18-452/18-750
Wireless Networks and Applications
Lecture 2: Wireless Challenges

Peter Steenkiste
Carnegie Mellon University

Fall Semester 2018
http://www.cs.cmu.edu/~prs/wirelessF18/

Announcements

• Information forms
  » Please fill one out if you missed the last lecture
• Waiting list updates
  » There should be room for students to enroll
• Recitation clarification
  » Recitations do not cause a conflict since they will be rare
• Reading list networking
  » The web site has an old list, but any textbook is fine
  » Use the index to find “OSI protocol stack”, ethernet, …
• I have updated the schedule online
  » Moved three lectures to recitation slot
  » First lecture is tomorrow!
  » The lectures are recorded and will be available on Canvas

Some Results from Survey

- Background
  - Yes
  - No

- Networking
  - Yes
  - No

- Wireless Comm.
  - Yes
  - No

- Signal processing
  - Yes
  - No

- Friday Conflict
  - Yes
  - Kind of
  - No

Outline

• Goals and structure of the course
• Administrative stuff
• A bit of history
• Wireless technologies
• Building a network
  » Designing a BIG system
  » The OSI model
  » Packet-based communication
  » Challenges in Wireless Networking
Why Use Wireless?

There are no wires!

Has several significant advantages:

- **Supports mobile users**
  - Move around office, campus, city, ... - users get hooked
  - Remote control devices (TV, garage door, ..)
  - Cordless phones, cell phones, ..
  - WiFi, GPRS, Bluetooth, ...

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

What is Hard about Wireless?

There are no wires!

- **In wired networks links are constant, reliable and physically isolated**
  - A 1 Gbps Ethernet always has the same properties
  - This is definitely not true for “54 Mbs” 802.11a

- **In wireless networks links are variable, error-prone and share the ether with each other and other external, uncontrolled sources**
  - Link properties can be extremely dynamic
  - For mobile devices they also differ across locations

Wireless is a shared medium

- **In wired communication, signals are contained in a conductor**
  - Copper or fiber
  - Guides energy to destination
  - Protects signal from external signals

- **Wireless communication uses broadcasting over the shared ether**
  - Energy is distributed in space
  - Signal must compete with many other signals in same frequency band

Attenuation and Errors

- **In wired networks error rate 10^{-10} or less**
  - Wireless networks are far from that target

- **Signal attenuates with distance and is affected by noise and competing signals**

- **Obstacles further attenuate the signal**

- **Probability of a successful reception depends on the “signal to interference and noise ratio” - the SINR**

- **More details later in the course**
How Do We Increase Network Capacity?

- Easy to do in wired networks: simply add wires
  » Fiber is especially attractive
- Adding wireless “links” increases interference.
  » Frequency reuse can help ... subject to spatial limitations
  » Or use different frequencies ... subject to frequency limitations
- The capacity of the wireless network is fundamentally limited.

Mobility Affects the Link Throughput

- Quality of the transmission depends on distance and obstacles blocking the “line of sight” (LOS)
  » “Slow fading” – the signal strength changes slowly
- Reflections off obstacles combined with mobility can cause “fast fading”
  » Very rapid changes in the signal
  » More on this later
- Hard to predict signal!

How is Wireless Different?

<table>
<thead>
<tr>
<th>Wired</th>
<th>Wireless</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Physical link properties are fixed and specified in standards</td>
<td>• Physical link properties can change rapidly in unpredictable ways</td>
</tr>
<tr>
<td>• Designed for low error rates and throughput is fixed and known</td>
<td>• Error rates vary a lot and throughput is very dynamic</td>
</tr>
<tr>
<td>• Datalink layer is simple and optimized for the physical layer</td>
<td>• How do you design an efficient datalink protocol?</td>
</tr>
<tr>
<td>• Internet was designed assuming wires</td>
<td>• How well will higher layer protocols work?</td>
</tr>
</tbody>
</table>

Implications of Variability in Wireless PHY Layer

- Wireless datalink protocols must optimize throughput across an unknown and dynamic transmission medium
  » It helps to understand what causes the changes
- Wireless “links” as observed by layers 3-7 will be unavoidably different from wired links
  » Variable bandwidth and latency
  » Intermittent connectivity
  » Must adapt to changes in connectivity and bandwidth
- Understanding the physical layer is the key to making wireless work well
  » Both at the wireless network and Internet level
Outline

- **RF introduction**
  - A cartoon view
  - Communication
  - Time versus frequency view
- **Modulation and multiplexing**
- **Channel capacity**
- **Antennas and signal propagation**
- **Modulation**
- **Diversity and coding**
- **OFDM**

---

From Signals to Packets

- **Packet Transmission**
  - **Sender** → **Receiver**
  - **Packets**
    - Header/Body
    - 0 0 1 0 1 1 1 0 0 0 1
  - **Bit Stream**
    - 0 0 1 0 1 1 1 0 0 0 1
  - **“Digital” Signal**
  - **Analog Signal**

---

RF Introduction

- **RF = Radio Frequency**
  - Electromagnetic signal that propagates through “ether”
  - Ranges 3 KHz .. 300 GHz
  - Or 100 km .. 0.1 cm (wavelength)
- **Travels at the speed of light**
- **Can take both a time and a frequency view**

---

Wireless Spectrum in the US
Cartoon View 1 – A Wave of Energy

- Think of it as energy that radiates from an antenna and is picked up by another antenna.
- Helps explain properties such as attenuation
  - Density of the energy reduces over time, distance
  - Signal strength is reduced, error rates go up
- Relevance to networking?
  - Error rates of “wireless” depend on distance
    - Also depends on many properties
  - Notion spatial reuse of frequencies
    - Basis of cellular and WiFi infrastructures

Cartoon View 2 – Rays of Energy

- Can also view it as a “ray” that propagates between two points
  - Rays can be reflected etc.
  - A channel can include multiple “rays” that take different paths – “multi-path” effect
- Implications for wireless networks
  - We can have provide connectivity without line of sight!
  - Receiver can receive multiple copies of the signal, which leads to signal distortion
  - Combined with mobility, it also leads to fast fading

(Not so) Cartoon View 3 – Electro-magnetic Signal

- Signal that propagates and changes over time with a certain frequency and has an amplitude and phase
  - Think: sine wave
- Relevance to networking?
  - The sender can change the properties of the EM signal over time to convey information
  - Receivers can observe these changes and extract the information

Time and Point View of Signal

- Can look at a point in space: signal will change in time according to a sine function
  - But transmitter can change phase, amplitude, frequency
- Can take a snapshot in time: signal will “look” like a sine function in space
  - Signal at different points are (rough) copies of each other
- Receiver can observe transmitter’s changes

Relevance to Networking?
Communication

Remember:
Cartoon view

- Sender changes signal in agree upon way and receiver interprets the changes
  » “Modulation” and “demodulation”
- Problem: the signal gets distorted on “channel”
  » Makes it harder for receiver to interpret changes

Sine Wave Parameters

- General sine wave
  » \( s(t) = A \sin(2\pi ft + \phi) \)
- Example on next slide shows the effect of varying each of the three parameters
  a) \( A = 1, f = 1 \text{ Hz}, \phi = 0; \text{ thus } T = 1s \)
  b) Reduced peak amplitude; \( A=0.5 \)
  c) Increased frequency; \( f = 2, \text{ thus } T = \frac{1}{2} \)
  d) Phase shift; \( \phi = \frac{\pi}{4} \text{ radians (45 degrees)} \)
- Note: \( 2\pi \text{ radians} = 360^\circ = 1 \text{ period} \)

Space and Time View Revisited

Key Idea of Wireless Communication

- The sender sends an EM signal and changes its properties over time
  » Changes reflect a digital signal, e.g., binary or multi-valued signal
  » Can change amplitude, phase, frequency, or a combination
- Receiver learns the digital signal by observing how the received signal changes
  » Note that signal is no longer a simple sine wave or even a periodic signal

“The wireless telegraph is not difficult to understand.
The ordinary telegraph is like a very long cat.
You pull the tail in New York, and it meows in Los Angeles.
The wireless is exactly the same, only without the cat.”
Outline

• RF introduction
  » A cartoon view
  » Communication
  » Time versus frequency view
• Modulation and multiplexing
• Channel capacity
• Antennas and signal propagation
• Modulation
• Diversity and coding
• OFDM

Challenge

• Cats, really? This is very informal!
  » Sender “changes signal” and receiver “observes changes”
• Wireless network designers need more precise information about the performance of wireless “links”
  » Can the receiver always decode the signal?
  » How many Kbit, Mbit, Gbit per second?
  » Does the physical environment, distance, mobility, weather, season, the color of my shirt, etc. matter?
• We need a more formal way of reasoning about wireless communication:
  Represent the signal in the frequency domain!

Time Domain View:
Periodic versus Aperiodic Signals

• Periodic signal - analog or digital signal pattern that repeats over time
  » \[ s(t + T) = s(t) \]
  – where \( T \) is the period of the signal
  » Allows us to take a frequency view – important to understand wireless challenges and solutions
• Aperiodic signal - analog or digital signal pattern that doesn't repeat over time
  » Hard to analyze
• Can “make” an aperiodic signal periodic by taking a time slice \( T \) and repeating it
  » Often what we do implicitly

Key Parameters of (Periodic) Signal

• Peak amplitude (\( A \)) - maximum value or strength of the signal over time; typically measured in volts
• Frequency (\( f \))
  » Rate, in cycles per second, or Hertz (Hz) at which the signal repeats
• Period (\( T \)) - amount of time it takes for one repetition of the signal
  » \( T = 1/f \)
• Phase (\( \phi \)) - measure of the relative position in time within a single period of a signal
• Wavelength (\( \lambda \)) - distance occupied by a single cycle of the signal
  » Or, the distance between two points of corresponding phase of two consecutive cycles
Key Property of Periodic EM Signals

- Any electromagnetic signal can be shown to consist of a collection of periodic analog signals (sine waves) at different amplitudes, frequencies, and phases.
- The period of the total signal is equal to the period of the fundamental frequency:
  - All other frequencies are an integer multiple of the fundamental frequency.
- There is a strong relationship between the “shape” of the signal in the time and frequency domain:
  - Discussed in more detail later.

Signal = Sum of Sine Waves

\[ \text{Signal} = \text{Sum of Sine Waves} \]

\[ = + 1.3 X + 0.56 X + 1.15 X \]

The Frequency Domain

- A (periodic) signal can be viewed as a sum of sine waves of different strengths:
  - Corresponds to energy at a certain frequency.
- Every signal has an equivalent representation in the frequency domain:
  - What frequencies are present and what is their strength (energy).
- We can translate between the two formats using a Fourier transform.