CS/ECE 439: Wireless Networking

Physical Layer
Wireless Physical Layer

- 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
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?
  - How about variable link properties and intermittent connectivity?

- **Wireless communications**
  - How does signal environment affect performance of a wireless link?
  - What wireless communication challenges can be hidden from higher layer protocols?
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
Cartoon View 1 – Energy Wave

- Think of it as energy that radiates from one 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
Cartoon View 2 – Rays of Energy

- Can also view it as a “ray” that propagates between two points
  - Rays can be reflected etc.
  - Can provide connectivity without line of sight
- A channel can also include multiple “rays” that take different paths
  - Known as multipath
But how can two hosts communicate?

- Encode information on modulated “Carrier signal”
  - Phase, frequency, and/or amplitude modulation
Analog vs. Digital Transmission

- **Analog and digital** correspond roughly to **continuous** and **discrete**

- **Data**: entities that convey meaning
  - **Analog**: continuously varying patterns of intensity (e.g., voice and video)
  - **Digital**: discrete values (e.g., integers, ASCII text)

- **Signals**: electric or electromagnetic encoding of data
  - **Analog**: continuously varying electromagnetic wave
  - **Digital**: sequence of voltage pulses
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
Key Parameters of a (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
Sine Wave Parameters

- **General sine wave**
  - \( s(t) = A \sin(2\pi ft + \phi) \)

- **Effect of parameters**
  - \( A = 1, f = 1 \text{ Hz, } \phi = 0; \text{ thus } T = 1\text{ s} \)

- **Note:** \( 2\pi \text{ radians} = 360^\circ = 1 \text{ period} \)
Sine Wave Parameters

- **General sine wave**
  - If x-axis = time
    - y-axis = value of a signal at a given point in space
  - If x-axis = space
    - y-axis = value of a signal at a given point in time

- note: $2\pi$ radians = 360° = 1 period
Sine Wave Parameters

- General sine wave
  - \( s(t) = A \sin(2\pi ft + \phi) \)
- Effect of parameters
  - Reduced peak amplitude; \( A=0.5 \)

- Note: \( 2\pi \) radians = 360° = 1 period
Sine Wave Parameters

- General sine wave
  \[ s(t) = A \sin(2\pi ft + \phi) \]

- Effect of parameters
  - Increased frequency; \( f = 2 \), thus \( T = \frac{1}{2} \)

- Note: \( 2\pi \text{ radians} = 360^\circ = 1 \text{ period} \)
Sine Wave Parameters

- General sine wave
  - \( s(t) = A \sin(2\pi ft + \phi) \)

- Effect of parameters
  - Phase shift
    - \( \phi = \pi/4 \) radians
      - (45 degrees)

- note: \( 2\pi \) radians = 360° = 1 period
Signal Modulation

- **Amplitude modulation (AM)**
  - Change the strength of the signal
  - High values -> stronger signal

- **Frequency modulation (FM)**
  - Change the frequency of the signal

- **Phase modulation (PM)**
  - Change the phase of the signal
Frequency-Domain Concepts

- **Electromagnetic signal**
  - 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
Frequency-Domain Concepts

- A (periodic) signal
  - A sum of sine waves of different strengths
  - Example: $f$ and $3f$
    - Note that $3f$ is an integer multiple of $f$

- Fundamental frequency
  - All frequency components are integer multiples of one frequency

\[
\frac{4}{\pi}[\sin(2\pi ft) + \frac{1}{3}\sin(2\pi 3ft)]
\]
Frequency-Domain Concepts

- A (periodic) signal
  - A sum of sine waves of different strengths
  - Example: $f$ and $3f$
    - Note that $3f$ is an integer multiple of $f$

- Fundamental frequency
  - Period of the signal = the period of the fundamental frequency

$$(4\pi)[\sin(2\pi ft) + (1/3)\sin(2\pi 3ft)]$$
Frequency-Domain Concepts

- **Spectrum**
  - Range of frequencies
  - From $f$ to $3f$

- **Effective bandwidth**
  - Narrow band of frequencies that most of the signal's energy is contained in

- **Absolute bandwidth**
  - Width of the spectrum
  - $3f - f = 2f$

\[(4/\pi)[\sin(2\pi ft) + (1/3)\sin(2\pi 3ft)]\]
Relationship between Data Rate and Bandwidth

- **Bandwidth translates to bits**
  - The greater the (spectral) bandwidth, the higher the information-carrying capacity of the signal (data bandwidth)
  - Intuition: if a signal can change faster, it can be modulated in a more detailed way and can carry more data

- **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
Signals to bits

- Each pulse lasts $1/2f$
- Data rate = $2f$ bps

What are the frequency components of the signal?
Signals to bits

- Each pulse lasts $1/2f$
  - Data rate = $2f$ bps

- Add two sine waves
  
  $\frac{4}{\pi} \sin(2\pi ft) + \frac{1}{3} \sin(2\pi 3ft)$
Signals to bits

- Each pulse lasts $1/2f$
  - Data rate = $2f$ bps

- Add a sine wave with frequency $5f$
Signals to bits

- Each pulse lasts $\frac{1}{2}f$
  - Data rate = $2f$ bps

- Add a sine wave with frequency $7f$
  - And so on …

Infinite frequencies = infinite bandwidth!

not quite …
Data rate

- Available bandwidth of bandwidth of 4MHz
- If $f = 10^6$ cycles/sec = 1MHz
  - Signal bandwidth = 4MHz
  - $T = 1$ bit/0.5 $\mu$sec
  - Data rate = 2 Mbps

Close enough to square wave to distinguish 0 and 1
Data rate

Available bandwidth of bandwidth of 8MHz

If $f = 2$MHz
- Signal bandwidth = 8MHz
- $T = 1$ bit/0.25 µsec
- Data rate = 4 Mbps

Close enough to square wave to distinguish 0 and 1

$2X \text{ BW} = 2X \text{ data rate}$
Data rate

Available bandwidth of bandwidth of 4MHz

If $f = 2$MHz
- Signal bandwidth = 4MHz
- $T = 1$ bit/0.25 µsec
- Data rate = 4 Mbps

What if this is good enough?

IF the receiver can distinguish between 0 and 1!
Goal

Sender changes the signal, e.g. the amplitude, in a way that the 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 from attenuation
- Can regenerate signal along the path (repeater versus amplifier)
Channel Capacity

- **Data rate**
  - Rate at which data can be communicated (bps)

- **Channel Capacity**
  - Maximum rate at which data can be transmitted over a given channel, under given conditions

- **Bandwidth**
  - 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
Sampling

Suppose you have the following 1Hz signal being received

How fast do you need to sample, to capture the signal?
Sampling

- Sampling a 1 Hz signal at 2 Hz is enough
  - Captures every peak and trough
Sampling a 1 Hz signal at 3 Hz is also enough

- In fact, more than enough samples to capture variation in signal
Sampling a 1 Hz signal at 1.5 Hz is not enough

Why?
Sampling

- Sampling a 1 Hz signal at 1.5 Hz is not enough
  - Can’t distinguish between multiple possible signals
  - Problem known as aliasing
What about more complex signals?

- Fourier’s theorem
  - Any continuous signal can be decomposed into a sum of sines and cosines at different frequencies
- Example: Sum of 1 Hz, 2 Hz, and 3 Hz sines
  - How fast to sample?
What about more complex signals?

- Fourier’s theorem
  - Any continuous signal can be decomposed into a sum of sines and cosines at different frequencies
  - Example: Sum of 1 Hz, 2 Hz, and 3 Hz sines
  - How fast to sample? --> answer: 6 Hz
Generalizing the Examples

- What data rate can a channel sustain?
- How is data rate related to bandwidth?
- How does noise affect these bounds?
- What else can limit maximum data rate?
What Data Rate can a Channel Sustain? How is Data Rate Related to Bandwidth?

- Transmitting $N$ distinct signals over a noiseless channel with bandwidth $B$, we can achieve at most a data rate of $2B \log_2 N$.

  - Number of signals per second $\rightarrow 2B \log_2 N \rightarrow$ Number of bits per signal

- ex.: a 3000 Hz channel can transmit data at a rate of at most 6000 bits/second

- Nyquist’s Sampling Theorem (H. Nyquist, 1920’s)
What Data Rate can a Channel Sustain? How is Data Rate Related to Bandwidth?

Transmitting $N$ distinct signals over a noiseless channel with bandwidth $B$, we can achieve at most a data rate of $2B \log_2 N$.

Number of signals per second $\rightarrow 2B \log_2 N \rightarrow$ Number of bits per signal

- **Baud rate**: Number of physical symbols transmitted per second
- **Bit rate**: Actual number of data bits transmitted per second

Nyquist’s Sampling Theorem (H. Nyquist, 1920’s)

- ex.: a 3000 Hz channel can transmit data at a rate of at most 6000 bits/second

Relationship
Depends on the number of bits encoded in each symbol
Noiseless Capacity

- Nyquist’s theorem: \(2B \log_2 N\)
- Example 1: sampling rate of a phone line
  - \(B = 4000\) Hz
  - \(2B = 8000\) samples/sec.
    - sample every 125 microseconds
Noiseless Capacity

- Nyquist’s theorem: $2B \log_2 N$
- Example 2: noiseless capacity
  - $B = 1200 \text{ Hz}$
  - $N = \text{each pulse encodes 16 symbols}$
  - $C =$
Noiseless Capacity

- Nyquist’s theorem: $2B \log_2 N$
- Example 2: noiseless capacity
  - $B = 1200$ Hz
  - $N = \text{each pulse encodes 16 symbols}$
  - $C = 2B \log_2 (N) = D \times \log_2 (N)$
  - $= 2400 \times 4 = 9600$ bps
How does Noise affect these Bounds?

- **Noise**
  - Blurs the symbols, reducing the number of symbols that can be reliably distinguished

- **Claude Shannon (1948)**
  - Extended Nyquist’s work to channels with additive white Gaussian noise (a good model for thermal noise)

  \[
  \text{channel capacity } C = B \log_2 (1 + S/N)
  \]

Where

- \( C \) is the maximum supportable bit rate
- \( B \) is the channel bandwidth
- \( S/N \) is the ratio between signal power and in-band noise power
- \( N \) is noise
How does Noise affect these Bounds?

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    \[
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- Represents error free capacity
  - also used to calculate the noise that can be tolerated to achieve a certain rate through a channel

- 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
Noisy Capacity

- Telephone channel
  - 3400 Hz at 40 dB SNR

\[ \text{SNR(dB)} = 10 \log_{10} \left( \frac{P_{\text{signal}}}{P_{\text{noise}}} \right) \]

decibels (dB) is a logarithmic unit of measurement that expresses the magnitude of a physical quantity (usually power or intensity) relative to a specified or implied reference level.
Decibels

- A ratio between signal powers is expressed in decibels
  \[ \text{decibels (db)} = 10 \log_{10}(P_1 / P_2) \]

- 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
Signal-to-Noise Ratio

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

\[
(SNR)_{dB} = 10 \log_{10} \frac{\text{signal power}}{\text{noise power}}
\]

- A high SNR
  - High-quality signal
- Low SNR
  - May be hard to “extract” the signal from the noise
- SNR sets upper bound on achievable data rate
Noisy Capacity

- **Telephone channel**
  - 3400 Hz at 40 dB SNR
  - $C = B \log_2 (1 + S/N)$ bits/s
  - $SNR = 40 \text{ dB}$
  - $40 = 10 \log_{10} (S/N)$
    - $S/N = 10,000$
  - $C = 3400 \log_2 (10001) = 44.8 \text{ kbps}$

$$SNR(\text{dB}) = 10 \log_{10} \left( \frac{P_{\text{signal}}}{P_{\text{noise}}} \right)$$
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
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.

$$C = B \log_2 \left( 1 + \frac{\text{SNR}}{\Gamma} \right)$$
More examples of Nyquist and Shannon Formulas

- Spectrum of a channel between 3 MHz and 4 MHz; \( \text{SNR}_{dB} = 24 \text{ dB} \)
  
  \[
  B = \]

  \[
  \text{SNR} = \]

- Using Shannon’s formula
  
  \[
  C = B \log_2 (1 + S/N) \]
More examples of Nyquist and Shannon Formulas

- Spectrum of a channel between 3 MHz and 4 MHz; \( SNR_{dB} = 24 \text{ dB} \)

\[
B = 4 \text{ MHz} - 3 \text{ MHz} = 1 \text{ MHz}
\]

\[
SNR_{dB} = 24 \text{ dB} = 10 \log_{10}(SNR)
\]

\[
SNR = 251
\]

- Using Shannon’s formula

\[
C = B \log_2 (1 + S/N)
\]

\[
C = 10^6 \times \log_2 (1 + 251) \approx 10^6 \times 8 = 8 \text{ Mbps}
\]
More examples of Nyquist and Shannon Formulas

- How many signaling levels are required?

\[ C = 2B \log_2 M \]
More examples of Nyquist and Shannon Formulas

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

- Look out for: dB versus linear values, \( \log_2 \) versus \( \log_{10} \)
Multiplexing

- **Capacity of transmission medium**
  - May exceed capacity required for transmission of a single signal

- **Multiplexing**
  - Carrying multiple signals on a single medium
  - More efficient use of transmission medium
Multiplexing

- **FDM: Frequency Division Multiplexing**
  - Channel spectrum divided into frequency bands
  - Each assigned fixed frequency band/reduced rate
  - Unused transmission time in frequency bands go idle
  - Example: 6-station LAN, 1,3,4 transmit, frequency bands 2,5,6 idle
Multiplexing

- **TDM: Time Division Multiplexing**
  - Access in "rounds"
    - Each user/node/etc… gets fixed length slot in each round
    - Each user can send at full speed some of the time
    - Unused slots go idle
  - Example: 6-slots with transmissions in slots 0, 3, and 4
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
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
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, …