CS356R: Introduction to Wireless Networking

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UT Austin

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Course Information

- Instructor: Lili Qiu, lili@cs.utexas.edu
- Office: GDC 6.806
- Lecture: M 9am – noon @ SZB 370
- Office hour: W 9:30am – noon or by appt.
- TA: Jian He T 2-4pm @ TA station desk 3
- Course homepage: 
  http://www.cs.utexas.edu/~lili/classes/F17-CS356R
- http://piazza.com
Course Material

• **Required textbook**
  - Mobile Communications by Jochen Schiller

• **Recommended references**
  - Computer Networking: A top down approach featuring the Internet by James Kurose and Keith Ross
  - 802.11 Wireless Networks: The Definitive Guide by Matthew S. Gast
  - Wireless Communications Principles and Practice by Ted Rappaport
  - Ad Hoc Networking by Charles E. Perkins
Course Workload

• **Grading**
  - Quizzes: 20%
  - Homework: 30%
  - Exam I: 18% (10/16)
  - Exam II: 32% (12/11)

• **We will strictly enforce UTCS code of conduct**
  - No sharing of course materials with current or future students
  - [https://wikis.utexas.edu/display/coursematerials/Sample+Use+Statements+for+Syllabus](https://wikis.utexas.edu/display/coursematerials/Sample+Use+Statements+for+Syllabus)
Motivation
Mobile and Wireless Services – Always Best Connected

LAN, WLAN 600 Mbps

4G 10 Mbps Bluetooth 500 kbit/s

4G/3G

0.5 – 10 Mbps

4G 10 Mbps

WLAN 600 Mbps

4G 10 Mbps

WLAN 600 Mbps

4G 10 Mbps

4G 10 Mbps
On the road
On the Road

UMTS, WLAN, DAB, GSM, WiMAX, LTE
cdma2000, TETRA, ...

GPS, 2G/3G/4G, WLAN, Bluetooth,
Ad hoc networks, radios
Home Networking

- Camcorder
- HDTV
- Game
- iPod
- High-quality speaker
- Surveillance
- WiFi
- UWB
- Bluetooth
- GSM, LTE, WiMAX
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Last-Mile

- Many users still don’t have broadband
  - Reasons: out of service area; some consider expensive

Broadband speed is still limited
- DSL: 300Kbps – 6Mbps
- Cable modem: depends on your neighbors
- Insufficient for several applications (e.g., high-quality video streaming)
Disaster Recovery Network

• 9/11, Tsunami, Irene, Hurricane Katrina, China, South Asian, Haidi earthquakes ...
  - Harvey: sensors, waze, drones, ...

• Wireless communication capability can make a difference between life and death!

• How to enable efficient, flexible, and resilient communication?
  - Rapid deployment
  - Efficient resource and energy usage
  - Flexible: unicast, broadcast, multicast, anycast
  - Resilient: survive in unfavorable and untrusted environment
Environmental Monitoring

- Micro-sensors, on-board processing, wireless interfaces feasible at very small scale--can monitor phenomena “up close”
- Enables spatially and temporally dense environmental monitoring

Embedded Networked Sensing will reveal previously unobservable phenomena
Wearable Technology
Internet of Things
Challenges in Wireless Networking Research
Challenge 1: Unreliable and Unpredictable Wireless Links

- **Wireless links are less reliable**
- **They may vary over time and space**

*Cerpa, Busek et. al

What Robert Poor (Ember) calls “The good, the bad and the ugly”
Challenge 2: Open Wireless Medium

- **Wireless interference**

  S1 → R1
  S2 → R2
Challenge 2: Open Wireless Medium

- **Wireless interference**
  - S1 → R1
  - S2 → R2

- **Hidden terminals**
  - S1 → R1 → R2 → S2
Challenge 2: Open Wireless Medium

- **Wireless interference**
  - S1 → R1
  - S2 → R1

- **Hidden terminals**
  - S1 → R1 ← R2

- **Exposed terminal**
  - R1 ← S1 ← S2 → R2
Challenge 2: Open Wireless Medium

- **Wireless interference**
  - $S1 \rightarrow R1$
  - $S2 \rightarrow R1$

- **Hidden terminals**
  - $S1 \rightarrow R1 \leftarrow S2$

- **Exposed terminals**
  - $R1 \leftarrow S1 \rightarrow S2 \rightarrow R2$

- **Wireless security**
  - Eavesdropping, Denial of service, ...
Challenge 3: Intermittent Connectivity

- Reasons for intermittent connectivity
  - Mobility
  - Environmental changes

- Existing networking protocols assume always-on networks

- Under intermittent connected networks
  - Routing, TCP, and applications all break

- Need a new paradigm to support communication under such environments
Challenge 4: Limited Resources

- Limited battery power
- Limited bandwidth
- Limited processing and storage power

Sensors, embedded controllers

Mobile phones
- voice, data
- simple graphical displays
- GSM

PDA
- data
- simpler graphical displays
- 802.11

Laptop
- fully functional
- standard applications
- battery; 802.11
Introduction to Wireless Networking
Internet Protocol Stack

- **Application**: supporting network applications
  - FTP, SMTP, HTTP
- **Transport**: data transfer between processes
  - TCP, UDP
- **Network**: routing of datagrams from source to destination
  - IP, routing protocols
- **Link**: data transfer between neighboring network elements
  - Ethernet, WiFi
- **Physical**: bits “on the wire”
  - Coaxial cable, optical fibers, radios
Physical Layer
Outline

- Signal
- Frequency allocation
- Signal propagation
- Multiplexing
- Modulation
- Spread Spectrum
Overview of Wireless Transmissions

sender

bit stream

source coding

channel coding

modulation

analog signal

receiver

bit stream

source decoding

channel decoding

demodulation
Signals

- Physical representation of data
- Function of time and location
- **Classification**
  - continuous time/discrete time
  - continuous values/discrete values
  - analog signal = continuous time and continuous values
  - digital signal = discrete time and discrete values
• Signal parameters of periodic signals:
  - period $T$, frequency $f = 1/T$
  - amplitude $A$
  - phase shift $\phi$
  - sine wave as special periodic signal for a carrier:

$$s(t) = A_t \sin(2 \pi f_t t + \phi_t)$$
Fourier Transform: Every Signal Can be Decomposed as a Collection of Harmonics

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

The more harmonics used, the smaller the approximation error.
Why Not Send Digital Signal in Wireless Communications?

• Digital signals need
  - infinite frequencies for perfect transmission
  - however, we have limited frequencies in wireless communications
Frequencies for Communication

**VLF = Very Low Frequency**
**LF = Low Frequency, submarine**
**MF = Medium Frequency, radio**
**HF = High Frequency, radio**
**VHF = Very High Frequency, TV**
**UHF = Ultra High Frequency**
**SHF = Super High Frequency**
**EHF = Extra High Frequency**
**UV = Ultraviolet Light**

Frequency and wave length: $\lambda = \frac{c}{f}$, wave length $\lambda$, speed of light $c \approx 3 \times 10^8 \text{m/s}$, frequency $f$
Frequencies and Regulations

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

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<td>Cordless Phones</td>
<td><strong>CT1+</strong> 885-887, 930-932 <strong>CT2</strong> 864-868 <strong>DECT</strong> 1880-1900</td>
<td><strong>PACS</strong> 1850-1910, 1930-1990 <strong>PACS-UB</strong> 1910-1930</td>
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Why Need A Wide Spectrum
Why Need A Wide Spectrum: Shannon Channel Capacity

• The maximum number of bits that can be transmitted per second by a physical channel is:

\[ W \log_2 (1 + \frac{S}{I+N}) \]

where \( W \) is the frequency range that the media allows to pass through, SINR is the signal noise ratio.
Signal, Noise, and Interference

• Signal (S)
• Noise (N)
  - Includes thermal noise and background radiation
  - Often modeled as additive white Gaussian noise
• Interference (I)
  - Signals from other transmitting sources
• $\text{SINR} = \frac{S}{(N+I)}$ (sometimes also denoted as SNR)
dB and Power conversion

• dB
  - Denote the difference between two power levels
  - (P2/P1)[dB] = 10 * log10 (P2/P1)
  - P2/P1 = 10^(A/10)
  - Example: P2 = 100 P1, P2/P1=10 dB

• dBm and dBW
  - Denote the power level relative to 1 mW or 1 W
  - P[dBm] = 10*log10(P/1mW)
  - P[dBW] = 10*log10(P/1W)
  - Example: P = 0.001 mW, P = 100 W
Signal Propagation Ranges

• Transmission range
  - communication possible
  - low error rate

• Detection range
  - detection of the signal possible
  - no communication possible

• Interference range
  - signal may not be detected
  - signal adds to the background noise
Outline

• Signal
• Frequency allocation
• Signal propagation
• Multiplexing
• Modulation
• Spread Spectrum
Signal Propagation

- Does signal propagation via a straight line?
Signal Propagation

- Propagation in free space always like light (straight line)
- Receiving power proportional to $1/d^2$
  ($d = \text{distance between sender and receiver}$)
- Receiving power additionally influenced by
  - shadowing
  - reflection at large obstacles
  - refraction depending on the density of a medium
  - scattering at small obstacles
  - diffraction at edges
  - fading (frequency dependent)
Path Loss

- Free space model
  \[ P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \]

- Two-ray ground reflection model
  \[ P_r(d) = \frac{P_t G_t G_r h_t^2 h_r^2}{d^4 L} \]
  \[ d_c = \frac{(4\pi h_t h_r)}{\lambda} \]

- Log-normal shadowing
  \[ P(d)[dB] = \bar{P}(d)[dB] + X_\sigma \]

- Indoor model
  \[ P_r(d)[dBm] = P_t(d)[dBm] - 10n\log\left(\frac{d}{d_0}\right) - \begin{cases} 
    nW \ast WAF & \text{nW} < C \\
    C \ast WAF & \text{nW} \geq C 
  \end{cases} \]

- \( P = 1 \text{ mW at } d_0=1\text{m}, \) what’s \( P_r \) at \( d=2\text{m} \)?
Multipath Propagation

- Signal can take many different paths between sender and receiver due to reflection, scattering, diffraction
- Time dispersion: signal is dispersed over time → interference with “neighbor” symbols, Inter Symbol Interference (ISI)
- The signal reaches a receiver directly and phase shifted → distorted signal based on the phases of different parts
Fading

• Channel characteristics change over time and location
  - e.g., movement of sender, receiver and/or scatters
• \( \rightarrow \) quick changes in the power received (short term/fast fading)
• Additional changes in
  - distance to sender
  - obstacles further away
• \( \rightarrow \) slow changes in the average power received (long term/slow fading)
Typical Picture

- Received Signal Power (dB)
- Log (distance)

- Path loss
- Shadow fading
- Rayleigh fading
Real world example
Outline

• Signal
• Frequency allocation
• Signal propagation
• **Multiplexing**
• Modulation
• Spread Spectrum
Multiplexing

- *Goal*: multiple use of a shared medium

- *Multiplexing in different dimensions*
Multiplexing

- **Goal:** multiple use of a shared medium

- **Multiplexing in 4 dimensions**
  - space \((s)\)
  - time \((t)\)
  - frequency \((f)\)
  - code \((c)\)

- **Important:** guard spaces needed!
Space Multiplexing

- Assign each region a channel
- Pros
  - no dynamic coordination necessary
  - works also for analog signals
- Cons
  - Inefficient resource utilization
Frequency Multiplexing

• Separation of the whole spectrum into smaller frequency bands

• A channel gets a certain band of the spectrum for the whole time

• Pros:
  - no dynamic coordination necessary
  - works also for analog signals

• Cons:
  - waste of bandwidth if the traffic is distributed unevenly
  - Inflexible
  - guard spaces
Time Multiplex

- A channel gets the whole spectrum for a certain amount of time

- **Pros:**
  - only one carrier in the medium at any time
  - throughput high even for many users

- **Cons:**
  - precise synchronization necessary
Time and Frequency Multiplexing

- Combination of both methods
- A channel gets a certain frequency band for a certain amount of time (e.g., GSM)
- Pros:
  - better protection against tapping
  - protection against frequency selective interference
  - higher data rates compared to code multiplex
- Cons:
  - precise coordination required
**Code Multiplexing**

- Each channel has a unique code
- All channels use the same spectrum simultaneously

**Pros:**
- bandwidth efficient
- no coordination and synchronization necessary
- good protection against interference and tapping

**Cons:**
- more complex signal regeneration
- need precise power control

**Implemented using spread spectrum technology**
Outline

• Signal
• Frequency allocation
• Signal propagation
• Multiplexing
• Modulation
• Spread Spectrum
Modulation I

- **Digital modulation**
  - Digital data is translated into an analog signal (baseband)
  - Difference in spectral efficiency, power efficiency, robustness

- **Analog modulation**
  - Shifts center frequency of baseband signal up to the radio carrier
  - Reasons?
Modulation I

• Digital modulation
  - Digital data is translated into an analog signal (baseband)
  - Difference in spectral efficiency, power efficiency, robustness

• Analog modulation
  - Shifts center frequency of baseband signal up to the radio carrier
  - Reasons
    • Antenna size is on the order of signal’s wavelength
    • More bandwidth available at higher carrier frequency
    • Medium characteristics: path loss, shadowing, reflection, scattering, diffraction depend on the signal’s wavelength
Modulation and Demodulation

Digital data flows through a digital modulation process to create an analog baseband signal. This signal is then modulated onto a radio carrier to form a radio transmitter signal.

The radio receiver demodulates the signal, recovering the analog baseband signal. Synchronization and decision processes are applied to recover the digital data.
Modulation Schemes

• Amplitude Modulation (AM)
• Frequency Modulation (FM)
• Phase Modulation (PM)
Digital Modulation

• Modulation of digital signals known as Shift Keying

• Amplitude Shift Keying (ASK):
  - Pros: simple
  - Cons: susceptible to noise
  - Example: optical system, IFR
Digital Modulation II

• Frequency Shift Keying (FSK):
  - Pros: less susceptible to noise
  - Cons: requires larger bandwidth
Digital Modulation III

- Phase Shift Keying (PSK):
  - Pros:
    - Less susceptible to noise
    - Bandwidth efficient
  - Cons:
    - Require synchronization in frequency and phase → complicates receivers and transmitter
Phase Shift Keying

- **BPSK (Binary Phase Shift Keying):**
  - bit value 0: sine wave
  - bit value 1: inverted sine wave
  - very simple PSK
  - low spectral efficiency
  - robust, used in satellite systems

- **QPSK (Quadrature Phase Shift Keying):**
  - 2 bits coded as one symbol
  - needs less bandwidth compared to BPSK
  - 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
• bit error rate increases with $n$

Example: 16-QAM (4 bits = 1 symbol)
• Symbols 0011 and 0001 have the same phase $\phi$, but different amplitude; 0000 and 1000 have same amplitude but different phase
• Used in Modem
Spread spectrum technology

- Problem of radio transmission: frequency dependent fading can wipe out narrow band signals for duration of the interference
- Solution: spread the narrow band signal into a broad band signal using a special code

- Side effects:
  - coexistence of several signals without dynamic coordination
  - tap-proof

- Alternatives: Direct Sequence, Frequency Hopping
DSSS
(Direct Sequence Spread Spectrum)

- XOR of the signal with pseudo-random number (chipping sequence)
  - generate a signal with a wider range of frequency: spread spectrum

\[ \text{user data} \]
\[ \text{XOR} \]
\[ \text{chipping sequence} \]
\[ = \]
\[ \text{resulting signal} \]

- \( t_b \): bit period
- \( t_c \): chip period
FHSS
(Frequency Hopping Spread Spectrum)

• **Discrete changes of carrier frequency**
  - sequence of frequency changes determined via pseudo random number sequence

• **Two versions**
  - Fast Hopping:
    several frequencies per user bit
  - Slow Hopping:
    several user bits per frequency

• **Advantages**
  - frequency selective fading and interference limited to short period
  - simple implementation
  - uses only small portion of spectrum at any time
FHSS: Example

- **Slow Hopping (3 bits/hop):**
  - $f_1$, $f_2$, $f_3$ frequencies
  - $t_d$: dwell time
  - $t_b$: bit period

- **Fast Hopping (3 hops/bit):**
  - Similar setup as slow hopping but with different frequencies
  - $t_d$: dwell time

**User Data:**
- Graphical representation showing user data transmission over time.
Comparison between Slow Hopping and Fast Hopping

- **Slow hopping**
  - Pros: cheaper
  - Cons: less immune to narrowband interference

- **Fast hopping**
  - Pros: more immune to narrowband interference
  - Cons: tight synchronization \(\Rightarrow\) increased complexity
Recap

• Name 5 layers in the Internet protocol stack.
• Pros and cons of layering.
• What is a signal?
• Difference between analog vs. digital signal?
• How do we represent different signals?
• Does a signal always follow a straight line?
• Path loss models
Recap (Cont.)

• Why do we need a wide bandwidth?
• What is multipath propagation?
• Types of multiplexing?
• Types of modulation?
• What is spread spectrum?