - distance attenuation reduces level of pulse
  - frequency attenuation distorts shape of pulse
  - distortion changes shape of pulse
  - dispersion smears pulses
- Physical and link layer devices help
  - amplifiers ameliorate attenuation
  - regenerators and repeaters reconstruct digital signals
    - spaced closely enough to keep bit error rate low
Physical Layer
Physical Media

PL.1  Line coding
PL.2  Signals and transmission
PL.3  Physical media
PL.3  Performance characteristics
Physical Media

Wire

- Unshielded twisted pair
  - cheap, moderate bandwidth (~100Mb/s)
  - and increasing with more sophisticated coding techniques
- Shielded twisted pair
  - expensive, higher bandwidth
- Coaxial cable
  - expensive, high bandwidth (~ 500 MHz)
Physical Media

Wire: Twisted Pair

- **UTP**: unshielded twisted pair
  - twisting reduces radiation and noise susceptibility
  - used for most wired LANs
    - CAT-{5|6|7} for data applications such as Ethernet
    - 100 Mb/s supported over 100 m for 100BaseT Ethernet
  - legacy telephone wiring
    - supports much lower data rates (1–10 Mb/s)
    - used by DSL (digital subscriber line)

- **STP**: shielded twisted pair
Physical Media
Wire: Shielded Twisted Pair

- **UTP:** unshielded twisted pair
- **STP:** shielded twisted pair (S for braided shielding)
  - adds conducting shield outside of twisted pair
  - more resistant to noise than UTP
  - more expensive than UTP; no longer commonly used ...
    - but needed for high data rates: cat 6A, 7, 8
  - **FTP:** foil shielding
    - U/FTP: each pair foil shielded
    - {F|S}/UTP: overall {foil | braided} shield; pairs unshielded
    - {F|S}/FTP: overall {foil | braided} shield; pairs foil shield
## Physical Media

### Wire: TP Types

<table>
<thead>
<tr>
<th>Category</th>
<th>Type</th>
<th>BW</th>
<th>Application</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cat 3</td>
<td>UTP</td>
<td>16 MHz</td>
<td>telephone</td>
<td></td>
</tr>
<tr>
<td>Cat 5</td>
<td>UTP</td>
<td>100 MHz</td>
<td>10BaseT 100BaseT</td>
<td>100m</td>
</tr>
<tr>
<td>Cat 5e</td>
<td>UTP</td>
<td>100 MHz</td>
<td>100BaseT</td>
<td>100m</td>
</tr>
<tr>
<td>Cat 6</td>
<td>UTP</td>
<td>250 MHz</td>
<td>1GBaseT 10GBaseT</td>
<td>100m 55m</td>
</tr>
<tr>
<td>Cat 6_A</td>
<td>U/FTP F/UTP</td>
<td>500 MHz</td>
<td>10GBaseT</td>
<td>100m</td>
</tr>
<tr>
<td>Cat 7</td>
<td>F/FTP S/FTP</td>
<td>1 GHz</td>
<td>10GBaseT</td>
<td>100m</td>
</tr>
<tr>
<td>Cat 7_A</td>
<td>F/FTP S/FTP</td>
<td>1 GHz</td>
<td>10GBaseT</td>
<td>100m</td>
</tr>
<tr>
<td>Cat 8</td>
<td>U/FTP F/UTP F/FTP S/FTP</td>
<td>2 GHz</td>
<td>40GBaseT</td>
<td></td>
</tr>
</tbody>
</table>
Physical Media

Wire: Coaxial Cable

- High quality shielded cable
  - used in some LANs (and early Ethernet)
  - used in CATV (RG6 better than RG59)
  - HFC: hybrid fiber coax for data
Physical Media
Fiber Optics

- Fiber optics
  - bandwidth $\approx$ 20 THz within 800–1700 nm
  - attenuation [dB/km]
  - dispersion: waveform smearing limits bandwidth-distance

*Much more about optical communication in EECS 881*
Physical Media

Fiber Optic Cable

- Lightwave travels along glass or plastic core
  - multimode: reflected along core/cladding boundary
  - single mode: guided with no reflections

- Transmitter
  - LED or solid-state laser
Physical Media
Fiber Optic Modes

- **Multimode**: 50 – 85 µm core
  - signal reflected in multiple modes
  - intermodal dispersion limits length to a few km
  *why?*

transmitted signal
Physical Media
Fiber Optic Modes

- **Multimode**: 50 – 85 μm core
  - signal reflected in multiple modes
  - intermodal dispersion limits length to a few km
    - different modes arrive at different times

\[ \text{consequence?} \]

transmitted signal

mode x

mode y
Physical Media
Fiber Optic Modes

- **Multimode**: 50 – 85 µm core
  - signal reflected in multiple modes
  - intermodal dispersion limits length to a few km
    - different modes arrive at different times
    - received signal is sum of modes

\[
\text{transmitted signal} \overset{\text{reflections}}{\rightarrow} \text{mode } x \rightarrow \text{mode } y \rightarrow \text{received signal} = x + y
\]
Physical Media
Fiber Optic Modes

- **Multimode**: 50 – 85 \( \mu \text{m} \) core
  - signal reflected in multiple modes
  - intermodal dispersion limits length to a few km

- **Single mode**: 8–10 \( \mu \text{m} \) core
  - core acts as *waveguide* with *no* reflections
  - suitable for 10s of km between digital regenerators
Physical Media
Fiber Optic Cable Constraints

- **Attenuation**
  - distance
  - frequency

- **Dispersion**: smearing limits bandwidth-$\times$-delay
  - intermodal: different modes travel different distances
  - chromatic: different wavelengths travel different velocities
  - polarisation mode: diff. polarisation states travel at diff.

- **Nonlinearities** limit WDM
  - stimulated Raman scattering (due to molecular vibrations)
  - stimulated Brillouin scattering (acoustic wave interaction)
  - carrier-induced cross-phase modulation ($c \uparrow$ w/other signals)
  - four-wave mixing (3 wavelengths induce fourth sum/diff)
Physical Media

Wireless Free Space

- Signals transmitted through free space
  - no waveguide
- Spectrum \( (\lambda f = c ; \ c = 3 \times 10^5 \text{ km/s}) \)
  - only some spectrum usable for communication
  - RF: radio frequency
  - optical
    - infrared 800–900 nm = 333–375 THz 41 THz spectrum

*Much more about wireless communication in EECS 882*

# Wireless Free Space Spectrum

<table>
<thead>
<tr>
<th>Band</th>
<th>Description</th>
<th>Frequencies</th>
<th>Wavelength</th>
<th>Propagation</th>
<th>Usage Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELF</td>
<td>ext. low</td>
<td>30– 300 Hz</td>
<td>10– 1Mm</td>
<td>GW</td>
<td>home automation</td>
</tr>
<tr>
<td>VF</td>
<td>voice</td>
<td>300–3000 Hz</td>
<td>1000–100km</td>
<td>GW</td>
<td>voice tel., modem</td>
</tr>
<tr>
<td>VLF</td>
<td>very low</td>
<td>3– 30kHz</td>
<td>100–10km</td>
<td>GW</td>
<td>atmos. noise, submarine</td>
</tr>
<tr>
<td>LF</td>
<td>low</td>
<td>30– 300kHz</td>
<td>10– 1km</td>
<td>GW</td>
<td>daytime, maritime</td>
</tr>
<tr>
<td>MF</td>
<td>medium</td>
<td>300–3000kHz</td>
<td>1000–100 m</td>
<td>GW</td>
<td>daytime, maritime, AM radio</td>
</tr>
<tr>
<td>HF</td>
<td>high</td>
<td>3 – 30MHz</td>
<td>100–10 m</td>
<td>SW</td>
<td>daytime, transportation</td>
</tr>
<tr>
<td>VHF</td>
<td>very high</td>
<td>30 –300MHz</td>
<td>10– 1 m</td>
<td>LOS</td>
<td>temp, cosmic, television, FM radio</td>
</tr>
<tr>
<td>UHF</td>
<td>ultra high</td>
<td>300–3000MHz</td>
<td>1000–100mm</td>
<td>LOS</td>
<td>cosmic noise, TV, cell tel, LAN/MAN</td>
</tr>
<tr>
<td>SHF</td>
<td>super high</td>
<td>3 –30GHz</td>
<td>100– 10mm</td>
<td>LOS</td>
<td>O₂, H₂O, p2p µwave, LAN/MAN</td>
</tr>
<tr>
<td>EHF</td>
<td>ext. high</td>
<td>30–300GHz</td>
<td>10– 1mm</td>
<td>LOS</td>
<td>O₂, H₂O vapor, wireless LAN/MAN</td>
</tr>
<tr>
<td>IR</td>
<td>infrared</td>
<td>300GHz–400THz</td>
<td>1000–770nm</td>
<td>LOS</td>
<td>optical comm</td>
</tr>
<tr>
<td>visible</td>
<td>visible</td>
<td>400–900THz</td>
<td>770–330 nm</td>
<td>LOS</td>
<td></td>
</tr>
</tbody>
</table>
Wireless Free Space
Propagation Modes

- Ground-wave propagation  < 2 MHz
- Sky wave propagation  2 – 30 MHz
- Line-of-sight propagation  > 30 MHz
Wireless Free Space
Propagation Modes: Ground Wave

- Ground-wave propagation \(< 2\; MHz\)
  - signals follow curvature of earth
  - scattered in upper atmosphere
- Sky wave propagation \(2 – 30\; MHz\)
- Line-of-sight propagation \(> 30\; MHz\)
Wireless Free Space
Propagation Modes: Sky Wave

- Ground-wave propagation $< 2$ MHz
- Sky wave propagation $2 - 30$ MHz
  - signals refracted off ionosphere
  - communication possible over thousands of kilometers
- Line-of-sight propagation $> 30$ MHz
Wireless Free Space

Propagation Modes: Line of Sight

- Ground-wave propagation < 2 MHz
- Sky wave propagation 2 – 30 MHz
- Line-of-sight propagation > 30 MHz
  - antennæ must be in view of one-another
  - terrain and earth curvature block signature
Wireless Free Space Licensing

- Licensed and regulated spectrum
  - ITU (international) and each country (FCC in US) regulate
  - most frequency bands require license to transmit
    - e.g. broadcast TV, radio, amateur radio, GMRS
  - some bands do not require explicit license application
    - e.g. US CB (citizen band), FRS (family radio system)
Wireless Free Space
Microwave Terrestrial Links

• Microwave links
  – typically point-to-point directional links
  – once ubiquitous for long-distance telephony
    • 4 GHz TD radio and 6 GHz TH radios
    • mostly replaced by fiber optic cables in 1980s
  – subject to fading during rain storms

• New interest
  – local loops and MANs
  – backhaul for 3G/4G to fibre infrastructure
  – point-to-point links
  – mmwave (60–90 GHz) can provide 1–10 Gb/s links
Wireless Free Space
Satellite Characteristics

- Satellite orbit characteristics

<table>
<thead>
<tr>
<th>Type</th>
<th>Altitude</th>
<th>Constellation Size</th>
<th>Link Delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEO low earth orbit</td>
<td>100 km – 1 000 km</td>
<td>~50 – 1000</td>
<td>~1–10 ms</td>
</tr>
<tr>
<td>MEO medium earth orbit</td>
<td>5 000 km – 15 000 km</td>
<td>~10</td>
<td>~35–85 ms</td>
</tr>
<tr>
<td>GEO geosynchronous EO</td>
<td>36786 km</td>
<td>3 (plus polar)</td>
<td>270 ms</td>
</tr>
</tbody>
</table>

- Tradeoffs
  - cost per satellite (GEO), high link power, high delay
  - total cost of constellation, constellation management
## Wireless Free Space
### Microwave Satellite Links

- **Satellite links**

<table>
<thead>
<tr>
<th>Band</th>
<th>Typical Frequency [GHz]</th>
<th>Bandwidth</th>
<th>Issues</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Downlink</td>
<td>Uplink</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>1.5</td>
<td>1.6</td>
<td>15 MHz</td>
</tr>
<tr>
<td>S</td>
<td>1.9</td>
<td>2.2</td>
<td>70 MHz</td>
</tr>
<tr>
<td>C</td>
<td>4.0</td>
<td>6.0</td>
<td>500 MHz</td>
</tr>
<tr>
<td>(K_u)</td>
<td>11</td>
<td>14</td>
<td>500 MHz</td>
</tr>
<tr>
<td>(K_a)</td>
<td>20</td>
<td>30</td>
<td>3.5 GHz</td>
</tr>
</tbody>
</table>
Wireless Free Space
Unlicensed Spectrum

- Unlicensed spectrum
  - regulations for use (FCC 15.243–249)
    - e.g. max transmit power
    - e.g. spread spectrum parameters
  - ISM: industrial, scientific, and medical
    - ... 900 MHz, 2.4 GHz, 5.8 GHz, 24GHz, 60GHz ...
  - UNII: unlicensed national information infrastructure
    - 5.8 GHz
  - may be use by *anyone* for *any* purpose (subject to regulations)

*problem?
Wireless Free Space
Unlicensed Spectrum

- Unlicensed spectrum
  - regulations for use (FCC 15.243–249)
    - e.g. max transmit power
    - e.g. spread spectrum parameters
  - ISM: industrial, scientific, and medical
    - ... 900 MHz, 2.4 GHz, 5.8 GHz, 24GHz, 60GHz, ...
  - UNII: unlicensed national information infrastructure
    - 5.8 GHz
  - may be use by anyone for any purpose (subject to regulations)
  - interference a significant problem
    - e.g. 2.4 GHz FHSS cordless phones against 802.11b
    - e.g. interference among 802.11 hubs in dense environments
Wireless Free Space

FCC Spectrum Allocation

• FCC allocates and licenses spectrum in US
  – static allocations lead to significant inefficiency in use

Wireless Free Space
RF Antennae and Attenuation

• Antennae
  – omnidirectional: RF radiated in all directions
  – directional: focused beam of radiation
    • reduces contention and improves *spatial reuse*
    • significantly complicates network design if mobile
      – beam steering
    • laser/maser: focused coherent light/microwave transmission

• Attenuation
  – signal strength decreases as $1/r^2$ in perfect medium
  – signal may decrease as $1/r^x$ with multipath interference
    • rural environments: $x > 2$
    • urban environments: $x \rightarrow 4$
Physical Layer
Performance Characteristics

PL.1  Line Coding
PL.2  Signals and transmission
PL.3  Physical media
PL.4  Performance characteristics
Physical Media Performance

Velocity

• Velocity $v = \frac{c}{n}$ [m/s]
  – speed of light $c = 3 \times 10^5$ km/s
  – index of refraction $n$

Consequences?
Physical Media Performance
Velocity and Delay

- **Velocity** $v = c / n$ [m/s]
  - speed of light $c = 3 \times 10^5$ km/s
  - index of refraction $n$
    - this is why velocity slower than $c$ in fiber and wire

- **Delay** $d = 1/v$ [s/m]
  - generally we will express delay in [s] given a path length
Physical Media Performance

Link Length

• **Link Length**
  – distance over which signals propagate
    • point-to-point: wire or fibre length
    • shared medium: longest path
  – constrained by physical properties of medium

*Consequences?*
Physical Media Performance
Link Length and Attenuation

- **Link Length**
  - distance over which signals propagate
    - point-to-point: wire length
    - shared medium: longest path
  - constrained by physical properties of medium

- **Attenuation**: decrease in signal intensity
  - over distance expressed as \([\text{dB/m}]\)
  - at a particular signal frequency
Physical Media Performance
Frequency Response and Attenuation

- Frequency range and attenuation
  - ability to propagate signals of a given frequency
- Characteristics of guided media
  - wire: generally falls off above a certain $f_{\text{max}}$
  - fiber optic cable & free space transparent to certain ranges

*analogy:*

- UV blocking sunglasses (high attenuation)
  - vs.
- standard glass (moderate attenuation)
  - vs.
- UV transparent black light glass (low attenuation)
Physical Media Performance

Frequency Response and Attenuation: Optical

- Fiber-optic cable transparency bands
  - 1300 and 1550 nm
  - 850 nm for lower cost

![Graph showing attenuation vs wavelength for 850, 1300, and 1550 nm wavelengths.](adapted from Tannenbaum 2003)
Physical Media Performance

Frequency Response and Attenuation: RF

- Atmospheric transparency bands
  - RF: 10MHz – 10GHz
    - VHF meter band, UHF millimeter band
  - Infrared: N-band

![Graph showing atmospheric opacity and frequency response](coolcosmos.ipac.caltech.edu/cosmic_classroom/ir_tutorial/irwindows.html)
Wireless Performance

Propagation Mechanisms

- Direct signal
- Reflection
- Diffraction
- Scattering
Wireless Performance

Propagation Mechanisms: Direct

- Direct signal
  - direct transmission from transmitter to receiver
- Reflection
- Diffraction
- Scattering
Wireless Performance

Propagation Mechanisms: Reflection

- Direct signal
- Reflection
  - reflected off object large relative to wavelength
- Diffraction
- Scattering
Wireless Performance

Propagation Mechanisms: Diffraction

- Direct signal
- Reflection
- Diffraction
  - bending by object comparable to wavelength
- Scattering
Wireless Performance

Propagation Mechanisms: Scattering

- Direct signal
- Reflection
- Diffraction
- Scattering
  - by many objects smaller than wavelength
  - multiple weaker signals
Wireless Performance

Propagation Mechanisms: Multipath

- Multipath
  - multiple signals using different propagation mechanisms

question?
Wireless Performance

Propagation Mechanisms: Multipath

- Multipath interference or distortion
  - multiple signals using different propagation mechanisms
  - time-shifted versions of signal interfere with one another
# Physical Media

## Performance Characteristics Summary

<table>
<thead>
<tr>
<th>Type</th>
<th>Medium</th>
<th>Frequency Range</th>
<th>Velocity</th>
<th>Delay</th>
<th>Typical Attenuation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire</td>
<td>twisted pair</td>
<td>0–1 MHz</td>
<td>0.67c</td>
<td>5 s/km</td>
<td>0.7 dB/km</td>
</tr>
<tr>
<td></td>
<td>coax</td>
<td>0–500 MHz</td>
<td>0.66–0.95c</td>
<td>4 s/km</td>
<td>7.0 dB/km</td>
</tr>
<tr>
<td>Optical fiber</td>
<td>glass</td>
<td>120–250 THz, 1700–800 nm</td>
<td>0.68c</td>
<td>5 s/km</td>
<td>0.2–0.5 dB/km</td>
</tr>
<tr>
<td>Wireless</td>
<td>microwave</td>
<td>1–300 GHz</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>infrared</td>
<td>0.3–428 THz</td>
<td>1.0c</td>
<td>3.3 s/km</td>
<td>1/r^2</td>
</tr>
<tr>
<td></td>
<td>visible</td>
<td>428–750 THz</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Physical Layer
Further Reading

### Physical Layer

#### Key Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DTMF</td>
<td>dual tone multi-frequency</td>
</tr>
<tr>
<td>QAM</td>
<td>quadrature amplitude modulation</td>
</tr>
<tr>
<td>SNR</td>
<td>signal-to-noise ratio</td>
</tr>
<tr>
<td>UTP</td>
<td>unshielded twisted pair</td>
</tr>
<tr>
<td>LEO</td>
<td>low-earth orbiting (satellite)</td>
</tr>
<tr>
<td>GEO</td>
<td>geosynchronous satellite</td>
</tr>
<tr>
<td>FCC</td>
<td>(US) Federal Communications Commission</td>
</tr>
<tr>
<td>ISM</td>
<td>industrial, scientific, and medical</td>
</tr>
</tbody>
</table>
Physical Layer

Acknowledgements

Some material in these foils comes from the textbook supplementary materials:

- Sterbenz & Touch, 
  *High-Speed Networking: A Systematic Approach to High-Bandwidth Low-Latency Communication*
  http://hsn-book.sterbenz.org