Advanced Digital Communications

- Wireless Channel - Multipath
- Multitone systems
- Timing/Synchronization

Simplified view of wireless channel - multipath

\[ H_{\text{Channel}}(f) = A_0 e^{-j2\pi f T_0} + A_1 e^{-j2\pi f T_1 + \theta_1} \]

- Attenuation and delay both related to distance
  - Attenuation \( \sim 1/d^2 \)
  - Delay \( \sim d \)
**Frequency view of the channel**

A1=0.1, T1=10ns and
A2=0.05, T2=30ns
i.e. d1=3m, d2=9m

- Channel shows considerable frequency selectivity
  - Causes intersymbol interference in time domain

**Real wireless channel**

http://tie02.google.com/images/zoom/r1h09e9b0pix/364704/868704/http://www.de-aod.de/People/Nicolausspath_propagation.jpg
Real wireless channel – frequency view

|H(f,t)|[dB]|H(f,t)|[dB|

Time-varying

Frequency-selective (multipath)

Communication theory view

- Multitone modulations
- Convolutional/Block coding and Viterbi/RS decoding
- Synchronization – tracking loops
- Channel Estimation
Very complicated – so divide & conquer

Basic multitone modulation

- Best performance if transmission is tailored to the channel
  - Use a lot of carriers
  - Each tone transmits narrow QAM signal and satisfies Nyquist criterion – i.e. no ISI per tone
  - Put less energy where channel is bad or where there is more noise
A bit of history

- 1948 Shannon constructs capacity bounds
  - AWGN channel with linear ISI - effectively uses multi-tone modulation
- Analog multi-tone
  - 1958 Collins Kineplex modem (first voiceband modem) - analog multitone
  - 1964 Holsinger's MIT thesis - modem that approximates Shannon's "water-filling"
  - 1967 Saltzberg, 1973 Bell Labs, 1980 IBM ...

- Digital multi-tone ~ 1990s
  - DMT for DSL - Major push by Prof. Cioffi's group at Stanford
  - Use DSP power to improve the robustness and algorithms for discrete multi-tone modulation
  - We will mostly focus on this type of modulation

Basic multi-tone transmission

- Each tone sees AWGN channel
  - no ISI
  - N QAM-like symbols (complex)
Digital multitone implementation (DMT/OFDM)

- Data rate penalty
- Cyclic prefix
- Symbol 1
- Symbol 2
- Multipath ISI

802.11a Wireless LAN example

- Up to 54Mbps symmetrically (<100m)
- 1-3 Tx power levels
- Complex baseband
  - unlike ADSL which is real baseband
- N=64 (-31 ... 31) (so 128 dimensions I and Q)
  - Symbol length = 80 samples, CP=16
  - Symbol rate 250kHz (T=4μS, T'=50ns), CPguard=0.8μs
- Broadcast channel - can’t optimize bit allocation
  - FCC demands flat spectrum so no energy-allocation
  - The only knob is data rate selection
  \[ R = k(1 \text{ bit } /2 \text{ dimensions}) \cdot (48 \text{ tones}) \cdot 250kHz \text{ or } 6 \cdot kMbps \]
Spectral mask

- Cannot use last 5 tones on each side

High-level system view

Data link control layer (DLC)

Physical radio layer (PHY)

<table>
<thead>
<tr>
<th>Digital</th>
<th>Analog</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viterbi decoder + descrambler</td>
<td>A/D</td>
</tr>
<tr>
<td>Demodulation + deinterleaver</td>
<td>Analog front-end</td>
</tr>
<tr>
<td>Guard interval extraction + FFT</td>
<td></td>
</tr>
<tr>
<td>Scrambler + forward error correction (FEC) coder</td>
<td></td>
</tr>
<tr>
<td>Interleaver + modulation</td>
<td></td>
</tr>
<tr>
<td>IFFT + guard interval insertion</td>
<td></td>
</tr>
</tbody>
</table>

Synchronization
Transceiver architecture

- Scrambler
- Encoder
- Interleaver
- Mapper
- Pilot insertion
- FFT/IFFT
- Cyclic prefix
- Windowing
- DAC
- Unconvert

- Descrambler
- Viterbi decoder
- Deinterleaver
- Demapper
- Channel estimator
- Synchronizer
- Remove prefix
- AGC & ADC
- LNA & Downconvert

Scrambling

- Need to randomize incoming data
- Enables a number of tracking algorithms in the receiver
- Provides flat spectrum in the given band

pseudo-random bit sequence (prbs) generator
Interleaver

- Protects the code from overload by burst errors
- Block interleaver
  - Block size is the # of coded bits in OFDM symbol
  - Two-step permutation
  - Adjacent coded bits mapped onto nonadjacent sub-carriers

Convolutional Encoder

- Rate 1/2 convolutional encoder
  - Punctured to obtain 2/3 and 3/4 rate
  - Omit some of the coded bits
- 64-state (constraint length K=7) code
- Viterbi algorithm applied in the decoder
Signal mapper

- BPSK, QPSK, 16-QAM, 64-QAM
  - Data divided into groups of (1, 2, 4, 6) bits and mapped to a constellation point (i.e. a complex number)
  - Gray-coded constellation mappings
  - Need the same average power for all mappings
    - Scale the output by $K_{\text{MOD}}$

Pilot insertion and FFT/IFFT

- Pilot insertion
  - Pilots BPSK, modulated by pseudo-random bit sequence

- FFT and IFFT shared
  - Just flip the Re and Im inputs
Receiver architecture

Pilot tracking and channel correction

- OFDM packet structure
Synchronizer (frequency offset tracking)

Processing Datapath

Delay 16

Delay 48

Numerically Controlled Oscillator

FFT

Output Symbols

Moving Average 64

Magnitude

Plateau Detector

Moving Average 16

Angle Arctan

Combine

Tracking Datapath

Channel estimator
Summary

- Real wireless channels selective in time and frequency
- Use lots of parallel narrowband transmissions to avoid frequency selectivity (sub-channels)
- Width of the band limited by time-selectivity of the channel
  - In narrowband sub-channel symbol lasts for long time so channel may change
- Modern systems use Fast Fourier Transform to create/receive many symbols on different tones/sub-channels
- Use the power of digital circuits to process the signals
  - Filter and synchronize

In 6.083/6.973 we’ll try to cut ACROSS
- Project oriented class (wireline or wireless modem)

Examples 802.11a, UWB, MIMO, CDMA