

18-759: Wireless Networks

Lectures 3: Physical Layer

Peter Steenkiste
Dina Papagiannaki
Spring Semester 2009
<http://www.cs.cmu.edu/~prs/wireless09/>

Peter A. Steenkiste

1

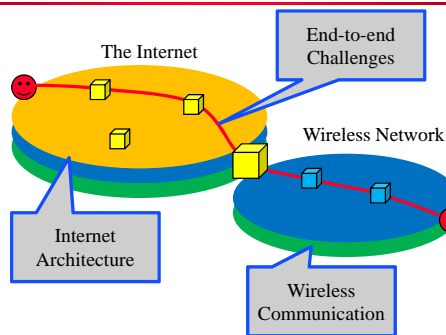
Outline

- RF introduction
 - » Time versus frequency view
 - » A cartoon view
- Modulation and multiplexing
- Channel capacity
- Antennas and signal propagation
- Equalization and diversity
- Modulation and coding
- Spectrum access

Peter A. Steenkiste

2

But First a Word about Prerequisites



Peter A. Steenkiste

3

Wireless Networks Builds on ...

- **General networking:**
 - » Internet architecture: who is responsible for what?
 - » How is it affected by wireless links or congestion in wireless multi-hop networks?
 - » How is it affected by mobility?
- **Wireless communications:**
 - » How does signal environment affect performance of a wireless link?
 - » What challenges can be hidden from higher layer protocols?
- **Must also consider projects**
 - » Requires some programming in Java and/or C

Peter A. Steenkiste

4

Course Structure

- 4 lectures of “Communications” overview
 - » Very high level – should be accessible to anybody (and boring for some)
- 4 lectures on cellular
 - » Should be largely stand alone
- 6 or so lectures on WLAN and PAN
 - » Largely stand alone, although some dependencies on the Internet (e.g. bridging)
- Second half of course is on broad range of topics, some of which depend heavily on Internet
 - » For example, TCP over wireless, wireless and the Internet, etc.

Peter A. Steenkiste

5

Conclusion

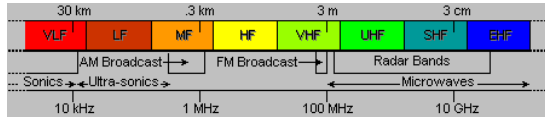
- Computer engineering background with a course in signals = target audience
- No background in signals – will require some extra effort
- Electrical engineering background with no background in network – possible
 - » If you commit to extra effort to catch up on some networking principles – we can provide reading list
 - » Still need to have some programming experience for the project

Peter A. Steenkiste

6

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

Peter A. Steenkiste

7

Time Domain View: Periodic versus Aperiodic Signals

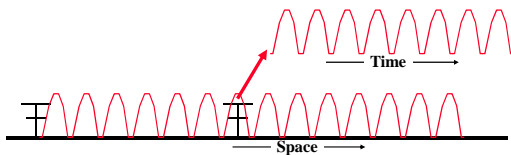
- **Periodic signal - analog or digital signal pattern that repeats over time**
 - » $s(t+T) = s(t)$
 - where T is the period of the signal
 - » Allows us to take a frequency view
- **Aperiodic signal - analog or digital signal pattern that doesn't repeat over time**
- Can “make” an aperiodic signal periodic by taking a slice T and repeating it
 - » Often what we do implicitly

Peter A. Steenkiste

8

Simple Example: Sine Wave

- RF signal travels at the speed of light
- Can look at a point in space: signal will change in time according to a sine function
- Can take a snapshot in time: signal will “look” like a sine function in space



Peter A. Steenkiste

9

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 (ϕ)** - measure of the relative position in time within a single period of a signal
- **Wavelength (λ)** - distance occupied by a single cycle of the signal
 - » Or, the distance between two points of corresponding phase of two consecutive cycles

Peter A. Steenkiste

10

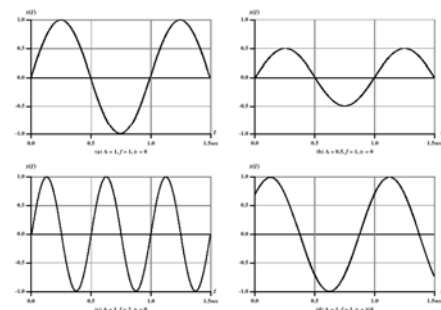
Sine Wave Parameters

- **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) $A = 1$, $f = 1$ Hz, $\phi = 0$; thus $T = 1$ s
 - » (b) Reduced peak amplitude; $A = 0.5$
 - » (c) Increased frequency; $f = 2$, thus $T = 1/2$
 - » (d) Phase shift; $\phi = \pi/4$ radians (45 degrees)
- **note: 2π radians = $360^\circ = 1$ period**

Peter A. Steenkiste

11

Space and Time View Revisited



Peter A.

$s(t) = A \sin(2\pi ft + \phi)$

12

Frequency-Domain Concepts

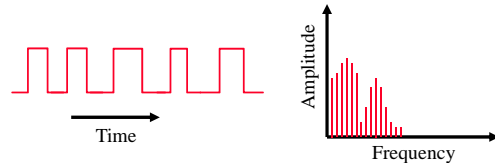
- Any electromagnetic signal can be shown to consist of a collection of periodic analog signals (sine waves) at different amplitudes, frequencies, and phases
- The period of the total signal is equal to the period of the fundamental frequency
 - › All other frequencies are an integer multiple of the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

Peter A. Steenkiste

13

The Frequency Domain

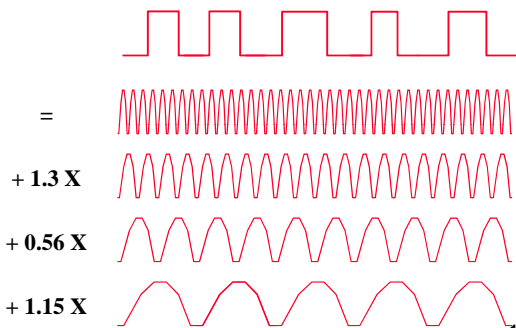
- A (periodic) signal can be viewed as a sum of sine waves of different strengths.
 - › Corresponds to energy at a certain frequency
- Every signal has an equivalent representation in the frequency domain.
 - › What frequencies are present and what is their strength (energy)
- Again: Similar to radio and TV signals.



Peter A. Steenkiste

14

Signal = Sum of Sine Waves



Peter A. Steenkiste

15

Frequency-Domain Concepts

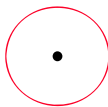
- Fundamental frequency - when all frequency components of a signal are integer multiples of one frequency, it's referred to as the fundamental frequency
- Spectrum - range of frequencies that a signal contains
- Absolute bandwidth - width of the spectrum of a signal
- Effective bandwidth (or just bandwidth) - narrow band of frequencies that most of the signal's energy is contained in

Peter A. Steenkiste

16

Cartoon View 1 - Energy Wave

- 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 and with distance
- Useful when studying attenuation
 - › Receiving antennas catch less energy with distance
 - › Notion of cellular infrastructure



Peter A. Steenkiste

17

Cartoon View 2 - Rays of Energy

- Can also view it as a “ray” that propagates between two points
 - › Can provide connectivity without line of sight
- A channel can also include multiple “rays” that take different paths
 - › Helps explain properties such as multipath



Peter A. Steenkiste

18

Outline

- RF introduction
- Modulation and multiplexing - review
 - › Analog versus digital signals
 - › Forms of modulation
 - › Baseband versus carrier modulation
 - › Multiplexing
- Channel capacity
- Antennas and signal propagation
- Equalization and diversity
- Modulation and coding
- Spectrum access

Peter A. Steenkiste

19

Analog and Digital Signals

- Sender changes the signal, e.g. the amplitude, in a way that receiver can recognize
- Analog: a continuously varying electromagnetic wave that may be propagated over a variety of media, depending on frequency
 - › Wired: Twisted pair, coaxial cable, fiber
 - › Wireless: Atmosphere or space propagation
 - › Cannot recover from distortions, noise
- Digital: discreet changes in the signal that correspond to a digital signal
 - › Less susceptible to noise but can suffer, e.g., attenuation
 - › Can regenerate signal along the path (repeater versus amplifier)

Peter A. Steenkiste

20

Digital Signal Modulation

- Sender changes the nature of the signal in a way that the receiver can recognize
- Amplitude modulation (AM): change the strength of the carrier based on information
 - › High values -> stronger signal
- Frequency (FM) and phase modulation (PM): change the frequency or phase of the signal
 - › Frequency or Phase shift keying
- Digital versions are sometimes called "shift keying"
 - › Amplitude (ASK), Frequency (FSK), Phase (PSK) Shift Keying
- Discussed later in more detail

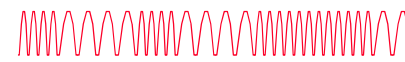
Peter A. Steenkiste

21

Amplitude and Frequency Modulation



0 0 1 1 0 0 1 1 0 0 0 1 1 1 0 0 0 1 1 1 0



0 1 1 0 1 1 0 0 0 1

Peter A. Steenkiste

22

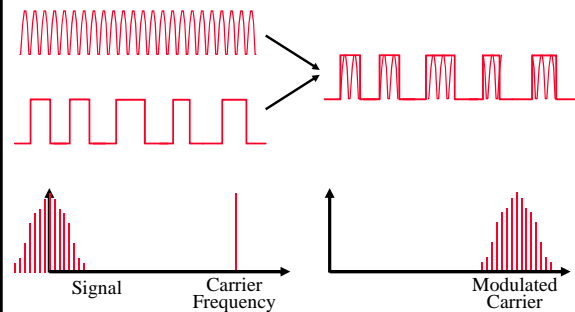
Baseband versus Carrier Modulation

- Baseband modulation: send the "bare" signal
 - › Use the lower part of the spectrum
- Baseband modulation has limited use
 - › Everybody competes – only makes sense for point-to-point links, but unattractive for wireless
 - › Use of higher frequencies requires transmission of a single high bandwidth signal
 - › Some media only transmit higher frequencies, e.g. optical
- Carrier modulation: use the (information) signal to modulate a higher frequency (carrier) signal
 - › Can be viewed as the product of the two signals
 - › Corresponds to a shift in the frequency domain
- Also applies to frequency and phase modulation
 - › E.g. change frequency of the carrier instead of its amplitude

Peter A. Steenkiste

23

Amplitude Carrier Modulation



Peter A. Steenkiste

24

Multiple Users Can Share the Ether

Different users use
Different carrier frequencies

Frequency

Peter A. Steenkiste 25

Multiplexing

- Capacity of transmission medium usually exceeds capacity required for transmission of a single signal
- Multiplexing - carrying multiple signals on a single medium
 - » More efficient use of transmission medium

Peter A. Steenkiste 26

Multiplexing Techniques

- Frequency-division multiplexing (FDM)
 - » divide the capacity in the frequency domain
- Time-division multiplexing (TDM)
 - » Divide the capacity in the time domain
 - » Fixed or variable length time slices

Peter A. Steenkiste 27

Frequency versus Time-division Multiplexing

- With frequency-division multiplexing different users use different parts of the frequency spectrum.
 - » I.e. each user can send all the time at reduced rate
 - » Example: roommates
 - » Hardware is slightly more expensive and is less efficient use of spectrum
- With time-division multiplexing different users send at different times.
 - » I.e. each user can send at full speed some of the time
 - » Example: a time-share condo
 - » Drawback is that there is some transition time between slots; becomes more of an issue with longer propagation times
- The two solutions can be combined.

Peter A. Steenkiste 28

Use of Spectrum

- Different users use the wire at different points in time.
- Aggregate bandwidth also requires more spectrum.

Peter A. Steenkiste 29

FDM Example: AMPS

- US analog cellular system in early 80's.
- Each call uses an up and down link channel.
 - » Channels are 30 KHz
- About 12.5 + 12.5 MHz available for up and down link channels per operator.
 - » Supports 416 channels in each direction
 - » 21 of the channels are used for data/control
 - » Total capacity (across operators) is double of this

Peter A. Steenkiste 30

TDM Example: GSM

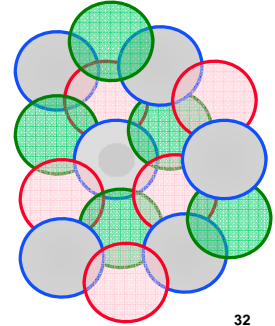
- Global System for Mobile communication.
 - › First introduced in Europe in early 90s
- Uses a combination of TDM and FDM.
- 25 MHz each for up and down links.
- Broken up in 200 KHz channels
 - › 125 channels in each direction
 - › Each channel can carry about 270 kbs
- Each channel is broken up in 8 time slots
 - › Slots are 0.577 msec long
 - › Results in 1000 channels, each with about 25 kbs of useful data; can be used for voice, data, control
- General Packet Radio Service (GPRS).
 - › Data service for GSM, e.g. 4 down and 1 up channel

Peter A. Steenkiste

31

Frequency Reuse in Space

- Frequencies can be reused in space
 - › Distance must be large enough
 - › Example: radio stations
- Basis for “cellular” network architecture
- Set of “base stations” connected to the wired network support set of nearby clients
 - › Star topology in each circle
 - › Cell phones, 802.11, ...



Peter A. Steenkiste

32

Outline

- RF introduction
- Modulation and multiplexing
- Channel capacity
- Antennas and signal propagation
- Equalization and diversity
- Modulation and coding
- Spectrum access

Peter A. Steenkiste

33

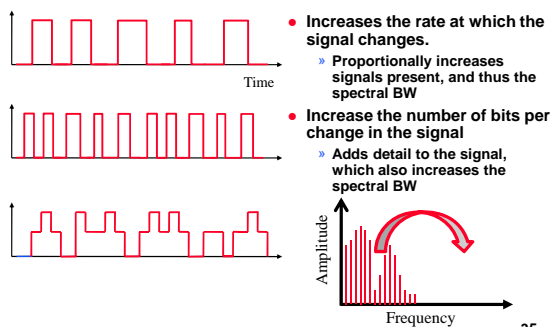
Relationship between Data Rate and Bandwidth

- The greater the (spectral) bandwidth, the higher the information-carrying capacity of the signal
- Intuition: if a signal can change faster, it can be modulated in a more detailed way and can carry more data
 - › E.g. more bits or higher fidelity music
- Extreme example: a signal that only changes once a second will not be able to carry a lot of bits or convey a very interesting TV channel

Peter A. Steenkiste

34

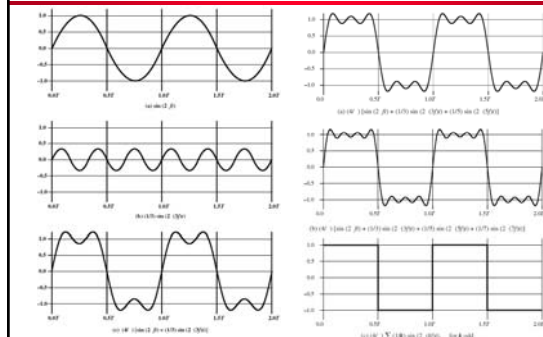
Increasing the Bit Rate



Peter A. Steenkiste

35

Adding Detail to the Signal

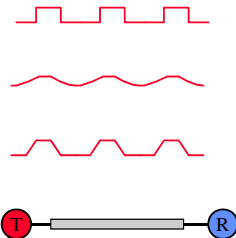


Peter A. Steenkiste

36

So Why Don't we Always Send a High Bandwidth Signal?

- Channels have a limit on the type of signals it can carry
- Wires only transmit signals in certain frequency range
 - Attenuation and distortion outside of range
 - Distortion makes it hard for receiver to extract the information
- Wireless radios are only allowed to use certain parts of the spectrum
 - Radios optimized for that frequency

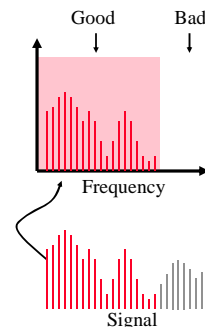


Peter A. Steenkiste

37

Transmission Channel Considerations

- Example: grey frequencies get attenuated significantly
- For wired networks, channel limits are an inherent property of the channel
 - Different types of fiber and copper have different properties
- As technology improves, these parameters change, even for the same wire
 - Thanks to our EE friends
- For wireless networks, limits are often imposed by policy
 - Can only use certain part of the spectrum
 - Radio uses filters to comply



Peter A. Steenkiste

38

Channel Capacity

- Data rate - rate at which data can be communicated (bps)
 - Channel Capacity – the maximum rate at which data can be transmitted over a given channel, under given conditions
- Bandwidth - the bandwidth of the transmitted signal as constrained by the transmitter and the nature of the transmission medium (Hertz)
- Noise - average level of noise over the communications path
- Error rate - rate at which errors occur
 - Error = transmit 1 and receive 0; transmit 0 and receive 1

Peter A. Steenkiste

39

The Nyquist Limit

- A noiseless channel of bandwidth B can at most transmit a binary signal at a capacity $2B$
 - E.g. a 3000 Hz channel can transmit data at a rate of at most 6000 bits/second
 - Assumes binary amplitude encoding
- For M levels: $C = 2B \log_2 M$
 - M discrete signal levels
- More aggressive encoding can increase the actual channel bandwidth
 - Example: modems
- Factors such as noise can reduce the capacity

Peter A. Steenkiste

40

Decibels

- A ratio between signal powers is expressed in decibels

$$\text{decibels (db)} = 10 \log_{10}(P_1 / P_2)$$
- Is used in many contexts:
 - The loss of a wireless channel
 - The gain of an amplifier
- Note that dB is a relative value.
- Can be made absolute by picking a reference point.
 - Decibel-Watt – power relative to 1W
 - Decibel-milliwatt – power relative to 1 milliwatt

Peter A. Steenkiste

41

Signal-to-Noise Ratio

- Ratio of the power in a signal to the power contained in the noise that is present at a particular point in the transmission
 - Typically measured at a receiver
- Signal-to-noise ratio (SNR, or S/N)

$$(SNR)_{dB} = 10 \log_{10} \frac{\text{signal power}}{\text{noise power}}$$
- A high SNR means a high-quality signal, low number of required intermediate repeaters
- SNR sets upper bound on achievable data rate

Peter A. Steenkiste

42

Shannon Capacity Formula

- **Equation:** $C = B \log_2(1 + \text{SNR})$
- **Represents error free capacity**
 - » It is possible to design a suitable signal code that will achieve error free transmission (you design the code)
- **Result is based on many assumptions**
 - » Formula assumes white noise (thermal noise)
 - » Impulse noise is not accounted for
 - » Various types of distortion are also not accounted for
- **We can also use Shannon's theorem to calculate the noise that can be tolerated to achieve a certain rate through a channel**

Peter A. Steenkiste

43

Shannon Discussion

- **Bandwidth B and noise N are not independent**
 - » N is the noise in the signal band, so it increases with the bandwidth
- **Shannon does not provide the coding that will meet the limit, but the formula is still useful**
- **The performance gap between Shannon and a practical system can be roughly accounted for by a gap parameter**
 - » Still subject to same assumptions
 - » Gap depends on error rate, coding, modulation, etc.

$$C = B \log_2(1 + \text{SNR}/\Gamma)$$

Peter A. Steenkiste

44

Example of Nyquist and Shannon Formulations

- **Spectrum of a channel between 3 MHz and 4 MHz ; $\text{SNR}_{\text{dB}} = 24 \text{ dB}$**
 - $B = 4 \text{ MHz} - 3 \text{ MHz} = 1 \text{ MHz}$
 - $\text{SNR}_{\text{dB}} = 24 \text{ dB} = 10 \log_{10}(\text{SNR})$
 - $\text{SNR} = 251$
- **Using Shannon's formula**
 - $C = 10^6 \times \log_2(1 + 251) \approx 10^6 \times 8 = 8 \text{ Mbps}$

Peter A. Steenkiste

45

Example of Nyquist and Shannon Formulations

- **How many signaling levels are required?**
 - $C = 2B \log_2 M$
 - $8 \times 10^6 = 2 \times (10^6) \times \log_2 M$
 - $4 = \log_2 M$
 - $M = 16$

Peter A. Steenkiste

46

Unused Slides

Peter A. Steenkiste

47

Analog and Digital Information

- **Initial RF use was for analog information**
 - » Radio and TV stations
 - » The information that is sent is of a continuous nature
- **Data networks (e.g. the Internet) are used for digital information: text files, databases, etc.**
 - » Information consists of discrete units (e.g. bits)
- **We can also send analog information as digital data**
 - » Sample the signal, i.e. analog -> digital
 - » Why?
 - » We can also send digital information as analog information, e.g. modem

Peter A. Steenkiste

48

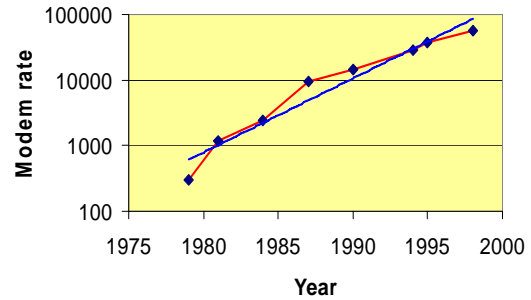
Analog versus Digital Transmission

- **Analog: transmit analog signals without regard to content**
 - › Attenuation limits length of transmission link
 - › Cascaded amplifiers boost signal's energy for longer distances but cause distortion
 - Analog data can tolerate (some) distortion
 - But introduces errors in digital data
- **Digital: can recognize the content of signal**
 - › Attenuation endangers integrity of data
 - › Repeaters can recover the signal and retransmit
 - Also true of analog signal that carries digital data: repeater can recover signal and generate new clean analog signal

Peter A. Stoenkovic

49

Example Impact of Technology: Modem Rates



Classifications of Transmission Media

- **Copper: twisted pair versus coax cable**
 - › Variety of modulation techniques are used
- **Fiber: modulate an optical signal**
 - › Lots of capacity available!
 - › Typically uses simple modulation schemes
- **Wireless: no solid medium to guided signal**
 - › Wide variety of distances: frequencies, distances, ...
 - › Often uses very aggressive modulation techniques (later)

Peter A. Stoenkovic

51