Wireless & Mobile Networking

CS 752/852 - Spring 2011

Tamer Nadeem
Dept. of Computer Science
Wireless Communication

[Diagram of wireless communication process]

1. Start with a message
2. Transmitter encodes the message
3. Encoded message is transmitted
4. Encoded message is received
5. Receiver decodes the message

[Diagram of transmitter and receiver components]

- Transmitter components: microphone, modulator, radio frequency oscillator
- Receiver components: tuned circuit, demodulator, amplifier, loudspeaker

[Diagram illustrating the interaction between transmitter and receiver]
Radio Signal Basics
Radio Signal

- When the electrons run through a wire (transmitting antenna), they create electromagnetic sinusoidal waves that can propagate through the space.
  - Electric field
  - Magnetic field
  - Propagation direction

- By attaching an antenna of the appropriate size to an electrical circuit, the electromagnetic waves can be broadcast efficiently and received by a receiver distance away.
Basics of Signal

- The number of oscillations per second of an electromagnetic wave is called its frequency, \( f \), measured in Hertz.
- The distance between two consecutive maxima is called the wavelength, designated by \( \lambda \).

- By knowing the frequency of a wave and its wavelength, we can find its velocity \( (v) \): \( v = \lambda f \).
- Velocity of a wave is only affected by the properties of the medium:
  - In vacuum, waves travel at the speed of light \( c = 3 \times 10^8 \) m/sec.
  - In copper or fiber, the speed slows down to about 2/3 of this value.
Fourier Transform

• Sinusoidal waves, also called harmonics, are represented as: \( s(t) = A_t \sin(2 \pi f_t t + \varphi_t) \)
  with frequency \( f \), amplitude \( A \), phase shift \( \varphi \)

• Every Signal Can be Decomposed as a Collection of Harmonics

\[
g(t) = \frac{1}{2} c + \sum_{n=1}^{\infty} a_n \sin(2\pi nft) + \sum_{n=1}^{\infty} b_n \cos(2\pi nft)
\]
Time Domain v.s. Frequency Domain

Knowing one can recover the other.
Signal Interference

- **Signals add up**

- **Apply Fourier transform**
Signal Bandwidth

- A typical signal will include many frequencies (Fourier theorem)

- **Spectrum**: The range of frequencies in a signal
  - In this case: \([f_1 \ldots f_2]\)

- **Bandwidth**: The width of the Spectrum
  - In this case: \((f_2 - f_1)\)
Signal Bandwidth

• The amount of information a wireless channel can carry is related to its bandwidth

• Most wireless transmissions use a narrow frequency band ($\Delta f << f$) where
  - $\Delta f$: frequency band
    • $f$: middle frequency where transmission occurs

• New technologies use spread spectrum techniques
  • a wider frequency band is used for transmission
Bandwidth Allocation

In the U.S., the FCC is responsible for allocating radio frequencies.

Why allocate the radio spectrum?
- Prevent interference between different devices
- It would be unfortunate if the local TV station interfered with police radio...

Generally, any transmitter is limited to a certain bandwidth
- e.g., a single 802.11 channel is 30 MHz “wide”

FCC also regulates the *power* and *placement* of transmitters
- Consumer devices generally limited to transmitting < 1 W of power
- Can't have two TV stations on channel 5 next to each other

- Radio Frequencies:
  3KHz < RF < 300GHz
Chart of the Electromagnetic Spectrum

<table>
<thead>
<tr>
<th>Wavelength (m)</th>
<th>10^3</th>
<th>10^2</th>
<th>10^1</th>
<th>1</th>
<th>10^-1</th>
<th>10^-2</th>
<th>10^-3</th>
<th>10^-4</th>
<th>10^-5</th>
<th>10^-6</th>
<th>10^-7</th>
<th>10^-8</th>
<th>10^-9</th>
<th>10^-10</th>
<th>10^-11</th>
<th>10^-12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavenumber (cm^-1)</td>
<td>10^-5</td>
<td>10^-4</td>
<td>10^-3</td>
<td>10^-2</td>
<td>10^-1</td>
<td>1</td>
<td>10</td>
<td>10^2</td>
<td>10^3</td>
<td>10^4</td>
<td>10^5</td>
<td>10^6</td>
<td>10^7</td>
<td>10^8</td>
<td>10^9</td>
<td>10^10</td>
</tr>
<tr>
<td>Electron Volt (eV)</td>
<td>10^-9</td>
<td>10^-8</td>
<td>10^-7</td>
<td>10^-6</td>
<td>10^-5</td>
<td>10^-4</td>
<td>10^-3</td>
<td>10^-2</td>
<td>10^-1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>10^2</td>
<td>10^3</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>10^8</td>
<td>10^7</td>
<td>10^6</td>
<td>10^5</td>
<td>10^4</td>
<td>10^3</td>
<td>10^2</td>
<td>10^1</td>
<td>1</td>
<td>10</td>
<td>100</td>
<td>10^3</td>
<td>10^4</td>
<td>10^5</td>
<td>10^6</td>
<td>10^7</td>
</tr>
</tbody>
</table>

**Radio Spectrum**

- **Broadcast and Wireless**
- **Microwave**

**Terahertz**

**Infrared**

**Ultraviolet**

**X-ray**

**Gamma**

**Sources and Uses of Frequency Bands**

- **AM radio** 600kHz-1.6MHz
- **FM radio** 88-108 MHz
- **Mobile Phones** 900MHz-2.4GHz
- **Radar** 1-100 GHz
- **Visible wavelength (nm)**
- **Fiber telecom** 0.7-1.4μ
- **Dental Curing** 200-350nm
- **Medical X-rays** 10-0.1Å
- **Cosmic ray observations** ≈1 Å

**Optics**

- **Visible Light** 425-750THz
- **Visible Light** 700-400nm

**Screening**

- **Screening** 0.2-4.0 THz
- **Night Vision** 10-0.7μ

**Remotes**

- **Remotes** 850 nm

**Suntan**

- **Suntan** 400-290nm

**Crystallography**

- **Crystallography** 2.2-0.7Å

- **Baggage screen** 10-1.0Å

- **PET imaging** 0.1-0.01Å
Frequencies and Regulations

- ITU-R holds auctions for new frequencies, manages frequency bands worldwide (WRC, World Radio Conferences)

<table>
<thead>
<tr>
<th></th>
<th>Europe</th>
<th>USA</th>
<th>Japan</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cordless Phones</strong></td>
<td>CT1+ 885-887, 930-932 CT2 864-868 DECT 1880-1900</td>
<td>PACS 1850-1910, 1930-1990 PACS-UB 1910-1930</td>
<td>PHS 1895-1918 JCT 254-380</td>
</tr>
<tr>
<td><strong>Wireless LANs</strong></td>
<td>IEEE 802.11 2400-2483 HIPERLAN 2 5150-5350, 5470-5725</td>
<td>902-928 IEEE 802.11 2400-2483 5150-5350, 5725-5825</td>
<td>IEEE 802.11 2471-2497 5150-5250</td>
</tr>
<tr>
<td><strong>Others</strong></td>
<td>RF-Control 27, 128, 418, 433, 868</td>
<td>RF-Control 315, 915</td>
<td>RF-Control 426, 868</td>
</tr>
</tbody>
</table>
Signal Propagation Basics
Wireless Communication

1. Start with a message
2. Encoded message is transmitted
3. Transmitter encodes the message
4. Encoded message is received
5. Receiver decodes the message

- Transmitter
  - Transmitting aerial
    - Microphone
    - Modulator
    - Radio frequency oscillator

- Receiver
  - Receiving aerial
    - Tuned circuit
    - Demodulator
    - Amplifier
    - Loudspeaker
Radio Propagation

- As it turns out, radio waves are
  - easy to generate
  - can travel long distances
  - can penetrate buildings
  - are omni-directional: can travel in all directions
  - can be narrowly focused at high frequencies (greater than 100MHz) using parabolic antennas (like satellite dishes)

Properties of radio waves are frequency dependent

- at low frequencies, they pass through obstacles well, but the power falls off sharply with distance from source
- at high frequencies, they tend to travel in straight lines and bounce of obstacles (they can also be absorbed by rain)
- are subject to interference from other radio wave sources
Basics of Radio Propagation

At VLF, LF, and MF bands, radio waves follow the ground. AM radio broadcasting uses MF band.

At HF bands, the ground waves tend to be absorbed by the Earth. The waves that reach the ionosphere (100-500 km above Earth surface), are reflected back to the Earth.
Basics of Radio Propagation

VHF transmission

- Directional antennas are used
- Waves follow more direct paths
- **LoS**: Line-of-Sight communication
- Reflected waves may interfere with the original signal
Basics of Radio Propagation

• Receiving power additionally influenced by
  • shadowing (e.g. through a wall or a door)
  • refraction depending on the density of a medium
  • reflection at large obstacles
  • scattering at small obstacles
  • diffraction at edges
Basics of Radio Propagation

• We are interested in propagation characteristics and models for waves with frequencies in range: few MHz to a few GHz

• Modeling the radio channel is important to
  • determine the coverage area of a transmitter
    • the transmitter power requirement
    • the battery lifetime
  • adopt modulation and coding schemes to improve the channel quality
    • determine the maximum channel capacity
Basics of Radio Propagation

• As the receiver unit moves, propagated signals have an impact on the received signal strength either constructively or destructively

• As the receiver unit moves over small distances, the instantaneous received signal will fluctuate rapidly giving rise to small-scale fading (Rayleigh fading)
  • in small scale fading, the received signal power may change as much as 3 or 4 orders of magnitude (30dB or 40dB), when the receiver moves a fraction of the wavelength

• As the receiver unit moves away from the transmitter over larger distances, the mean received signal gradually decreases. This is called large-scale fading (path loss)

• The models that predict the mean signal strength for an arbitrary-receiver transmitter (T-R) separation distance are called large-scale propagation models
  • useful for estimating the coverage area of transmitters
Small- and Large-scale fading

Received Power (dBm)

T-R Separation (meters)
What is a decibel (dB)?

• By convention, a decibel (dB) decibel is a logarithmic unit used to describe a ratio

• For example, given two values $P_1$ and $P_2$, the difference between $\log P_1$ and $\log P_2$ is expressed in dB by

\[
10 \log (P_1/P_2) \text{ dB}
\]

• for example if the transmit power $P_1 = 100W$, and the received power is $P_2 = 1 W$, the path loss (in dB) is

\[
10\log (100/1) = 20\text{dB}
\]
What is a decibel (dB)?

- The use of dB is convenient as large numbers (rather, their difference) is expressed by numbers of small size
  - examples:
    - Tx power = 100W, received power = 1W
      - Tx power is 100 times the received power
      - difference is **20dB**
    - Tx power = 100W, received power = 1mW
      - Tx power is 100,000 times the received power
      - difference is **50dB**
    - Tx power = 1000W, received power = 1mW
      - Tx power is 1,000,000 times the received power
      - difference is **60dB**
What is a decibel (dB)?

- 10 times the power gives +10 dB
- Twice the power gives +3 dB
- Same power gives 0 dB difference
- One half the power gives −3 dB
- One tenth the power gives −10 dB
mW and dBm

Decibels refers to relative *changes* in magnitude, not absolute values.

So ... we define the **dBW (decibel-Watt)** as a reference:
- 1 Watt of transmission power == 0 dBW
- Example: WGBH, 89.7FM in Boston transmits at 100,000 Watts
- Power in dBW = 10 * log(100,000W / 1W) = 10 * 5 = 50 dBW

For wireless networks, the **dBm (decibel-milliwatt)** is more useful:
- 1 mW transmission power == 0 dBm
- 10 mW == 10 dBm
- 0.1 mW == -10 dBm
- 802.11b networks have a max transmit power of 100 mW == 20 dBm
Free-Space Propagation Model

• Used to predict the received signal strength when transmitter and receiver have clear, unobstructed LOS path between them.

• The received power decays as a function of T-R separation distance raised to some power.

• **Path Loss**: Signal attenuation as a positive quantity measured in dB defined as the difference (in dB) between the effective transmitter power and the received power
Free-Space Propagation Model

• In free space, receiving power proportional to $1/d^2$ ($d =$ distance between transmitter and receiver)

• Writing path loss in log scale:
  $PL = 10 \log(P_t) - 10\log(Pr)$

$$\frac{P_r}{P_t} = G_r G_t \left(\frac{\lambda}{4\pi d}\right)^2$$

- $P_r$: received power
- $P_t$: transmitted power
- $G_r, G_t$: receiver and transmitter antenna gain
- $\lambda (=c/f)$: wave length
Long Distance Path Loss Model

- The average large-scale path loss for an arbitrary T-R separation is expressed as a function of distance by using a path loss exponent $n$

\[
\overline{PL}(d) \propto \left( \frac{d}{d_0} \right)^n
\]

\[
\overline{PL}(dB) = \overline{PL}(d_0) + 10n \log\left( \frac{d}{d_0} \right)
\]

- The value of $n$ depends on the propagation environment: for free space it is 2; when obstructions are present it has a larger value

- Reference distance ($d_0$):
  - In large coverage cellular systems, 1km reference distances are commonly used
  - In microcellular systems, much smaller distances are used: such as 100m or 1m
Path Loss Exponent for Different Environments

<table>
<thead>
<tr>
<th>Environment</th>
<th>Path Loss Exponent, $n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free space</td>
<td>2</td>
</tr>
<tr>
<td>Urban area cellular radio</td>
<td>2.7 to 3.5</td>
</tr>
<tr>
<td>Shadowed urban cellular radio</td>
<td>3 to 5</td>
</tr>
<tr>
<td>In building line-of-sight</td>
<td>1.6 to 1.8</td>
</tr>
<tr>
<td>Obstructed in building</td>
<td>4 to 6</td>
</tr>
<tr>
<td>Obstructed in factories</td>
<td>2 to 3</td>
</tr>
</tbody>
</table>
Multipath Fading

- Signal can take many different paths between sender and receiver due to reflection, scattering, diffraction

- **Multipath Affect Signal Strength**
  - Multi-path components are *delayed* depending on path length (*delay spread*)
  - Phase shift causes frequency dependent constructive / destructive interference
Multipath Fading

- Example: reflection from the ground: received power decreases proportional to $1/d^4$ instead of $1/d^2$ due to the destructive interference between the direct signal and the signal reflected from the ground.

- Due to constructive and destructive interference of multiple transmitted waves, signal strength may vary widely as a function of receiver position.
Multipath Fading

- Channel characteristics change over location & time

Example:

\[ \cos(2\pi ft) \]

\[ \frac{\alpha_1 \cos(2\pi f [t - \frac{d_1}{c}])}{d_1} - \frac{\alpha_2 \cos(2\pi f [t - \frac{d_2}{c}])}{d_2} \]

Phase difference:

\[ 2\pi (f \frac{d_1}{c} - f \frac{d_2}{c}) + \pi = 2\pi f \frac{d_1 - d_2}{c} + \pi = 2\pi \frac{d_1 - d_2}{\lambda} + \pi \]
Multipath Fading

- Suppose at $d_1 - d_2$ the two waves totally destruct. (what does it mean?)
  \[ f \frac{d_1 - d_2}{c} = \frac{d_1 - d_2}{\lambda} = \text{integer} \]

- Q: can we find places where the two waves construct?

\[ 2\pi f \frac{d_1 - d_2}{c} + \pi = 2\pi \frac{d_1 - d_2}{\lambda} + \pi \]
Multipath Can Spread Delay

Time dispersion: signal is dispersed over time

LOS pulse
multipath pulses

LOS: Line Of Sight

signal at receiver

Delay spread

Multipath Profile
Multipath Can Cause ISI

dispersed signal can cause interference between “neighbor” symbols, Inter Symbol Interference (ISI)

Assume 300 meters delay spread, the arrival time difference is 300/3x10^8 = 1 ms

→ if symbol rate > 1 Ms/sec, we will have serious ISI

In practice, fractional ISI can already substantially increase loss rate
Path loss and Received Power

- **In log normal propagation environment:**
  - PL(d) (path loss) and Pr(d) (received power at a distance d) are random variables with a normal distribution in dB about a distance dependent mean.

- **Sometime we are interested in answering following kind of questions:**
  - What is mean received $P_r(d)$ power (mean$_{P_r(d)}$) at a distance d from a transmitter.
  - What is the probability that the receiver power $P_r(d)$ (expressed in dB power units) at distance d is above (or below) some fixed value $\gamma$ (again expressed in dB power units such as dBm or dBW).
Received Power and Normal Distribution

- In answering these kind of question, we have to use the properties of normal (gaussian distribution).

- $P_r(d)$ is normally distributed that is characterized by:
  - a mean ($\mu$)
  - a standard deviation ($\sigma$)

- We are interested in Probability that $P_r(d) \geq \gamma$ or $P_r(d) \leq \gamma$
Received Power and Normal Distribution PDF

Figure shows the PDF of a normal distribution for the received power $P_r$ at some fixed distance $d$ ($m = 10$, $s = 5$)

Note: x-axis is received power, y-axis probability

EXAMPLE:

Probability that $P_r$ is smaller than 3.3 (i.e. $\text{Prob}(P_r \leq 3.3)$) is given by measure of hashed area
Signal Modulation Basics
Wireless Communication

1. Start with a message
2. Encoded message is transmitted
3. Transmitter encodes the message
4. Encoded message is received
5. Receiver decodes the message

Diagram showing the process of wireless communication:

- Transmitter:
  - Transmitter aerial
  - Microphone
  - Modulator
  - Radio frequency oscillator

- Receiver:
  - Tuned circuit
  - Demodulator
  - Amplifier
  - Loudspeaker

Illustration of a couple communicating wirelessly.
Why Modulation?

How do we send *information* in a radio signal?

Carrier wave
- An RF signal – usually a sinusoid – that carries information
- Carrier is usually a much higher frequency than the information itself!
  - *Ex: 2.4 GHz 802.11b networks carry a lot less than 2.4 GBit/sec of data*....
  - *Rather, carry up to 11 MBit/sec of information*
- Why use a carrier??
  - *Easier to generate a sinusoid signal, and it will travel further.*

Carrier wave frequency
- The frequency of a radio transmission is the center frequency of the carrier
  - *Actual frequency of the carrier changes over time, e.g., with FM transmission*
ON/OFF Keying (OOK)

- Simplest, oldest form of modulation
- Morse code (1837) developed for telegraphy
Carrier Modulation

• Continuous radio wave “carrier” has zero bandwidth (single frequency)
  • but carries no information

• Want to change (modulate) the wave over time to convey a message
  • Will increase bandwidth: More information -> More bandwidth
  • Receiver must demodulate the carrier to get back the original signal
Carrier Modulation

• Objective
  • encode data into analog signals at the right frequency range with limited usage of spectrum

• Basic schemes
  • Analogue Modulation:
    • Amplitude Modulation (AM)
    • Frequency Modulation (FM)
  • Digital Modulation
    • Phase Shift Keying (PSK)
    • Quadrature Amplitude Modulation (QAM)
Amplitude Modulation

- AM radio, broadcast TV
- Make amplitude of carrier wave proportional to the signal of interest (modulating signal)

- Vulnerable to distortion from atmospheric attenuation
Amplitude Modulation

- Modulation by a sine wave:

\[ v(t) = A_C \cos(2\pi f_C t) \{1 + m \cos(2\pi f_m t)\} \]

- \( A_C \): unmodulated peak carrier amplitude
- \( f_C \): carrier frequency
- \( f_m \): modulation frequency
- \( m \): modulation index ("degree" of modulation)

- \( m \) must be between 0 and 1
- If \( m > 1 \) get overmodulation (bad … distortion)
AM Spectrum

- Expand \( v(t) = A_C \cos (2\pi f_C t) \{1 + m \cos (2\pi f_m t)\} \)

- Using trig identities to get:
  \[
  v(t) = A_C \cos (2\pi f_C t) \\
  + 0.5mA_C \cos (2\pi [f_C-f_m]t) \\
  + 0.5mA_C \cos (2\pi [f_C+f_m]t)
  \]

- This expression consists of 3 sine waves at frequencies of carrier \( f_C \), lower sideband \( f_C-f_m \) and upper sideband \( f_C+f_m \).
Varying Modulation Index

modulating signal
unmodulated carrier \( (m = 0) \)
modulated carrier \( (m = 0.5) \)
modulated carrier \( (m = 1.0) \)
modulated carrier \( (m > 1, \text{ overmodulated}) \)

carrier turned off here
Frequency Modulation

- FM radio
- Make *frequency* of carrier wave proportional to signal

![Frequency Modulation](image)

- More resistant to atmospheric effects
Frequency Modulation

- Modulation by a sine wave:

\[ v(t) = A_C \cos \left\{ 2\pi f_C t - m \sin (2\pi f_m t) \right\} \]

- \( A_C \) = unmodulated peak carrier amplitude
- \( f_C \) = carrier frequency
- \( f_m \) = modulation frequency
- \( m \) = modulation index ("degree" of modulation)

- Modulation index:

\[ m = \frac{\text{peak carrier deviation} (\Delta f)}{\text{modulating frequency} (f_m)} \]
FM Spectrum

- Sideband structure is more complicated.

- Theoretically an infinite number of sidebands is generated. But most power is in the first \( m+1 \) sidebands.

- Bandwidth: \( 2(m+1)f_m \)
Digital Modulation

How do we modulate *digital* signals?

Amplitude shift keying (ASK)
- “0” bit is the absence of the carrier (flat signal)
- “1” bit is the presence of the carrier with some fixed amplitude

Frequency shift keying (FSK)
- “0” bit is carrier at frequency $f_0$; “1” bit is carrier at frequency $f_1$
Phase Shift Keying: BPSK

- BPSK (Binary Phase Shift Keying):
  - bit value 0: sine wave
  - bit value 1: inverted sine wave
  - very simple PSK

- Properties
  - robust, used e.g. in satellite systems
Phase Shift Keying: QPSK

- QPSK (Quadrature Phase Shift Keying):
  - 2 bits coded as one symbol
  - symbol determines shift of sine wave
  - often also transmission of relative, not absolute phase shift: DQPSK - Differential QPSK
Quadrature Amplitude Modulation

• Quadrature Amplitude Modulation (QAM): combines amplitude and phase modulation

• It is possible to code n bits using one symbol $2^n$ discrete levels

• Example: 16-QAM (4 bits = 1 symbol)

• Symbols 0011 and 0001 have the same phase $\phi$, but different amplitude
  a. 0000 and 1000 have same amplitude but different phase
Signal-to-Noise (S/N)

- **SNR: signal-to-noise ratio**
  - Larger SNR – easier to extract signal from noise (a “good thing”)

- **SNR versus BER tradeoffs**
  - Given physical layer:
    - increase power $\rightarrow$ increase SNR $\rightarrow$ decrease BER
  - Given SNR: choose physical layer that meets BER requirement, giving highest throughput
  - SNR may change with mobility: dynamically adapt physical layer (modulation technique, rate)
Why Spread Spectrum?

\[ C = B \log_2(1+S/N) \]  

\[ \ldots \text{[Shannon]} \]

To achieve the same channel capacity \( C \)

- Large \( S/N \), small \( B \)
- Small \( S/N \), large \( B \)
- Increase \( S/N \) is inefficient due to the logarithmic relationship

\[ \text{e.g. } B = 30 \text{ KHz} \]

\[ \text{e.g. } B = 1.25 \text{ MHz} \]
Spread Spectrum

Methods for spreading the bandwidth of the transmitted signal over a frequency band (spectrum) which is wider than the minimum bandwidth required to transmit the signal.

- Reduce effect of jamming
  - Military scenarios
- Reduce effect of other interferences
- More “secure”
  - Signal “merged” in noise and interference
Direct Sequence SS

- **Direct sequence (DS):** most prevalent
  - Signal is spread by a wide bandwidth pseudorandom sequence (code sequence)
  - Signals appear as wideband noise to unintended receivers

- **Not for intra-cell multiple access**
  - Nodes in the same cell use same code sequence
Frequency Hopping SS (FHSS)

- 2.4GHz band divided into 75 1MHz subchannels
- Sender and receive agree on a hopping pattern (pseudo random series). 22 hopping patterns defined
- Different hopping sequences enable co-existence of multiple BSSs
- Robust against narrow-band interferences
## Preview: Challenges and Techniques of Wireless Design

<table>
<thead>
<tr>
<th></th>
<th>Performance affected</th>
<th>Mitigation techniques</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shadow fading (large-scale fading)</td>
<td>received signal strength</td>
<td>use fade margin—increase power or reduce distance</td>
</tr>
<tr>
<td>Fast fading (small-scale fading)</td>
<td>bit/packet error rate at deep fade</td>
<td>diversity</td>
</tr>
<tr>
<td>Delay spread (small-scale fading)</td>
<td>ISI</td>
<td>equalization; spread-spectrum; OFDM; directional antenna</td>
</tr>
</tbody>
</table>
Questions