PHY II: The Wireless Channel and OFDM

COS 598a: Wireless Networking and Sensing Systems

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[Parts adapted from P. Steenkiste, D. Tse]
Context: Propagation modes

- **Multipath propagation**
  - Most common form of propagation
  - Happens above ~ 30 MHz
  - Subject to many forms of degradation

- **Ground-wave propagation**
  - More or less follows the contour of the earth
  - For frequencies up to about 2 MHz, e.g. AM radio

- **Sky wave propagation**
  - Signal “bounces” off the ionosphere back to earth – can go multiple hops
  - Used for amateur radio and international broadcasts
Besides line of sight, signal can reach receiver in three other “indirect” ways:

- **Reflection**: signal is reflected from a large object.
- **Diffraction**: signal is scattered by the edge of a large object – “bends”.
- **Scattering**: signal is scattered by an object that is small relative to the wavelength.
Refraction

- Speed of EM signals depends on the density of the material
  - Vacuum: $3 \times 10^8$ m/sec
  - Denser: slower

- Density is captured by *refractive index*

- Explains “bending” of signals in some environments
  - *e.g.* sky wave propagation
  - *e.g.* propagation through walls
Sinusoidal carrier, line of sight only

- Transmitted signal: \( x(t) = a(t) \cdot \cos(2\pi f_c t + \varphi(t)) \)

- Path **attenuation** \( a \), **distance** \( d \), **time of flight** \( \tau \)
  - Complex channel \( h = ae^{j2\pi d/\lambda} \)

- Received signal: \( y(t) = h \cdot x(t) + n(t) \)
  - Relation: \( \frac{d}{\lambda} = f_c \tau \)
• Channel is now \( h = a_1 e^{j2\pi d_1/\lambda} + a_2 e^{j2\pi d_2/\lambda} \)

• Suppose \( d_2 - d_1 = \lambda/2 \) and \( d_1 \approx d_2 \):
  – Then \( h \approx 0 \) so receive approx. zero (destructive fading)

At different \( \lambda \), \( h \neq 0 \): fading is selective in frequency
Multipath causes frequency selectivity

- Interference between reflected and line-of-sight radio waves results in frequency dependent fading
What does the channel look like in time?

Channel impulse response $h(t)$

$\tau_1, \alpha_1, d_1, \tau_1$

$\alpha_2, d_2, \tau_2$

Delay spread $T_d$
Problem: Inter-symbol interference (ISI)

- Transmitted signal
- Received signal with ISI
Problem: Inter-symbol interference (ISI)

- Transmitted signal
- Received signal with ISI
- ISI at one symbol depends on the value of other symbols
Solution: Slow down

- Transmitted signal
- Received signal

Input waveform, $w_{in}(t)$

Individual pulse response

Received waveform, $w_{out}(t)$ (sum of pulse responses)

No ISI

Intersymbol interference
Symbol time determines frequency bandwidth

**Symbol time**

Slowing down by a factor of two halves the frequency bandwidth of the sender’s signal
A narrowband signal “fits into” the coherence bandwidth

- Over what frequency range is the channel approximately the same? This is the coherence bandwidth $W_c \approx \frac{1}{2T_d}$
**Summary: Wideband versus narrowband**

- **Frequency selective fading** distorts wide-band signals.

- **Multipath** causes ISI.

- **Narrow band signals** require **longer symbols**.
Benefits of narrowband

Channel impulse response

1 Channel (serial)

2 Channels

8 Channels

Channel transfer function

Signal is “broadband”

Channels are “narrowband”
Channel model

1. Transmits signal $x$: modulated carrier at frequency $f$

2. Signal is attenuated

3. Multi-path + mobility cause fading

4. Noise is added

5. Doppler effects distort signal

6. Receives distorted Signal $y$

$$x \times h + n = y$$
OFDM - Orthogonal Frequency Division Multiplexing

- Distribute bits over N subcarriers that use different frequencies in the band B
  - Multi-carrier modulation
  - Each signal uses ~B/N bandwidth
- Since each subcarrier only encodes 1/N of the bit stream, each symbol takes N times longer in time
- Challenge is efficiently packing many subcarriers in a band - later
Distributing bits over subcarriers

Channel impulse response

Single Channel

2 Channels

8 Channels

Channels are transmitted at different frequencies (sub-carriers)

Resistance improves with number of channels
OFDM subcarriers are “Orthogonal”

- Peaks of spectral density of each carrier coincide with the zeros of the other carriers
  - Carriers can be packed very densely with minimal interference
  - Requires very good control over frequencies
Densely Packing OFDM Channels

Conventional multicarrier techniques

Orthogonal multicarrier techniques

Saving of bandwidth

50% bandwidth saving
Problem: Adjacent Symbol Interference
Problem: Receiver synchronization

Receiver's view of Symbol 1 contains actual Symbols 1 and 2
Interference solution: Inter-symbol guard interval

Guard interval between adjacent symbols mitigates adjacent symbol interference
Synchronization solution: Cyclic prefix

Receiver: Symbol OK!
Example: IEEE 802.11a, 802.11g

- OFDM with up to 48 subcarriers
  - Subcarrier spacing is 312.5 KHz
  - Subcarriers modulated: BPSK, QPSK, 16-QAM, or 64-QAM

- Uses a convolutional code at a rate of $\frac{1}{2}, \frac{2}{3}, \frac{3}{4},$ or $\frac{5}{6}$ to provide forward error correction

- Results in data rates of 6, 9, 12, 18, 24, 36, 48, and 54 MBps

- Cyclic prefix is 25% of a symbol time (16 vs 64)
OFDM Transmitter

Convolutional Encoder → Serial to Parallel → iFFT → Parallel To Serial

Cyclic Prefix → DAC → Modulation → Parallel To Serial

$\text{Modulation}$

$\text{Convolutional Encoder}$

$\text{Serial to Parallel}$

$\text{iFFT}$

$\text{Parallel To Serial}$

$\text{Cyclic Prefix}$

$\text{DAC}$

$\text{Modulation}$

$\text{Parallel To Serial}$
OFDM in 802.11

- Uses punctured code: add redundancy and then drop some bits to reach a certain level of redundancy