Analog Telecommunications  
(Physical Layer)

OSI 7-layer Reference Model
Electrical Parameters: Energy Measurements

- **Voltage**
  - Measure of electrical energy per unit charge
  - Analogous to pressure in a fluid system
  - Unit of measurement: Volt (V)

- **Current**
  - Flow of charge
  - Analogous to volume/time in a fluid system
  - Unit: Ampere (A)

- **Power**
  - Rate of flow of energy
  - Unit: Watt (W)
  - Complex function of voltage and current
  - Most important measure in communications
  - Quality of a channel is proportional to ratio \( P_s / P_n \) signal to noise ratio

Electrical Parameters: Material Properties

- **Resistance**: Causes proportional drop in voltage when current flows (consumes energy)
  - Unit: Ohm (Ω)

- **Inductance**: Tendency to oppose change in current (due to storing magnetic energy)
  - Unit: Henry (H)

- **Capacitance**: Tendency to oppose change in voltage (due to storing charge)
  - Unit: Farad (F)

- **Impedance**: Collective effect of resistance, inductance, and capacitance on time-varying voltage when time-varying current flows; in general, impedance is a complex function of frequency
  - Unit: Ohm (Ω)
Analog vs Digital Signals

Analog signals change continuously:

Digital signals have discrete values:

Analog Signal Characteristics

Mathematically \( S(t) = A \sin \left( \frac{2\pi t}{p} - \frac{\pi \phi}{180} \right) \)

- \( A \) is the amplitude
- \( p \) is the period
- \( f = 1/p \) is the frequency in cycles/sec or “Hertz”
- \( \phi \) is the phase angle in degrees

Signal power is related to \( A \), for example if \( S(t) \) is a voltage \( P = A^2 / 2Z \) where \( Z \) is a characteristic of the load called “impedance”
Bandwidth: Analog Channel Capacity

- A signal that changes value over time is said to be “AC” or alternating current
  - By contrast, a battery produces a steady current, called “DC”, or direct current, that does not change until the battery discharges
- The information capacity a signal can hold is related to the range of frequencies the signal contains, called “bandwidth” \( W = f_H - f_L \)
- For example, if a signal can contain frequencies from 1000 to 5000 Hertz, then the signal bandwidth is \( W = 5000 - 1000 = 4000 \) Hertz
- Sometimes the high frequency is so much larger than the low one that the bandwidth is approximated by the high frequency
  - e.g., 20 to 20,000 Hz means a bandwidth of ~ 20kHz

Spectrum

For very large and small numbers we use prefixes:

<table>
<thead>
<tr>
<th>Prefix</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Giga or G</td>
<td>G</td>
<td>(10^9)</td>
</tr>
<tr>
<td>Mega or M</td>
<td>M</td>
<td>(10^6)</td>
</tr>
<tr>
<td>kilo or k</td>
<td>k</td>
<td>(10^3)</td>
</tr>
<tr>
<td>milli or m</td>
<td>m</td>
<td>(10^{-3})</td>
</tr>
<tr>
<td>micro or (\mu)</td>
<td>(\mu)</td>
<td>(10^{-6})</td>
</tr>
<tr>
<td>nano or n</td>
<td>n</td>
<td>(10^{-9})</td>
</tr>
</tbody>
</table>

The range of usable frequencies is
- from DC (no frequency)
- to \(10^{15}\) Hertz and higher

Note: in computers \(K=1024, M=1024^2\)
in telecommunications \(k=1000, M=1000^2\)
you are expected to use the right one!
Spectrum (continued)

Some important frequency ranges are:

- 20-20,000 Hz Audible sound
- 550-1650 kHz AM radio
- ~10-50 MHz Short wave radio
- ~50-550 MHz TV and FM radio (VHF/UHF)
- $10^{12}$-$10^{15}$ Hz Light waves

NOTE: These numbers cover a wide range! Therefore we will use scientific notation and three or four significant digits in this course.

Fourier Analysis

Consider a periodic function $g(t)$.

- $f_0$ is the fundamental frequency of periodic change of the signal’s pattern
- $d$ is the DC component

Then the signal can be described to any level of accuracy by the Fourier Series:

$$g(t) = d + \sum_{n=1}^{\infty} a_n \sin(2\pi f_0 t - \phi_n \pi / 180)$$

In other words, a repetitive signal of any shape can be described as the sum of sinusoidal signals plus a constant (DC) component.

Generally, the values of $a_n$ grow smaller as $n$ increases; so the series up to the point where $a_n$ is negligible is a good approximation of $g(t)$.
Bandwidth of Human Voice

- Older telephone systems pass frequencies from 300 Hz to 3300 Hz
  - that is, the bandwidth = 3 kHz
- 3kHz is sufficient to allow human speech to be understood clearly
- High fidelity audio systems reproduce the range of human hearing, which is generally about 20 Hz to 20 kHz in young people

Transmission Media - Twisted Pairs

- Telephone signals have been transmitted over wire pairs for many years
- Two wires allow a closed circuit path for current (bandwidth?????)
- Twisting wires with the right number of turns per meter reduces sensitivity to noise
- Pairs are often used in “balanced mode” where the signal phase ( f ) on one line is reversed; when the receiver reverses the phase again, most of the electrical noise pickup is canceled
Transmission Media - Coaxial Cable

- Coaxial cable ("co-ax") consists of a central conductor surrounded by an insulating layer, which in turn is surrounded by a braided shield; the shield gives good immunity to noise.
- Frequencies to 500 Mhz for a few miles
  - beyond 2 miles an amplifier (repeater) must be used
  - "Baseband" mode carries signal in digital form
    - more on this next week
  - "Broadband" mode, such as cable TV, carries multiple channels but requires a more complex receiver.

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Transmission Media - Microwave Radio

- Radio operating at very high frequencies (normally in the GHz range) can pass a signal with bandwidth tens of MegaHertz or higher.
- Analog microwave has been replaced by digital
  - more next week
- At microwave frequencies, radio is limited to line-of-sight and requires a parabolic dish antenna; obstacles block the transmission.
- Microwave is typically limited to about 20 miles due to the curvature of the earth.
Transmission Media - Wireless Systems

- Analog radio is a “legacy” communications system today
  - AM (550 kHz to 1650 kHz) noisy
    - but occupies an over-the-horizon band
  - Short Wave (around 10 MHz to 50 MHz) worldwide
    - but even noisier!
  - FM (88 MHz to 108 MHz) has higher fidelity, lower noise
    - and audio band of NTSC TV, in the same vicinity
    - makes inefficient use of prime spectrum
- Mobile radio used by security forces, hams
  - very poor signal to noise ratio, intermittent response
- Analog cellular phones
  - giving way to digital rapidly
  - we’ll see why next class

Link Performance - Attenuation

- Transmission media (particularly wires) have a loss in signal, called attenuation, that is geometrically proportional to distance
- Normally, to compensate for attenuation the signal must be amplified at intervals down the link (but any noise is also amplified)
Measuring Signals

- **dB (decibel):** Unit of signal gain or loss equal to
  \[ 10 \log \left( \frac{P_{\text{meas}}}{P_{\text{ref}}} \right) \]
- \( P_{\text{meas}} \) is measured signal power and \( P_{\text{ref}} \) is reference signal power
- Example: an amplifier that makes a signal 100x as large has a gain of \( 10 \log 100 = 20 \text{ dB} \)
- Normally, signals multiply when passing through cascaded blocks; but when using dB they add

- Using simple algebra, this can be also rewritten as
  \[ P_{\text{meas}}/P_{\text{ref}} = 10 \text{ dB/10} \]

About Decibels

- Any ratio (for example, signal/noise) can be expressed in dB.
  - \( S/N = 189 \text{ microwatts} / 3 \text{ microwatts} \)
    \[ = 10 \log (189/3) = 18 \text{ dB} \]
- Attenuation to 5% of original signal
  \[ = 10 \log 0.05 = -13 \text{ dB} \]
- If the signal is measured in volts, \( P = V^2/Z \), so
  \[ P_{\text{meas}}/P_{\text{ref}} = 10 \log \left( \frac{V_{\text{meas}}^2/Z}{V_{\text{ref}}^2/Z} \right) \]
  \[ = 20 \log \left( \frac{V_{\text{meas}}}{V_{\text{ref}}} \right) = \text{dB}, \; \text{where Z is impedance} \]
- Example of finding gain in dB: An amplifier which has an output of 1.0W when its input is .05W has gain:
  \[ =10 \log (1.0/0.05) = 10 \log 20 = 13 \text{ dB} \]
An Example Using dB To Find Signal Strength

Overall gain is
15 dB (first amplifier) -40 dB (line loss) + 22 dB(second amplifier)
= - 3 dB.

Using the formula from the preceding slide
\[ \frac{P_{\text{meas}}}{P_{\text{ref}}} = 10 \, \text{dB/10} \]

We have
\[ P_{\text{meas}} = P_{\text{ref}} \times 10^{\frac{\text{dB}}{10}} = .5 \times 10^{-3/10} = .25 \text{ W} \]

Handy facts: 
- \(10\log_{10}(2) = 3.01\) => a factor of 2 is 3dB
- \(10\log_{10}(.5) = -3.01\) => a factor of 1/2 is -3dB

Link Performance - Propagation Delay

- In a vacuum, electromagnetic energy travels at the speed of light, \(c = 186,000\) miles/sec (or \(c = 3 \times 10^8\) meters/sec)
- Light travels more slowly in glass, and electrical signals travel slower along a wire; a reasonable estimate ~30\% slower, or ~130,000 miles/sec (or 2.1 \(\times 10^8\) meters/sec)
- Propagation delay, \(D = \frac{\text{distance}}{v_{\text{medium}}}\)
  - \(D = \frac{\text{distance in miles}}{130,000} = \frac{\text{distance in meters}}{(2.1 \times 10^8)}\)
- Propagation delay is most significant in satellite links, one-hop delay is: \(2 \times 22,300 / 186,000 = .24\) seconds
- Round-trip delay is double, or about 1/2 second
Link Performance - Duplexity

- **Simplex**
- **Half Duplex**
- **Full Duplex**
  - (can be achieved by using two wire pairs/fibers, or by assigning different frequency bands to “send” and “receive”)

Multiplexing

- Multiplexing (“muxing”) allows multiple flows to share a channel, within the limits of the overall capacity
- Frequency division (FDM) - analogous to radio spectrum but within a cable
Analog Signal Characteristics
(again)

Mathematically

\[ S(t) = A \sin \left( \frac{2 \pi t}{p} - \frac{\pi \phi}{180} \right) \]

- A is the amplitude
- p is the period
- \( f = \frac{1}{p} \) is the frequency in cycles/sec or “Hertz”
- \( \phi \) is the phase angle in degrees

Signal power is related to A, for example if S(t) is a voltage
\[ P = \frac{A^2}{2Z} \]
where Z is a characteristic of the load called “impedance”

Modulation

Modulation means varying some property of a signal to impress information on the signal

- **Amplitude modulation**
- **Frequency modulation**
- **Phase modulation**
Quadrature Amplitude Modulation (with even parity)

---c-------------|---3--------------|---j-----------

110 001 100 110 011 011 010 100

---

Quadrature Amplitude Modulation

<table>
<thead>
<tr>
<th>Bit Combination</th>
<th>Phase Shift °</th>
<th>Amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>000</td>
<td>0</td>
<td>low</td>
</tr>
<tr>
<td>001</td>
<td>0</td>
<td>high</td>
</tr>
<tr>
<td>010</td>
<td>90</td>
<td>low</td>
</tr>
<tr>
<td>011</td>
<td>90</td>
<td>high</td>
</tr>
<tr>
<td>100</td>
<td>180</td>
<td>low</td>
</tr>
<tr>
<td>101</td>
<td>180</td>
<td>high</td>
</tr>
<tr>
<td>110</td>
<td>270</td>
<td>low</td>
</tr>
<tr>
<td>111</td>
<td>270</td>
<td>high</td>
</tr>
</tbody>
</table>

• first and second bit taken as a binary number are the multiple of 90°
• third bit indicates the amplitude
ASCII

<table>
<thead>
<tr>
<th>b7</th>
<th>b6</th>
<th>b5</th>
<th>b4</th>
<th>b3</th>
<th>b2</th>
<th>b1</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 0 0 0 0</td>
<td>NUL DLE SP</td>
<td>0</td>
<td>@</td>
<td>P</td>
<td>p</td>
<td></td>
</tr>
<tr>
<td>0 0 0 0 1</td>
<td>SOH DC1</td>
<td>1</td>
<td>A</td>
<td>Q</td>
<td>a</td>
<td>q</td>
</tr>
<tr>
<td>0 0 0 1 0</td>
<td>STX DC2</td>
<td>2</td>
<td>B</td>
<td>R</td>
<td>b</td>
<td>r</td>
</tr>
<tr>
<td>0 0 0 1 1</td>
<td>ETX DC3</td>
<td>3</td>
<td>C</td>
<td>S</td>
<td>c</td>
<td>s</td>
</tr>
<tr>
<td>0 0 0 0 0</td>
<td>EOT DC4</td>
<td>4</td>
<td>D</td>
<td>T</td>
<td>d</td>
<td>t</td>
</tr>
<tr>
<td>0 0 0 1 0</td>
<td>ENQ NAK</td>
<td>5</td>
<td>E</td>
<td>U</td>
<td>e</td>
<td>u</td>
</tr>
<tr>
<td>0 0 1 0 0</td>
<td>ACKSYN &amp;</td>
<td>6</td>
<td>F</td>
<td>V</td>
<td>f</td>
<td>v</td>
</tr>
<tr>
<td>0 0 1 0 0</td>
<td>BEL ETB</td>
<td>7</td>
<td>G</td>
<td>W</td>
<td>g</td>
<td>w</td>
</tr>
<tr>
<td>1 0 0 0 0</td>
<td>BS CAN</td>
<td>8</td>
<td>H</td>
<td>X</td>
<td>h</td>
<td>x</td>
</tr>
<tr>
<td>1 0 0 1 0</td>
<td>HT EM</td>
<td>9</td>
<td>I</td>
<td>Y</td>
<td>i</td>
<td>y</td>
</tr>
<tr>
<td>1 0 1 0 0</td>
<td>LF SUB</td>
<td>:</td>
<td>J</td>
<td>Z</td>
<td>j</td>
<td>z</td>
</tr>
<tr>
<td>1 0 1 1 1</td>
<td>VT ESC</td>
<td>;</td>
<td>K</td>
<td>[</td>
<td>k</td>
<td>{</td>
</tr>
<tr>
<td>1 1 0 0 0</td>
<td>FF FS</td>
<td>&lt;</td>
<td>L</td>
<td>\</td>
<td>l</td>
<td>]</td>
</tr>
</tbody>
</table>
| 1 1 0 1 0 | CR GS | = | M | } | m | }
| 1 1 1 0 0 | SO RS | > | N | ^ | n | ~ |
| 1 1 1 1 1 | SI US | / | O | _ | o | DEL |

Quadrature Amplitude Modulation

Example

-----D-----|-----q-----|-----d-----
Multiple Bits Per Baud

- QAM is an example of the way modern modems can pack a lot of information into a sample.
- Depending on the quality of the analog channel, it is possible to encode several bits into every sample taken from the channel: multiple bits per baud.
- Given $n$ levels of signal that can be discriminated in each sample based on amplitude frequency or phase, the bit rate is:
  \[ C = b \log_2 n \]
  where $C$ is the channel capacity as before and $b$ is the signalling rate (also called sampling rate or baud rate).
- We will learn in the next class that Shannon’s law defines an absolute limit for $C$.

Facsimile Transmission

- Facsimile (fax) is a specialized application of data communications that generally uses a modem.
- Fax scanners capture the contents of a page in bitmap-mapped form, where each resolvable picture element (pixel) is either present or absent to some degree. (The output quality of a fax is often better than the scanner capture, and computer-generated faxes look better.)
- Compression protocols provide for squeezing out all the white space, requiring only the shaded pixels to be transmitted (more on this next lecture).
- Special fax protocols (e.g., “group 3”) take advantage of characteristics of documents.
Circuit Switching

- Establishes temporary connections among communicating elements

Hub Switching
Hierarchical Switching

Trunk Circuit Switching

Concentration  Connection  Expansion
Inside A Circuit Switch

Connections made at crosspoints

Control Computer

SIGNALING

Circuit Switching for Modem Data

- Real-time capability
- Call setup delay
- End system must place call
- Blocking (e.g., busy signal) possible
- Once you have a circuit you can use it until to choose to release it
Private Branch Exchange (PBX)

- A PBX is a small circuit switch that provides local dial-up service and access to a larger system, such as the public switched system.
- New PBXs are completely digital, but analog plain old telephone system (POTS) interfaces are available.

Important Data Communications Components

- **Channel or link** - provides an information path
- **Data terminal equipment (DTE)** (e.g. computer).
- **Data circuit terminating equipment (DCE)** (e.g. modem).
- DTE and DCE must match at some interface (e.g. RS-232).
- **Modem** - modulates and demodulates a “carrier” that fits in the channel, but a
- **Digital Service Unit (DSU)** - provides digital communication directly over link, no modulation required.
- **Multiplexer** - combines multiple information flows into a single flow and can reverse this process (demultiplex)
Homework

- graph the function: $5 \sin (2000 \pi t - 1.571)$ volts (use graph or quadrille paper, or draw a grid to provide reference lines)
- Express in dB the gain of an amplifier with output of 150W, when the input is 0.75W
- If attenuation results in an output = .02 X input (measured in Watts), express this loss in dB.
- For the figure below, (a) calculate the overall dB and (b) find the output
- sketch the QAM signal for “FAT” in 8-bit ASCII with odd parity (parity bit goes rightmost)

<table>
<thead>
<tr>
<th>input</th>
<th>Amplifier</th>
<th>Line loss</th>
<th>Amplifier</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>.25 W</td>
<td>43 dB</td>
<td>-57 dB</td>
<td>20 dB</td>
<td></td>
</tr>
</tbody>
</table>

Project DLC1

due 9-26

- Purpose - Understand how bit stuffing/unstuffing works by programming them using the Network Workbench
  - See UIP Chapter 3
- Assignment:
  - Create bit stuffing/destuffing routines. There is a stub function in code/stuff.cpp with the correct interfaces.
  - Test your routines in the Workbench using dlc1.cpp
  - Document your code with adequate comments.
  - Submit your results by upload. Attach file stuff.cpp. Be sure to label the attachments with the file name.
  - [http://netlab.gmu.edu/networkbench/Project-grading.txt](http://netlab.gmu.edu/networkbench/Project-grading.txt)
  - You will be using a web-upload system to submit projects. Information will be provided by email.
Synchronous Transmission: Framing

In synchronous transmission, the sender must provide a whole block of information to be sent at once.

Each such block is called a “frame” and is identified by a beginning and ending “flag” or “framing” character.

A commonly used flag is 01111110 (7E hex).

When a flag is detected, the receiver “syncs up” with the frame and begins receiving bits; reception continues until the next flag is seen.

In this way, synchronization occurs in every frame, not in every character.

Framing (continued)

The flag bit pattern must not appear in the frame data, or else the receiver will detect prematurely the end of frame.

To prevent the flag appearing within the frame data, the transmitter stuffs in extra bits as needed. The receiver must detect and remove (or unstuff) these extra bits.

The sender transmits an opening flag and then begins transmitting the frame data. Whenever five consecutive one bits appear, the sender stuffs in an extra zero bit. When the frame is fully transmitted, the sender transmits a closing flag.

The receiver detects and discards the opening flag and then begins accepting data bits, removing every zero bit that follows five consecutive one bits. Once the receiver detects a closing flag, reception of data bits is halted.
Bit Stuffing/Unstuffing Example

Original Data Frame
0011111110100101011100111110101101001

Transmitted Data Frame
01111110011111101011100111110110111001

Received Data Frame
0011111110100101011100111110101101001