Small-scale multipath fading

- Multipath fading due to constructive and destructive interference of the transmitted waves at very high carrier frequency.

Example

- Difference in phases of direct and reflected waves:
  \[ \frac{2\pi}{\lambda}[(2d-r) - r] + \pi = \frac{4\pi}{\lambda}d + \pi \]
  where \( \lambda \) is the wavelength of the signal.
- Movement of \( \lambda/4 \) goes from a peak to a valley. (this is 0.3m at frequency 900 MHz)

Fading is also Frequency Selective

Why?
\[ \Delta \text{ in wavelength} = \frac{4\pi(d-r)}{\lambda} + \frac{4\pi f}{c}(d-r) + \pi \]
 depends on frequency.
When \( f \) changes by \( c/[4(d-r)] \), valley becomes peak.

Multipath Channel as LTI System

- Wireless channels can be modeled as LTI systems:
  \[ y(t) = \sum a_i x(t - \tau_i) \]
  where \( a_i, \tau_i \) are the gain and delay of path \( i \).
- The impulse response is:
  \[ h(\tau) = \sum a_i \delta(\tau - \tau_i) \]
  with frequency response \( H(f) \).

How to turn unreliable physical channel into a reliable link?

- If a bit is sent when the channel is in deep fade, it will be lost.

Diversity

- Let probability in deep fade = \( p \) (say 0.2, unacceptable.)
- Provide \( L \) independent "looks" at the information bit.
- As long as at least one of the "looks" are not in deep fade, then information can be recovered.
- Probability of error reduced to \( p^L \).
- The independent looks can be at different points in space (time) or frequency.
Spatial Diversity via Antennas

Antennas should be at a wavelength or more apart.

Spatial Diversity via Motion (aka. Time Diversity)

Can get diversity if we send the same symbol at times separated by approximately $\lambda/v$ seconds apart.

For 900 MHz cellular and vehicular speed of 100 km/hr, $\lambda/v = 10$ milliseconds.

If the delay constraint is $D$ milliseconds, then we can send the symbol $D/10$ times, so as to get $D/10$-fold diversity.

Frequency Diversity

- Multipath wireless channels are frequency-selective.
- By repeating the same information bit at different frequencies (frequency hopping), we get frequency diversity.

Glamorous History of Frequency Hopping

Example: OFDM in 802.11a

- 48 sub-carriers over a 20 MHz channel.
- Information is conveyed in the frequency domain, and converted into time-domain signal by IDFT.

Time Diversity via Interleaving: GSM Example

Amount of time diversity limited by delay constraint and how fast channel varies.
In GSM, delay constraint is 40ms (voice).
OFDM in 802.11a

- Channel bandwidth determines the total symbol rate (number of sub-carriers x symbol rate of each sub-carrier)
- Aggregate data rates range from 6, 9, 12, 18, 24, 36, 48, 54kbps, depending on how many bits are modulated into each transmitted symbol on each carrier.
- When channel strength is strong, the number of possible levels each symbol can take on is larger, conveying more bits per symbol. (eg. 2, 4 or 8 levels)
- By coding and interleaving over the sub-carriers, frequency diversity is achieved.
- Repeating the same symbol across different sub-carriers is the simplest form of coding: repetition coding. Higher spectral efficiency can be achieved by more efficient coding.