Agenda today

- Characterizing channels
  - linearity
  - non-linearity
  - time-variability
- Measuring channels
- Overview to some channels
  - wired channels
    - coaxial cables
    - twisted cables
  - wireless cellular channel
    - large-scale path loss
    - small scale modeling, e.g
      - delay spread
      - coherence bandwidth
      - Doppler spread

Analog and digital transmission in various channels [8]
Communication channels and medium

- A **physical medium** is an inherent part of a communications system
  - Wires (copper, optical fibers), wireless radio spectra
- Communications systems include **electronic or optical devices** that are part of the transmission path followed by a signal
  - Equalizers, amplifiers, signal conditioners (regenerators)
  - Medium determines **only part** of channels behavior. The other part is determined how transmitter and receiver are connected to the medium and what is transmitted in the channel
  - Therefore, by telecommunication channel we refer to the **combined end-to-end physical medium** and attached devices
- Often the concept “**filter**” models a channel. This is due to the fact that all telecommunication channels can be always modeled as filters. Their parameters can be
  - deterministic
  - random
  - time variable
  - linear/non-linear

Selecting the medium/media

- What is **amount of traffic** to be distributed?
- What is the **cost** we can afford?
- What is the **interference** environment?
- Is mechanical **robustness** adequate?
- Point-to-point or **networking** usage?
- Capability to transfer **power** (for instance forrepeaters)?
- Often the first selection is done between
  - Wired
  - Wireless
- Often one can consider if **digital** or **analog** message is to be transmitted
  - analog PSTN takes 300-3400 kHz
  - digital PCM takes 64 kbit/s
  - digital, encoded GSM speech only 13 kbit/s
  - what is the adequate compression level?
Guided and unguided medium

- Medium conveys message by electromagnetic waves
  - wireless/wired (medium)
  - baseband/carrier wave (transmission band)
  - digital/analog (message format)

- In free space information propagates at \( v = \frac{c}{\sqrt{\varepsilon}} \), \( \lambda = \frac{c}{v} f_0 \)

- In transmission lines, coaxial cables and waveguides the channel output power decreases exponentially with distance, yielding loss
  \[
  L = \frac{1}{g} = \frac{P_{in}}{P_{out}} = 10^{\frac{\alpha}{10}}
  \]
  \[
  L_{dB} = -10 \log(g) = -10 \log(10^{\frac{\alpha}{10}}) = \alpha d
  \]

- Generally, in radio transmission, free-space loss is
  \[
  L = \left( \frac{4\pi d}{\lambda} \right)^2 = \left( \frac{4\pi d}{c} \right)^2 \Rightarrow L_{dB} = 92.4 + 20 \log(f_0) + 20 \log(d_{sep})
  \]

- In addition, with directive antennas having transmitter & receiver gains \( g_T \) and \( g_R \), output power can still be increased:
  \[
  P_{out} = g_T g_R \frac{P_{in}}{L}
  \]

Guided and unguided medium ... summary

<table>
<thead>
<tr>
<th>Transmission medium</th>
<th>Frequency</th>
<th>Loss (dB/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Twisted-wire pair (18 gauge)</td>
<td>10 kHz</td>
<td>2</td>
</tr>
<tr>
<td>Coaxial cable</td>
<td>100 kHz</td>
<td>1</td>
</tr>
<tr>
<td>Fiber-optic cable</td>
<td>400 THz</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Some wired channel loss parameters

- **Wireless**: easy deployment, radio spectra sets capacity limit. Attenuation as function of distance \( d \) follows \( d^{n(f)} \), \( n(f) = 2.5 = n^* \)
  \[
  A_{\text{wireless}} = A_0 + n \log_{10} d \text{[dB]} \quad \text{(fixed frequency)}
  \]

- **Wired**: more capacity by setting extra wires (may be complex, costly, time consuming). Attenuation as function of frequency follows \( 10^{k(f)d} \), where \( k(f) \) is the attenuation parameter (\( \alpha \)), yielding
  \[
  A_{\text{wired}} = k(f) d \text{[dB]}
  \]

- Therefore, in general, wireless systems may maintain signal energy longer than wired systems. However, actual received power depends greatly on actual channel parameters.

*for cellular channel frequency is fixed, \( n^*>2 \)
Channels parameters

- Characterized by
  - attenuation [dB/km], transfer function
  - impedance [Ω], matching
  - bandwidth [Hz], data rate

- Transmission impairments change channel’s effective properties
  - system internal/external interference
    - cross-talk - leakage power [dB] from other users
    - channel may introduce inter-symbolic interference (ISI)
    - channel may absorb interference from other sources
    - wideband noise [W/Hz]
  - distortion, linear (uncompensated transfer function)/nonlinear (non-linearity in circuit elements)

- Channel parameters are a function of frequency, transmission length, temperature ...

Data rate limits

- Data rate depends on: channel bandwidth, the number of levels in transmitted signal and channel SNR (received signal power)

- For an L level signal with theoretical sinc-pulse signaling transmitted maximum rate is (Nyquist rate)
  \[ r = 2B_s \ln_2(L) \Rightarrow r_s = 2B_s \ln_2(L) L = 2^n \]

- There is absolute maximum of information capacity that can be transmitted in a channel we discussed earlier, namely Shannon’s channel capacity:
  \[ C = B \log_2(1 + SNR) \]

- Example: A transmission channel has the bandwidth \( B_s = 1 \text{ MHz} \) and SNR = 63. Find the appropriate bit rate and number of signal levels. Solution: Theoretical maximum bit rate is
  \[ C = B \log_2(1 + 63) = 10 \log_2(64) = 6 \text{ Mbps} \]
  In practice, a smaller bit rate can be achieved. Assume
  \[ r_s = 4 \text{ Mbps} = 2B_s \log(L) \Rightarrow L = 4 \]

\[ r: \text{ symbol rate}, \quad r_b: \text{ bit rate} \]
Measuring channels

- Parameters of greater interest are transfer function and impedance. 
  **Transfer function** can be measured by 
  - Launching **white noise** (in the frequency range to be measured) to the channel (frequency response) 
  - Launching **impulse to the channel** (theoretical). In practice, short, limited amplitude pulse will do (impulse response) 
  - Launching **sweeping tone(s)** to the channel (frequency response)

- **Impedance** can be measured by measuring voltage across the load in the input/output port:
  \[
  \frac{V_2}{V_1} = \frac{Z_g + Z_L}{Z_L} \Rightarrow Z_L = \frac{V_2}{V_1} - Z_g
  \]

- **Transfer characteristics** of nonlinear channels can be deducted from generated extra frequency components (we will discuss this soon with non-linearity)

Impedance matching

- Often (as with coaxial cables) channel interfaces must be impedance matched to maximize power transfer and to avoid power reflections
- In applying power to a transmission channel (or a circuit) source and loading impedances must be complex conjugates in order to maximize power dissipated in the load
- **Perfect match** means efficiency of 50%
- Setting impedances \( Z_g \) and \( Z_L \) to fulfill this condition is called **impedance matching**
Linear channels [1]

- **Linear channels** have the output that is input signal multiplied by a constant and delayed by a finite delay: 
  \[ y(t) = Kx(t - t_d) \]
  \[ Y(f) = F[y(t)] = K \exp(-j\omega t_d) X(f) \]
  
  due to the fact that system output is also 
  \[ Y(f) = H(f) X(f) \]
  
  Therefore, for linear systems 
  \[ |H(f)| = |K|, \arg H(f) = -2\pi t_d \]
  
- Linear distortion can be 
  - amplitude distortion: \[ |H(f)| = |K| \]
  - delay distortion: \[ \arg H(f) = -2\pi t_d \]
  
- Solving above gives **phase delay**, defined by 
  \[ t_d(f) = -\arg H(f)/2\pi f \]
  
  It describes the phase delay experienced by each frequency component

- In **distortionless channel** all Fourier-components retain their relative phase positions while propagating in channel

Nonlinear channels [1]

- System non-linearity means that its transfer characteristic is nonlinear
- For non-linear channels output is 
  \[ y(t) = a_1 x(t) + a_2 x^2(t) + a_3 x^3(t) + \ldots \]
  Assume sinusoidal input \[ x(t) = \cos \omega t \], then 
  \[ y(t) = \left( \frac{a_1}{2} \right) + \left( \frac{3a_2}{8} \right) \cos 2\omega t + \left( \frac{a_3}{2} \right) \cos 3\omega t + \ldots \]
  
  where \( D_n \)'s are the distortion coefficients

- **n-th order distortion** [%] is determined with respect of the fundamental frequency: 
  \( D_n [%] = (D_n / D_1) \times 100 \%

- Assume that the input is 
  \[ y(t) = \cos \omega_1 t + A \cos (\omega_1 + \omega_2) t \]
  3rd order intercept [1,p.55] occurs* where 
  \[ A = 4a_3 / (3a_2) \]
  
  This is easy to measure and is used to characterize nonlinear systems

*See the prove in the supplementary material (A. Burr: Modulation and Coding)
Wireline channels: Twisted pair

- Comes in two flavors: Shielded (STP) / Unshielded (UTP)
- Twisting reduces interference, and crosstalk (antenna-behavior)
- Applications
  - Connects data and especially PSTN local loop analog links (Intra-building telephone from wiring closet to desktop)
  - In old installations, loading coils added to improve quality in 3 kHz band, resulting more attenuation at higher frequencies (ADSL)
  - STP used especially in high-speed transmission as in token ring-networks

Twisted pair - UTP categories in LANs

- **Category 1**: mainly used to carry voice (telephone wiring prior to 1980). Not certified to carry data of any type.
- **Category 2**: used to carry data at rates up to 4 Mbps. Popular in older Token-passing ring LANs using 4 Mbps specs (IEEE 802.5). Rated bandwidth $BW = 1 \text{ MHz}$.
- **Category 3**: known as voice grade. Used primarily in older Ethernet 10base-T* LANs (IEEE 802.3). Certified to carry 10 Mbps data. $BW= 16 \text{ MHz}$, 3-4 twists/feet.
- **Category 4**: primarily used for token-based or 10 Base-T. $BW = 20 \text{ MHz}$.
- **Category 5**: most popular Ethernet cabling category. Capable of carrying data at rates up to 100 Mbps (Fast Ethernet, IEEE 802.3u) and used for 100 base-T and 10 base-T networks. Rated $BW = 100 \text{ MHz}$. 3-4 twists/inch.

*100 m / CAT 3 cables*
Unshielded and shielded twisted pairs attenuation compared

- Electronic Industries Association has specified in EIA-568-A twisted pairs for different applications.

### Table: Twisted Pair Attenuation

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Category 3 UTP</th>
<th>Category 5 UTP</th>
<th>Category 3 150Ω STP</th>
<th>Category 5 150Ω STP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.6</td>
<td>2.0</td>
<td>1.1</td>
<td>41</td>
</tr>
<tr>
<td>4</td>
<td>5.6</td>
<td>4.1</td>
<td>2.2</td>
<td>32</td>
</tr>
<tr>
<td>16</td>
<td>13.1</td>
<td>8.2</td>
<td>4.4</td>
<td>23</td>
</tr>
<tr>
<td>25</td>
<td>10.4</td>
<td>10.4</td>
<td>6.3</td>
<td>32</td>
</tr>
<tr>
<td>100</td>
<td>22.0</td>
<td>22.0</td>
<td>12.3</td>
<td>32</td>
</tr>
<tr>
<td>300</td>
<td>—</td>
<td>21.4</td>
<td>—</td>
<td>31.3</td>
</tr>
</tbody>
</table>

**Twisted pair - application examples [6]**

- Comes in different wire thickness, e.g. 0.016 inch (24 gauge)
- The longer the cable, the smaller the bandwidth

### Diagram: Twisted Cable Attenuations

- DS-1, DS-2: Digital Signal 1.2
- Synchronous Optical Network’s (SONET) physical level signal

Data rates & distances for 24-gauge twisted pair

<table>
<thead>
<tr>
<th>Standard</th>
<th>Data Rate</th>
<th>Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>DS-1</td>
<td>1.544 Mbps</td>
<td>16,000 feet, 5.5 km</td>
</tr>
<tr>
<td>DS-2</td>
<td>6.312 Mbps</td>
<td>12,000 feet, 3.7 km</td>
</tr>
<tr>
<td>1/4 STS-1</td>
<td>12.96 Mbps</td>
<td>4500 feet, 1.4 km</td>
</tr>
<tr>
<td>1/2 STS-1</td>
<td>25.92 Mbps</td>
<td>3000 feet, 0.9 km</td>
</tr>
<tr>
<td>STS-1</td>
<td>51.84 Mbps</td>
<td>1000 feet, 300 m</td>
</tr>
</tbody>
</table>

**Note:**
- 26 gauge
- 24 gauge
- 22 gauge
- 19 gauge
- Attenuation (dB/m)
- Lower attenuation rate: analog telephone
- Higher attenuation rate: for DSL
Wireline channels: Coaxial cables

- Mechanics
  - Cylindrical braided outer conductor surrounds insulated inner wire conductor

- Properties
  - Well shielded structure -> immunity to external noise
  - High bandwidth, up to GHz-range (distance/model)

- Applications
  - CATV (Cable TV networks)
  - Ethernet LANs
  - Earlier a backbone of PSTN
Slow (S) and fast fading (a) in cellular channel

Received power fluctuations can be modeled to consist of:

- **Shadow fading**, slow rate, local averaged signal power component has a Gaussian distribution (in dB) (Caused by larger obstacles between TX and RX)

\[
p(S) = \frac{1}{\sigma_S \sqrt{2\pi}} \exp \left( -\frac{(S - S_0)^2}{2\sigma_S^2} \right)
\]

\[S_0 = C / r^\alpha, \alpha = 2...5 \text{ (global, average power)}\]

- **Rayleigh/Rice fading**, high rate component due to various sources of multipath. Rayleigh distribution (non-line of sight paths) is defined as

\[
p(a) = \frac{1}{\sigma_a^2} \exp \left( -\frac{a^2}{2\sigma_a^2} \right), E[a^2] = 2\sigma_a^2
\]

- **High rate Doppler shifts**
The time variable channel impulse response is

\[ h_b(t, \tau) = \sum_{i=0}^{N-1} a_i(t, \tau) \exp(j2\pi f_r(t) + \phi(t, \tau)) \delta(\tau - \tau_i(t)) \]

For time invariant channels each impulse response is the same or has the same statistics and then

\[ h(\tau) = \sum_{i=0}^{N-1} a_i \exp(-j\theta) \delta(\tau - \tau_i) \]

**Doppler bandwidth**

- Multipath created small-scale fading effects
  - rapid changes in signal strength due to movement and/or time
  - random frequency modulation due to Doppler shifts on different multipath propagation paths
  - time dispersion due to multipath propagation delay
- The difference in path lengths to X & Y from source S is \( \Delta l = d \cos \theta = v \Delta t \cos \theta \)
- The phase change between locations X & Y is then
  \[ \Delta \phi = \frac{2\pi}{\lambda} \Delta l = \frac{2\pi v \Delta t}{\lambda} \cos \theta \]

\[ f_d = \frac{1}{2\pi} \frac{\Delta \phi}{\Delta t} = \frac{v}{\lambda} \cos \theta \]

\[ \text{Doppler effect [7]} \]

*Angular frequency is the derivative of angular phase - Will be discussed in details with frequency modulation*
Optical Fiber

- Light sources (lasers, LEDs) generate pulses of light that are transmitted on optical fiber
  - Very long distances (>1000 km)
  - Very high speeds (>40 Gbps/wavelength)
  - Nearly error-free (BER of $10^{-15}$)
- Profound influence on network architecture
  - Dominates long distance transmission
  - Distance less of a cost factor in communications
  - Plentiful bandwidth for new services

Transmission in Optical Fiber

- Very fine glass cylindrical core surrounded by concentric layer of glass (cladding)
- Core has higher index of refraction than cladding
- Light rays incident at less than critical angle $\theta_c$ is completely reflected back into the core
Multimode & Single-mode Fiber

- Multimode: Thicker core, shorter reach
  - Rays on different paths interfere causing dispersion & limiting bit rate
- Single mode: Very thin core supports only one mode (path)
  - More expensive lasers, but achieves very high speeds

Optical Fiber Properties

Advantages
- **Very low attenuation**
- **Noise immunity**
- **Extremely high bandwidth**
- Security: Very difficult to tap without breaking
- No corrosion
- More compact & lighter than copper wire

Disadvantages
- New types of optical signal impairments & dispersion
- Polarization dependence
- Wavelength dependence
- Limited bend radius
- If physical arc of cable too high, light lost or won’t reflect
- Will break
- Difficult to splice
- Mechanical vibration becomes signal noise
**Very Low Attenuation**

- Water Vapor Absorption (removed in new fiber designs)
- Infrared absorption

![Graph showing attenuation vs. wavelength](image)

- 850 nm Low-cost LEDs
- 1300 nm Metropolitan Area Networks “Short Haul”
- 1550 nm Long Distance Networks “Long Haul”

**Huge Available Bandwidth**

- Optical range from $\lambda_1$ to $\lambda_1 + \Delta \lambda$ contains bandwidth

$$B = f_1 - f_2 = \frac{\nu}{\lambda_1} - \frac{\nu}{\lambda_1 + \Delta \lambda}$$

$$= \frac{\nu}{\lambda_1} \left( \frac{\Delta \lambda / \lambda_1}{1 + \Delta \lambda / \lambda_1} \right) \approx \frac{\nu \Delta \lambda}{\lambda_1^2}$$

- Example: $\lambda_1 = 1450$ nm
  $\lambda_1 + \Delta \lambda = 1650$ nm:

$$B = \frac{2 \times 10^8 \text{m/s}}{200 \text{nm}^2 (1450 \text{ nm})^2} \approx 19 \text{ THz}$$

![Graph showing bandwidth calculation](image)

Ref [6]
References

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