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

![Diagram showing clock, data, and Manchester encoding with 0.7 Volts and -0.7 Volts](image-url)
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
  - \( A = 1, f = 1 \text{ Hz}, \phi = 0; \text{ thus } T = 1s \)

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

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

- Effect of parameters
  - Phase shift
    \[ \phi = \pi/4 \text{ radians} \]
    (45 degrees)

- note: \(2\pi \text{ radians} = 360^\circ = 1 \text{ period}\)
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

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

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

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

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

$$\frac{4}{\pi} [\sin(2\pi ft) + \frac{1}{3} \sin(2\pi 3ft)]$$
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 = $2f \text{ bps}$

- Add two sine waves
  $$(4/\pi)\sin(2\pi ft) + (1/3)\sin(2\pi 3ft)$$
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 \( \frac{1}{2f} \)
  - 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 \( f = 2\text{MHz} \)
    - Signal bandwidth = 8MHz
    - \( T = 1 \text{ bit/0.25 } \mu\text{sec} \)
    - Data rate = 4 Mbps

2X BW = 2X data rate

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

Available bandwidth of bandwidth of 4MHz

If $f = 2$ MHz

- Signal bandwidth = 4 MHz
- $T = 1$ 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

- Sampling a 1 Hz signal at 3 Hz is also enough
  - In fact, more than enough samples to capture variation in signal
Sampling

- 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 
  \[2B \log_2 N\]

- 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)
  - Depends on the number of bits encoded in each symbol

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

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

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

- Nyquist’s theorem: $2B \log_2 N$

Example 2: noiseless capacity

- $B = 1200 \text{ Hz}$
- $N = \text{ each pulse encodes 16 symbols}$
- $C = 2B \log_2 (N) = D \times \log_2 (N)$
  $= 2400 \times 4 = 9600 \text{ bps}$
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?

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

- 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

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

- 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
  - $SNR = 40$ dB
    - $40 = 10 \log_{10} (S/N)$
    - $S/N = 10,000$
  - $C = 3400 \log_2 (10001) = 44.8$ kbps

$$SNR(dB) = 10 \log_{10} \left( \frac{P_{signal}}{P_{noise}} \right)$$
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
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; $\text{SNR}_{\text{dB}} = 24$ dB

\[
B = \ldots
\]

\[
\text{SNR} = \ldots
\]

- Using Shannon’s formula

\[
C = B \log_2 (1 + \text{S/N})
\]
More examples of Nyquist and Shannon Formulas

- Spectrum of a channel between 3 MHz and 4 MHz; $\text{SNR}_{dB} = 24 \text{ dB}$
  
  $$B = 4 \text{ MHz} - 3 \text{ MHz} = 1 \text{ MHz}$$
  
  $$\text{SNR}_{dB} = 24 \text{ dB} = 10 \log_{10}(\text{SNR})$$
  
  $$\text{SNR} = 251$$

- 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?
  \[ C = 2B \log_2 M \]
  \[ 8 \times 10^6 = 2 \times \left(10^6\right) \times \log_2 M \]
  \[ 4 = \log_2 M \]
  \[ M = 16 \]

- 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
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, …