WIRELESS COMMUNICATIONS

• Preliminaries
• Radio Environment
• Modulation
• Performance

PRELIMINARIES

• dB's and dBm's
• Frequency/Time Relationship
• Bandwidth, Symbol Rate, and Bit Rate
**DECIBELS**

- *Relative* signal strengths are measured on a log scale to facilitate the comparison of large differences.

- Relative power (e.g., loss or gain)
  - gain or loss in dB = $10 \log (P_2/P_1)$

- Power relative to $P_0$
  - $P$ (dBW) = $10 \log (P/1$ Watt)
  - $P$ (dBm) = $10 \log (P/1$ mWatt)
  - $0$ dBW = $30$ dBm

**FREQUENCY-TIME RELATIONSHIP**

- Signal uniquely represented in time or frequency domain
- Fourier coefficients are frequency components of signal

\[
X(f) = \int_{-\infty}^{\infty} x(t)e^{-j2\pi ft} dt \quad x(t) = \int_{-\infty}^{\infty} X(f)e^{j2\pi ft} df
\]

Time-limited signals have infinite frequency content
Band-limited signals have infinite time duration
“Uncertainty Principle”
SIGNAL BANDWIDTH

- For bandlimited signals, bandwidth $B$ defined as range of positive frequencies for which $|X(f)| > 0$.
- In practice, all signals are time-limited, not band-limited → Need alternate bandwidth definition

### Bandlimited

#### Null-to-Null

### 3dB

BANDWIDTH AND TRANSMISSION RATE

Symbol Rate = $1/T$

“Bandwidth” = $1/T$

Bit Rate = Symbol Rate $\times$ Number of Bits/Symbol

$k = \text{Number of Bits/Symbol} = \log_2(M)$
COMMUNICATION SYSTEM

- Source encoder converts message (or bits) into bits.
- Transmitter converts bits into a transmitted signal at some carrier frequency → modulation
- Channel introduces distortion, noise, and interference.
- Receiver detects the signal and converts to bits.
- Source decoder converts back to original format.

RADIO ENVIRONMENT

- Path Loss
- Shadow Fading
- Multipath
  - Flat fading
  - Doppler spread
  - Delay spread
- Interference
PATH LOSS MODEL

- Different, often complicated, models are used for different environments.

- A simple model for path loss, $L$, is
  \[ L = \frac{P_r}{P_t} = K \frac{1}{d^\alpha} \]
  where $P_r$ is the local mean received signal power, $P_t$ is the transmitted power, and $d$ is TX/RX distance.
  The path loss exponent $\alpha = 2$ in free space; $2 \leq \alpha \leq 4$ in typical environments.

PATH LOSS LIMITATIONS

- The received signal-to-noise power ratio, SNR, is
  \[ \text{SNR} = \frac{P_r}{P_n} = \frac{K P_t}{d^\alpha} \cdot \frac{1}{N_0 B} \]
  where $N_0$ is the one-sided noise spectrum and $B$ is the signal bandwidth.
  
- Given the performance requirement $\text{SNR} \geq \text{SNR}_0$, the path loss imposes limits on the bit rate and the signal coverage.
  \[ B \leq \frac{K P_t}{d^\alpha N_0 \text{SNR}_0} \quad \text{or} \quad d \leq \left( \frac{K P_t}{N_0 B \text{SNR}_0} \right)^{1/\alpha} \]
EXAMPLE – OUTDOOR

\[ \text{SNR}_0 = 8 \text{ dB} \]
\[ K = -38 \text{ dB} \]
\[ N_0 = -204 \text{ dB/Hz} \]
\[ \alpha = 4 \]
\[ P_t = 0 \text{ dB (1 Watt)} \]

Suppose it is desired to provide coverage for cells with 1 km radius

\[ B \leq 6.3 \text{ kHz} \]

Alternatively, suppose \( B = 200 \text{ kHz} \),

\[ d \leq 420 \text{ meters} \]

EXAMPLE – INDOOR

\[ \text{SNR}_0 = 12 \text{ dB} \]
\[ K = -45 \text{ dB} \]
\[ N_0 = -204 \text{ dB/Hz} \]
\[ \alpha = 3.5 \]

\[ B = 100 \text{ MHz} \]
\[ d = 100 \text{ meters} \]

\[ P_t = \frac{N_0 B \text{ SNR}_0 d^\alpha}{K} \]

\[ = 200 \text{ mW} \]
SHADOW FADING

- The received signal is shadowed by obstructions such as hills and buildings.
- This results in variations in the local mean received signal power,

\[ P_r(dB) = P_r(dB) + G_s \]

where \( G_s \sim N(0, \sigma_s^2) \), \( 4 \leq \sigma_s \leq 10\, \text{dB} \).

- Implications
  - nonuniform coverage
  - increases the required transmit power

MULTIPATH

\[ h(t) = \sum a_i e^{j\theta} \delta(t-t_i) \]

Constructive and destructive interference of arriving rays
FLAT FADING

- The delay spread is small compared to the symbol period.
- The received signal envelope, $r$, follows a Rayleigh or Rician distribution.

$$P_r(dB) = P_t(dB) + G_S + 20 \log r$$

- Implications
  - increases the required transmit power
  - causes bursts of errors

DOPPLER SPREAD

- A measure of the spectral broadening caused by the channel time variation.

$$f_D \leq \frac{v}{\lambda}$$

Example: 900 MHz, 60 mph, $f_D = 80$ Hz
5 GHz, 5 mph, $f_D = 37$ Hz

- Implications
  - signal amplitude and phase decorrelate
  - after a time period $\sim 1/f_D$
**DELAY SPREAD**

**TIME DOMAIN INTERPRETATION**

Two-ray model
\( \tau = \text{rms delay spread} \)

- \( \frac{\tau}{T} \text{ small} \rightarrow \text{negligible intersymbol interference} \)
- \( \frac{\tau}{T} \text{ large} \rightarrow \text{significant intersymbol interference, which causes an irreducible error floor} \)

**DELAY SPREAD**

**FREQUENCY DOMAIN INTERPRETATION**

- \( \frac{\tau}{T} \text{ small} \rightarrow \text{flat fading} \)
- \( \frac{\tau}{T} \text{ large} \rightarrow \text{frequency-selective fading} \)
The rms delay spread imposes a limit on the maximum bit rate. For example, for QPSK

\[ \frac{\tau}{T} = \text{rms delay spread} \div \text{symbol period} \]

<table>
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<th>Modulation</th>
<th>Modulation</th>
<th>Coherent Detection</th>
<th>+</th>
<th>BPSK</th>
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<th>Irreducible Pb</th>
<th>Maximum Bit Rate</th>
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<td>8 kbps</td>
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<tr>
<td>Mobile (city)</td>
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<td>Microcells</td>
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<tr>
<td>Large Building</td>
<td>100 nsec</td>
<td>2 Mbps</td>
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**INTERFERENCE**

- Frequencies are reused often to maximize spectral efficiency.

- For interference-limited systems, the noise floor is dominated by co-channel interference.

\[ \frac{S}{I + N} \approx \frac{S}{I} \cdot \left( \frac{D}{R} \right)^{\alpha} \]

- Implications
  - high reuse efficiency requires interference mitigation
PASSBAND DIGITAL MODULATION

\[ s(t) = \sum_{n=-\infty}^{\infty} A_n(t) \cos(2\pi f_c t + \theta_n(t)) \]

- Bits encoded in amplitude, phase, or frequency of \( s(t) \).
- \( A_n \) and \( \theta_n(t) \) are constant over a bit time \( T_b \)
- These values change every \( T_b \)

ASK, PSK, AND FSK

- **Amplitude Shift Keying (ASK)**
  \[ s(t) = m(t) A_n \cos(2\pi f_c t) = \begin{cases} A_n \cos(2\pi f_c t) & m(nT_b) = 1 \\ 0 & m(nT_b) = 0 \end{cases} \]

- **Phase Shift Keying (PSK)**
  \[ s(t) = A \cos(2\pi f_c t + m(nT_b) \pi) \begin{cases} A \cos(2\pi f_c t + \pi) & m(nT_b) = 1 \\ A \cos(2\pi f_c t) & m(nT_b) = -1 \end{cases} \]

- **Frequency Shift Keying**
  \[ s(t) = \begin{cases} A_1 \cos(2\pi f_c t) & m(nT_b) = 1 \\ A_2 \cos(2\pi f_c t) & m(nT_b) = -1 \end{cases} \]
PERFORMANCE

AWGN

PERFORMANCE

FLAT FADEING