IT 601: Mobile Computing

Session 2

Wireless Transmission Basics

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Spectrum and bandwidth

• Electromagnetic signals are made up of many frequencies
• Shown in the next example

\[ s(t) = \left(\frac{4}{\pi}\right) \left[ \sin(2\pi ft) + \frac{1}{3} \sin 2\pi (3f^t) t \right] \]
FIG 1

Source: Stallings
Spectrum and bandwidth

• The 2\textsuperscript{nd} frequency is an integer multiple of the first frequency
  – When all of the frequency components of a signal are integer multiples of one frequency, the latter frequency is called \textit{fundamental frequency} \(( f)\)
  – \textit{Period} of the resultant signal is equal to the period of the fundamental frequency
    • Period of \( s(t) \) is \( T = 1/f \)
Fourier Analysis

• Any signal is made up of components at various frequencies, in which each component is a sinusoid.
  – Adding enough sinusoidal signals with appropriate amplitude, frequency and phase, any electromagnetic signal can be constructed
Spectrum and bandwidth

• It is the range of frequencies that a signal contains (among its components)
  – In the example, *spectrum is from f to 3f*
  – absolute bandwidth is the width of the spectrum
• $3f - f = 2f$
Data Rate and bandwidth

- There is a direct relationship between data rate (or signal carrying capacity) and bandwidth
- Suppose we let a positive pulse represent 1 and negative pulse represent 0
  - Then the waveform (next slide) represents 1010..
  - Duration of each pulse is \( t_{\text{bit}} = \frac{1}{2} \frac{1}{f} \)
  - Thus data rate is \( \frac{1}{t_{\text{bit}}} = 2f \) bits/sec
- As we add more and more frequencies the wave looks more like a square wave
FIG 2

Source: Stallings
Example

• Looking at FIG 2(a) the bandwidth = 5f-f = 4f
  – If f=1MHz = $10^6$ cycles/sec, then bandwidth = 4MHz
  – The period of the fundamental frequency = $T = 1/f = 1 \mu s$
  – So each bit takes up 0.5 $\mu$s i.e. data rate is $1/0.5$ Mbps = 2 Mbps
Example

- Looking at FIG 1(c) the bandwidth = 3f-f = 2f
  - If f=2MHz = 2x10^{6} cycles/sec, then bandwidth = 4MHz
  - The period of the fundamental frequency = T = 1/f = 0.5 \mu s
  - So each bit takes up 0.25 \mu s i.e. data rate is 1/0.25 Mbps = 4 Mbps
Example

• Thus a given bandwidth can support different data rate, depending on the ability of the receiver to discern the difference between 0 and 1 in the presence of noise and interference
Gain and Loss

• Ratio between power levels of two signals is referred to as Gain
  – gain (dB) = \(10 \log_{10} \left( \frac{P_{\text{out}}}{P_{\text{in}}} \right)\)
  – loss (dB) = \(-10 \log_{10} \left( \frac{P_{\text{out}}}{P_{\text{in}}} \right) = 10 \log_{10} \left( \frac{P_{\text{in}}}{P_{\text{out}}} \right)\)
  – \(P_{\text{out}}\) is output power level and \(P_{\text{in}}\) is input power level

• Signal of power 10mw transmitted over wireless channel, and receiver receives the signal with 2mw power:
  – gain (db) = \(10 \log_{10} \left( \frac{2}{10} \right) = -10 \times (0.698) = -6.98 \text{ dB}\)
  – loss (db) = 6.98 dB
dBW power

• dB-Watt
  – power in dB transmitted with respect to a base power of 1 Watt
    • \( \text{dBW} = 10 \log_{10} P \)
      – \( P \) is power transmitted in Watt
  – if power transmitted is 1 Watt
    • \( \text{dBW} = 10 \log_{10} 1 = 0 \text{ dBW} \)
    – 1000 watt transmission is 30 dBW
dBm power

- dB-milliwatt
  - better metric in wireless network
  - power in dB transmitted with respect to a base power of 1 milliwatt
    - $\text{dBm} = 10 \log_{10} P$
      - $P$ is power transmitted in milliwatt
    - if power transmitted is 1 milliwatt
      - $\text{dBm} = 10 \log_{10} 1 = 0 \text{ dBm}$
    - 10 milliwatt transmission is 10 dBm
    - 802.11b can transmit at a maximum power of 100mw = 20 dBm
Channel Capacity

Four concepts:

• Data Rate: rate (in bps) at which data can be communicated

• Bandwidth: bandwidth of the transmitted signal as constrained by the transmitter and the medium, expressed in Hz

• Noise: interfering electromagnetic signal that tend to reduce the integrity of data signal

• Error rate: rate at which receiver receives bits in error i.e. it receives a 0 when actually a 1 was sent and vice-versa
Nyquist Bandwidth

- Given a bandwidth of $B$, the highest signal rate that can be carried is $2B$ (when signal transmitted is binary (two voltage levels))
  - When $M$ voltage levels are used, then each signal level can represent $\log_2 M$ bits. Hence the Nyquist bandwidth (capacity) is given by
    $$ C = 2B \log_2 M $$
Shannon’s Capacity Formula

• When there is noise in the medium, capacity is given by
  \[ C \leq B \log_2 (1 + \text{SNR}) \]
  • SNR = signal power/noise power
  \[ \text{SNR}_{\text{dB}} = 10 \log_{10} \text{SNR} \]
Bandwidth Allocation

• Necessary to avoid interference between different radio devices
  – Microwave woven should not interfere with TV transmission
  – Generally a radio transmitter is limited to a certain bandwidth
    • 802.11 channel has 30MHz bandwidth
  – Power and placement of transmitter are regulated by authority
    • Consumer devices are generally limited to less than 1W power
ISM and UNII Band

- **Industrial, Scientific and Medical (ISM) band**
  - 902-928 MHz in the USA
  - 433 and 868 MHz in Europe
  - 2400 MHz – 2483.5 MHz (license-free almost everywhere)
  - Peak power 1W (30dBm)
    - but most devices operate at 100mW or less
  - 802.11 uses the ISM band of 2.4GHz

- **Unlicensed National Information Infrastructure (UNII) bands**
  - 5.725 – 5.875 GHz
Antenna

- An electrical conductor or system of conductors used for radiating electromagnetic energy into space or for collecting electromagnetic energy from the space
  - An integral part of a wireless system
Radiation Patterns

• Antenna radiates power in all directions
  – but typically does not radiate equally in all directions
• Ideal antenna is one that radiates equal power in all direction
  – called an isotropic antenna
  – all points with equal power are located on a sphere with the antenna as its center
Omnidirectional Antenna

- Produces omnidirectional radiation pattern of equal strength in all directions
- Vector A and B are of equal length
Directional Antenna

• Radiates most power in one axis (direction)
  – radiates less in other direction
  – vector B is longer than vector A: more power radiated along B than A
  – directional along X
Dipole Antenna

- Half-wave dipole or Hertz antenna consists of two straight collinear conductors of equal length.
- Length of the antenna is half the wavelength of the signal.

Half-wave dipole
Quarter-wave antenna

- Quarter-wave or marconi antenna has a vertical conductor of length quarter of the wavelength of the signal

\[ \frac{\lambda}{4} \]
Sectorized Antenna

- Several directional antenna combined on a single pole to provide sectorized antenna
- Each sector serves receivers listening in its direction

3 sector antenna
Antenna Gain

• A measure of the directionality of an antenna
• Defined as the power output, in a particular direction, compared to that produced in any direction by a perfect isotropic antenna
  – Example: if an antenna has a gain of 3dB, the antenna is better (in that direction) than isotropic antenna by a factor of 2
Antenna Gain

- Antenna gain is dependent on *effective area* of an antenna.
  - effective area is related to the physical size of the antenna and its shape
  - Antenna Gain is given by
    \[ G = \frac{4\pi A_e}{\lambda^2} = \frac{4\pi f^2 A_e}{c^2} \]

  where
  - \( G \) = antenna gain
  - \( A_e \) = effective area
  - \( f \) = carrier frequency
  - \( c \) = speed of light
  - \( \lambda \) = carrier wavelength
Signal Propagation

- **Transmission range:** receiver receives signal with an error rate low enough to be able to communicate
- **Detection range:** transmitted power is high enough to detect the transmitter, but high error rate forbids communication
- **Interference range:** sender interferes with other transmissions by adding to the noise
Signal Propagation

• Radio waves exhibit three fundamental propagation behavior
  – Ground wave (< 2 MHz) : waves with low frequency follow earth’s surface
    • can propagate long distances
    • Used for submarine communication or AM radio
  – Sky wave (2-30 MHz) : waves reflect at the ionosphere and bounce back and forth between ionosphere and earth, travelling around the world
    • Used by international broadcast and amateur radio
Signal propagation

transmitter

earth

receiver

Ground wave propagation (< 2 MHz)
sky wave propagation (2 - 30MHz)
Signal Propagation

– Line of Sight (> 30 MHz) : emitted waves follow a straight line of sight
  • allows straight communication with satellites or microwave links on the ground
  • used by mobile phone system, satellite systems
Signal propagation

transmitter

earth

receiver

Line of Sight (LOS) propagation (> 30 MHz)
Free Space loss

- Transmitted signal attenuates over distance because it is spread over larger and larger area
  - This is known as free space loss and for isotropic antennas

\[
\frac{P_t}{P_r} = \frac{(4\pi d)^2}{\lambda^2} = \frac{(4\pi f d)^2}{c^2}
\]

\(P_t\) = power at the transmitting antenna
\(P_r\) = power at the receiving antenna
\(\lambda\) = carrier wavelength
\(d\) = propagation distance between the antennas
\(c\) = speed of light
Free Space loss

– For other antennas

\[
\frac{P_t}{P_r} = \frac{(4\pi d)^2}{G_r G_t \lambda^2} = \frac{(\lambda d)^2}{A_r A_t}
\]

\(G_t = \text{Gain of transmitting antenna}\)

\(G_r = \text{Gain of receiving antenna}\)

\(A_t = \text{effective area of transmitting antenna}\)

\(A_r = \text{effective area of receiving antenna}\)
Thermal Noise

- Thermal noise is introduced due to thermal agitation of electrons
  - Present in all transmission media and all electronic devices
  - a function of temperature
  - uniformly distributed across the frequency spectrum and hence is often referred to as white noise
  - amount of noise found in a bandwidth of 1 Hz is
    \[ N_0 = kT \]
  - \( N_0 \) = noise power density in watts per 1 Hz of bandwidth
  - \( k = \) Boltzman’s constant = \( 1.3803 \times 10^{-23} \) J/K
  - \( T = \) temperature, in Kelvins
  - \( N = \) thermal noise in watts present in a bandwidth of \( B \)
    \[ = kTB \]
Data rate and error rate

• A parameter related to SNR that is more convenient for determining digital data rates and error rates
  – ratio of signal energy per bit to noise power density per Hertz, $E_b/N_0$
  – $R = \text{bit rate of transmission}$, $S= \text{power of the signal}$, $T_b = \text{time required to send 1 bit}$. Then $R = 1/T_b$

$$E_b = S \times T_b$$
so

$$\frac{E_b}{N_0} = \frac{S}{R} = \frac{S}{kTR}$$
Data rate and error rate

• Bit error rate is a decreasing function of $E_b/N_0$
  – If bit rate $R$ is to increase, then to keep bit error rate (or $E_b/N_0$) same, the transmitted signal power must increase, relative to noise

• $E_b/N_0$ is related to SNR as follows

$$\frac{E_b}{N_0} = \frac{S}{N} \frac{B}{R}$$

$B = \text{signal bandwidth}$
(since $N = N_0 B$)
Doppler’s Shift

• When a client is mobile, the frequency of received signal could be less or more than that of the transmitted signal due to Doppler’s effect
• If the mobile is moving towards the direction of arrival of the wave, the Doppler’s shift is positive
• If the mobile is moving away from the direction of arrival of the wave, the Doppler’s shift is negative
Doppler’s Shift

\[ f_d = \frac{v}{\lambda} \cos \theta \]

where

- \( f_d \) = change in frequency due to Doppler’s shift
- \( v \) = constant velocity of the mobile receiver
- \( \lambda \) = wavelength of the transmission
Doppler’s shift

\[ f = f_c + f_d \]

where

\( f = \) the received carrier frequency

\( f_c = \) carrier frequency being transmitted

\( f_d = \) Doppler’s shift as per the formula in the prev slide
Multipath Propagation

- Wireless signal can arrive at the receiver through different paths
  - LOS
  - Reflections from objects
  - Diffraction

- Occurs at the edge of an impenetrable body that is large compared to the wavelength of the signal
Multipath Propagation (source: Stallings)
Inter Symbol Interference (ISI) in multipath (source: Stallings)
Effect of Multipath Propagation

- Multiple copies of the signal may arrive with different phases. If the phases add destructively, the signal level reduces relative to noise.
- Inter Symbol Interference (ISI)
Multiplexing

• A fundamental mechanism in communication system and networks
• Enables multiple users to share a medium
• For wireless communication, multiplexing can be carried out in four dimensions: space, time, frequency and code
Space division multiplexing

- Channels are assigned on the basis of “space” (but operate on same frequency)

- The assignment makes sure that the transmission do not interfere with each (with a guard band in between)
Space division multiplexing

Source: Schiller
Frequency Division Multiplexing

- Frequency domain is subdivided into several non-overlapping frequency bands
- Each channel is assigned its own frequency band (with guard spaces in between)
Frequency Division Multiplexing

Source: Schiller
Time Division Multiplexing

• A channel is given the whole bandwidth for a certain amount of time
  – All senders use the same frequency, but at different point of time
Time Division Multiplexing

Source: Schiller
Frequency and time division multiplexing

• A channel use a certain frequency for a certain amount of time and then uses a different frequency at some other time
  – Used in GSM systems
Frequency and time division multiplexing

Source: Schiller
Code division multiplexing

- separation of channels achieved by assigning each channel its own *code*
- guard spaces are realized by having *distance* in code space (e.g. orthogonal codes)
- transmitter can transmit in the same frequency band at the same time, but have to use different code
- Provides good protection against interference and tapping
- but the receivers have relatively high complexity
  - has to know the code and must separate the channel with user data from the noise composed of other transmission
  - has to be synchronized with the transmitter
Code division multiplexing

Source: Schiller
Modulation

• Process of combining input signal and a carrier frequency at the transmitter

• Digital to analog modulation
  – necessary if the medium only carries analog signal

• Analog to analog modulation
  – needed to have effective transmission (otherwise the antenna needed to transmit original signal could be large)
  – permits frequency division multiplexing
Amplitude Shift Keying (ASK)

- ASK is the most simple digital modulation scheme
- Two binary values, 0 and 1, are represented by two different amplitude
- In wireless, a constant amplitude cannot be guaranteed, so ASK is typically not used
Amplitude Shift Keying (ASK)
Frequency Shift Keying (FSK)

• The simplest form of FSK is binary FSK
  – assigns one frequency $f_1$ to binary 1 and another frequency $f_2$ binary 0
• Simple way to implement is to switch between two oscillators one with $f_1$ and the other with $f_2$
• The receiver can demodulate by having two bandpass filter
Frequency Shift Keying (FSK)
Phase Shift Keying (PSK)

- Uses shifts in the phase of a signal to represent data
- Shifting the phase by $180^0$ each time data changes: called binary PSK
- The receiver must synchronize in frequency and phase with the transmitter
Phase Shift Keying (PSK)
Quadrature Phase Shift Keying (Q-PSK)

- Higher bit rate can be achieved for the same bandwidth by coding two bits into one phase shift.
  - $45^0$ for data 11
  - $135^0$ for data 10
  - $225^0$ for data 00
  - $315^0$ for data 01
Spread Spectrum

• Spreading the bandwidth needed to transmit data
  – Spread signal has the same energy as the original signal, but is spread over a larger frequency range
  – provides resistance to narrowband interference
Spread Spectrum

Sender

- User signal
- Spreading

Receiver

- Despread
- Apply bandpass filter

- User signal
- Broadband interference
- Narrowband interference
Direct Sequence Spread Spectrum

• Takes a user bit sequence and performs an XOR with, what is known as, *chipping sequence*

• Each user bit duration $t_b$

• chipping sequence has smaller pulses $t_c$

• If chipping sequence is generated properly it may appear as random noise
  – sometimes called pseudo-noise (PN)

• $t_b/t_c$ is known as the *spreading factor*
  – determines the bandwidth of the resultant signal

• Used by 802.11b
Direct Sequence Spread Spectrum

![Diagram of Direct Sequence Spread Spectrum]

- **User Data**
  -\( t_b \)

- **Chipping Sequence**
  -\( t_c \)
  - XOR

- **Spread Signal**
Frequency Hopping Spread Spectrum

- Total available bandwidth is split into many channels of smaller bandwidth and guard spaces.
- Transmitter and receiver stay on one of these channels for a certain time and then hop to another channel.
- Implements FDM and TDM.
- Pattern of channel usage: *hopping sequence*.
- Time spent on a particular channel: *dwell time*.
Frequency Hopping Spread Spectrum

- Slow hopping
  - Transmitter uses one frequency for several bit period
  - Systems are cheaper, but are prone to narrow band interference
- Fast hopping
  - Transmitter changes frequency several times in one bit period
  - Transmitter and receivers have to stay synchronized within smaller tolerances
  - Better immuned to narrow band interference as they stick to one frequency for a very short period
- Receiver must know the hopping sequence and stay synchronized with the transmitter
- Used by bluetooth
Frequency hopping spread spectrum

- slow hopping: 3 bits/hop
- fast hopping: 3 hops/bit

$t_d = $ dwell time