Advanced Computer Networks
263-3501-00

Wireless Networks Fundamentals

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Course Outline

1. General principles of network design
   - Review of basic concepts from earlier course(s)
   - Design principles and arguments

2. Wireless and mobile networking
   - Basic MAC and PHY principles
   - Bluetooth, Wifi, GSM, 3G, 4G
   - Mobility and Cloud services

3. Datacenter and high-performance networking
   - Supercomputer interconnects, datacenter topologies
   - Infiniband, RDMA, etc.
   - L7 switching, load balancing, OpenFlow, network virtualization
   - Virtual machine networking, IOV, soft switches
Overview

- First week: Wireless fundamentals
  - Why is wireless so different from wired
  - Physical layer principles
  - MAC principles

- Second week: Wireless Systems I
  - PAN (Bluetooth), WLAN (802.11, WiMAX)

- Third week: Wireless Systems II
  - Cellular: GSM, UMTS, LTE

- Fourth week: Mobility
  - Mobile IP, SIP, Wireless TCP

- Fifth week:
  - Energy efficient networking
  - White Space Networking
Electromagnetic Spectrum

- **Low Frequency**
  - Wavelength: $10^7$ m, $10^6$ m, 100 km, 10 km, 1 km, 100 m, 1 m, 0.1 m, 1 cm
  - Frequency (Hz): 10, 100, 1 k, 10 k, 100 k, 1 M, 10 M, 100 M, 1 G, 10 G

- **High Frequency**
  - Wavelength: 1 cm, 1 mm, 100 μm, 10 μm, 1 μm, 100 nm, 10 nm, 1 nm, 100 pm, 10 pm
  - Frequency (Hz): 10 G, 100 G, 1 T, 10 T, 100 T, $10^{15}$, $10^{16}$, $10^{17}$, $10^{18}$, $10^{19}$

- **Microwave**
  - Wavelength: 1 cm, 1 mm, 100 μm, 10 μm, 1 μm, 100 nm, 10 nm, 1 nm, 100 pm, 10 pm
  - Frequency (Hz): 10 G, 100 G, 1 T, 10 T, 100 T, $10^{15}$, $10^{16}$, $10^{17}$, $10^{18}$, $10^{19}$

- **Visible Light**
  - Wavelength: 400 nm - 700 nm

- **Ultraviolet Radiation**
  - Wavelength: < 400 nm

- **Infrared Radiation**
  - Wavelength: > 700 nm
Different Wireless Networks and their frequency range

Figure 1.1 Some Milestones in Wireless Communications
Why so many?

- Diverse deployments
  - Licensed frequency bands or not
  - Infrastructure based, no infrastructure
- Technologies have different
  - Signal penetration
  - Frequency use
  - Cost
- Different applications have different requirements
  - Energy consumption
  - Range
  - Bandwidth
  - Mobility
  - Cost
Exponential Mobile Growth

Source: Cisco VNI Mobile, 2012
Wireless Speed Trends
Mobility Support and Data Rates of different Wireless Systems
Why use Wireless?

There are no wires!

Has several significant advantages

- No need to install and maintain wires
  - Reduces cost – important in offices, hotels
  - Simplifies deployment – important in homes, hotspots

- Support for mobile users
  - Move around office, campus, city
  - Cordless phones, cell phones
What is Hard about Wireless?

There are no wires!

- In wired networks links are constant, reliable and physically isolated
- In wireless networks links are variable, error-prone, and share the ether with other and other external, uncontrolled sources
Antennas

- Isotropic antenna
  - radiating equal power in all directions
  - does not exist in reality
- Dipole antenna
  - Omni-directional in xz-plane
  - 'figure-eight' pattern plane and zy-plane
- Directional antenna
  - emits power in one preferred direction
Signal propagation

- **Decibel (dB)**
  - $X_1/X_0 \ [\text{dB}] = 10 \log_{10} (X_1/X_0)$

- **Attenuation [dB] = 10 log10 (transmitted power / received power)**

- **Theory: Path loss model**
  - Receiving power is proportional to $1/d^a$: $\frac{P_r}{P_t} = \left(\frac{\lambda}{4 \pi d}\right)^a$
  - $a=2,3,...8$ called path loss exponent, depends on environment
  - $\lambda$: wavelength, depends on frequency
  - **Attenuation**: $Loss = \frac{P_t}{P_r} = \left(\frac{4 \pi d}{\lambda}\right)^a$
  - Or in dB for $a=2$: $Loss_{db} = 10 \log \frac{P_t}{P_r} = 20 \log \left(\frac{4 \pi d}{\lambda}\right)$
Signal propagation (2)

- Example: what is the attenuation between 10 and 100 meters distance, given $a=2$?
  - $\text{Attenuation}(10,100,2) = 10 \log \left( \frac{P_t}{P_r} \right) = 10 \log \left( \frac{P_0/10^2}{P_0/100^2} \right) = 20 \text{ dB}$

- Example path loss exponent

<table>
<thead>
<tr>
<th>Terrain-Type</th>
<th>Path-loss-exponent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free Space</td>
<td>2</td>
</tr>
<tr>
<td>Plain surface</td>
<td>4</td>
</tr>
<tr>
<td>city</td>
<td>2.7 – 3.5</td>
</tr>
<tr>
<td>city with shadowing effects</td>
<td>3 – 5</td>
</tr>
<tr>
<td>buildings with line of sight</td>
<td>1.6 – 1.8</td>
</tr>
<tr>
<td>buildings without line of sight</td>
<td>4 – 6</td>
</tr>
</tbody>
</table>
Signal propagation (3)

- Reality

- ...more issues: fading, mobility, etc..

Slow and fast fading
Log-normal shadowing radio propagation

- The *Log-normal shadowing* model generalizes *path loss* model to account for effects like shadowing, scattering, etc.

- Attenuation at distance $d$ (in dB):
  
  \[
  \frac{P_t}{P_r} \text{[dB]} = a \cdot 10 \log\left(\frac{4\pi d}{\lambda}\right) + X \text{[dB]}
  \]

  - $X$[dB] is a gaussian random variable with zero mean and standard deviation $\sigma$
  - Value for $\sigma$ depends on environment, typical values 2...8
  - Might receiver stronger power at larger distances (!)
When can a signal be correctly decoded?

- Signal to interference plus noise ratio
  - \( \text{SINR} = \frac{S}{N + I} \)
  - \( N \): Background Noise, \( I \): Interference from other stations
  - Often measured in dB: \( \text{SINR}(\text{dB}) = 10 \times \log_{}(S/(N+I)) \)

- A certain SINR is required to achieve a certain bit-error-rate (BER)
  - SINR of 10dB for a BER of \( 10^{-6} \) in 802.11b
  - Understanding and Mitigating the Impact of RF Interference on 802.11 Networks [SIGCOMM 2007]
When can a signal be correctly decoded (2)?
Receiver Diversity

- Multiple receiver antennas per device
- Three variations:
  - **Selection combining**: select antenna with best signal
  - **Threshold combining**: select first antenna with signal above threshold
  - **Maximal ratio combining**: adjust phase so that all signals have the same phase, then weighted sum is used as final signal
Multiple antennas to transmit the signal
  - But just a single receiver antenna

Problem: different transmitter signals might cancel each other out at receiver

Solution: phase each signal to make sure the signals arrive in phase at the receiver
  - Phase shift is calculated by receiver and fed back to the transmitter
Multiple Input Multiple Output

Example: Sending two symbols $x_1$ and $x_2$
- send each symbol with a separate antenna (double transmission rate)
- symbols are received by the two receiving antennas as
  \[ y_1 = h_{11}x_1 + h_{12}x_2 + n_1 \]
  \[ y_2 = h_{21}x_1 + h_{22}x_2 + n_2 \]
- $h_{ij}$ expresses how symbols are attenuated
- $n_1$ & $n_2$ is the noise
Wireless Signals and Connectivity in Practice

- “Link-level Measurements from an 802.11b Mesh Network”, Dan Aguayo John Bicket, Sanjit Biswas, Robert Morris, SigComm 2004
  - Roofnet: testbed at MIT campus
  - Get a sense of the wireless link, and how hard it is to measure and engineer for
Roofnet

- Wireless Testbed at MIT Campus
  - Area: $4\text{km}^2$
- Nodes on buildings
- “Link-level Measurements from an 802.11b Mesh Network”, Dan Aguayo, John Bicket, Sanjit Biswas, Robert Morris, SigComm 2004
Roofnet (2)

- Dipole antennas
- WLAN 802.11b
Broadcast traffic in Roofnet

Broadcast packet delivery probability

- 70-100%
- 30-70%
- 1-30%

Lossy radio links are common
Delivery vs S/N in Roofnet

S/N does not predict delivery probability
SINR vs Distance in Roofnet

No strong correlation between signal strength and distance from transmitter
Roofnet: Take Away

- Wireless links may behave very different from models (e.g., path loss and also log-normal shadowing)
  - No good correlation of SINR and distance
  - High SINR does not guarantee good delivery probability
- Predicting wireless performance is very difficult
Transmitting digital data

- How should digital data be transmitted over the air?
- Remember: every periodic signal can be represented by infinitely many sines and cosines

- In wireless networks we cannot use digital transmission:
  - Wireless networks operate in a specific and finite frequency band
Modulation in Wireless Networks

- Digital modulation
  - Convert digital signal into analog signal

- Analog modulation
  - Shift analog signal into the frequency band used by the wireless network

- Notation used:
  - \( g(t) = A \sin(2\pi ft + \phi) \)
    - Amplitude \( A \)
    - Frequency \( f \)
    - Phase \( \phi \)
Modulation (2)

- Amplitude shift keying (ASK)
  - Low bandwidth requirement
  - But very susceptible to interference

- Frequency shift keying (FSK)
  - Example: Binary FSK (BPSK)
  - Needs larger bandwidth
  - But less susceptible to errors

- Phase shift keying (PSK)
  - More complex
  - Robust against interference
Modulation: Quadrature Phase Shift Keying (QPSK)

- Idea: Use a phase shift of 90° to create four distinguished signals (each encoding 2 bits)
  - Representation of modulation scheme in the phase domain

- \[ Q = A \sin(\phi) \]
  - \[ I = A \cos(\phi) \]

- Problem with QPSK: requires producing a reference signal
  - Solved with DQPSK (Differential QPSK): Phase shift is not relative to a reference signal but to the phase of the previous two bits
Spread Spectrum

- Spread the bandwidth needed to transmit data
- Provides resistance against *narrowband interference*

sender:
- spread data (i)
- new data requires broader band (ii)

channel:
- interference adds to the signal

receiver:
- de-spread the signal
- filter out broadband noise
- receive narrowband data
General Model of Spread Spectrum Digital Communication System

- Frequency scheme (for FHSS)
- Chipping Sequence (for DSSS)
Frequency Hopping Spread Spectrum (FHSS)

- Total available bandwidth is split into many smaller bandwidth channels
- Transmitter/receiver stay on one of those channels for a certain time and then hop to next channel
Direct Sequence Spread Spectrum

- Sender and receive share chipping sequence
- Transmission: transmit XOR of data and chipping sequence
- Receiver: decode data by XORing with chipping sequence
Direct Sequence Spread Spectrum

Why does this work?

- Assume data represented by -1, 1 (instead of 0, 1)
  - Using -1,1 allows us to use vector scalar product *
  - In practice DSSS systems use XOR and a 0,1 system
- B = Chipping sequence, B*B = 1, Spreading factor T/Tc
- Transmitting data: C=A*B,
- Receiving data: C*B=A*B*B=A

What if we have interference?

- Signal on the air: A*B + I
- Received data: A*B*B + I*B = A + I*B
Comparison FHSS and DSSS

- FHSS is good in case of frequency selective interference
- FHSS is simpler than DSSS
- FHSS uses only a portion of the bandwidth at any given time
- But DSSS are more robust to fading and multipath effects
Medium Access Control in Wireless Networks
Can we apply access methods from fixed networks?

- Recall CSMA/CD
  - Carrier Sense Multiple Access with Collision Detection
  - Originally defined in 802.3 (10 Mbit/s Ethernet)
  - Send as soon as medium is free, listen into the medium if a collision occurs, stop sending in case of collision
  - Works on wire as more or less the same signal strength can be assumed all over the wire

- Why does CSMA/CD not work in wireless
  - Signal strength decreases at least proportional to the square of the distance
  - CS and CD is applied by sender, but collision happens at receiver
Hidden Terminal Problem

- A sends to B, C cannot receive A
- C wants to send B, C senses “free” medium (CS fails)
- Collision at B, A cannot receive collision (CD fails)
- A is “hidden” for C
Exposed Terminal Problem

- B sends to A, C wants to send to D
- C has to wait, CS signals medium is in use
- Since A is outside of the radio range of C waiting is not necessary
- C is “exposed” to B
Multiplexing Wireless Transmissions

- **SDM (Space Division Multiplexing)**
  - Use cells to reuse frequencies, or,
  - use directional antennas (separate users by individual beams)

- **FDM (Frequency Division Multiplexing)**
  - Assign a certain frequency band to a transmission channel (refers to a sender/receiver that want to exchange data)
  - Permanent (radio broadcast), slow hopping (GSM), fast hopping (Bluetooth)

- **TDM (Time Division Multiplexing)**
  - Separate different channels by time
  - Almost all wired MAC schemes make use of this (Ethernet, Token Ring, ATM)

- **CDM (Code Division Multiplexing)**
  - Codes with certain characteristics can be applied to the transmissions to separate different users (just like DSSS)

- In practice: a combination of those techniques are used
Multiplexing (2)

- SDM, FDM, TDM and CDM techniques when used in the context of Medium Access Control are referred to:
  - SDMA: Space Division Multiple Access
  - FDMA: Frequency Division Multiple Access
  - TDMA: Time Division Multiple Access
  - CDMA: Code Division Multiple Access

- FDM also used for creating duplex channels
  - FDD: Frequency Division Duplex (Separate Uplink and Downlink Channel)
Space Division Multiplexing

- Reuse distance in cellular
- Extremely simplified example:
  - Assume SINR of at least 9dB is required, assume no noise
  - Assume path loss $a=3$
  - Then: $\text{SINR} = \frac{S}{I} = \frac{(D-R)^a}{R^a} = \frac{(D/R - 1)^a}{R^a}$
  - $\text{SINR}(\text{db}) = a \times 10 \times \log_{10}(D/R - 1) = 9\text{db}$
    which gives $D/R \sim 3$

  A frequency reuse at distance 2 might be feasible

Example from Mobile Computing 05/06, Wattenhofer
FDD and FDMA

- Download: 200kHz wide channels from 935-960MHz
- Uplink: 200kHz wide channels from 890.2-915MHz
- Base station selects channels
  - Different channels for different users (FDMA) and uplink/download (FDD)
TDMA (1): Fixed TDMA

- Time slots are allocated for channels in a fixed pattern (e.g. round robin)
- Used in GSM or DECT
- Good for connections with fixed bandwidth (such as voice)
- Guarantees fixed delay (e.g., station transmits every 10ms as in DECT)
- Inefficient: Waste of bandwidth if slot is not used
TDMA (2): Competition for slots

- Slotted Aloha with backoff protocol
  - Uncoordinated access but transmission always at the beginning of a slot
  - If collision → backoff a random number
  - Flexible if new stations join/leave

- CSMA/CA: Carrier Sense Multiple Access with Collision Avoidance
  - Sense media
  - If free transmit
  - If busy, backoff a random amount of time
  - Used in 802.11
TDMA (3): Reservation-based

- DAMA: Demand Assigned Multiple Access
- Idea:
  - Divide time into “reservation period” and “transmission period”
  - Reservation period = stations reserve future slots
    - Contention phase: collisions can occur in this phase
  - Collision-free transmission during reserved slots
- Contention phase uses *Slotted Aloha* scheme
- Explicit reservation
TDM (4): Other reservation schemes

- **PRMA: packet reservation multiple access**
  - Slots are numbered modulo N
  - Implicit reservation: assigned slots remain assigned until the station has no more data to send

- **Reservation TDMA**
  - N mini-slots are followed by N*k data-slots
  - Each station has allotted its own mini-slot and can use it to reserve up to k data-slots
  - Unused slots can be used by other stations
Polling

- If one station can be heard by all others, this central station can poll other terminals according to some scheme
- Poll = request a station to transmit a packet and ACK the packet

- Schemes
  - Round robin
  - Randomly
  - According to a list established during a contention phase

- Polling is used in 802.11, Bluetooth
What about the *hidden terminal* and *exposed terminal* problem?

- No hidden or exposed terminal problem if a central base station controls transmission pattern of stations
  - Polling
  - Stations send in reserved slots
  - Stations send round robin
  - Stations send with different frequencies

- Hidden and exposed terminal if stations compete for TDM slots
  - Slotted Aloha
  - CSMA/CA
  - Reservation phase in reservation-based protocols

- Hidden and exposed terminal if there is no base station (ad hoc networks)
MACA: Multiple Access with Collision Avoidance

- Avoid hidden terminal problem
  - A wants to send to B
  - A sends RTS (request to send) packet to B
  - B acks with a CTS packet (clear to send)
  - C waits after receiving CTS packet
  - Both RTS and CTS packets contains sender address, receiver address and the length of the future transmission

- Optionally used in 802.11
MACA (2)

- Problems:
  - Collisions can still occur during the sending of an RTS (both A and C could send an RTS that collides at B)
    - But RTS packet is much smaller than data packet
  - Extra RTS/CTS packets are overhead, especially for short time-critical data packets
MACA (3)

- MACA can also avoid the exposed terminal problem
  - B wants to send to A, and C wants to send to D
  - B and A exchange RTS/CTS
  - C does not hear the CTS of A, thus it does not have to wait
References

- Link-level Measurements from an 802.11b Mesh Network, Dan Aguayo John Bicket, Sanjit Biswas, Robert Morris, Sigcomm 2004
- Digital Modulation in Communication System – An Introduction, HP Whitepaper