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Wireless Networks and Applications
Lecture 3: Physical Layer
Capacity and Signal Propagation

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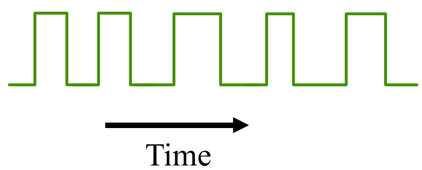
http://www.cs.cmu.edu/~prs/wirelessS24/

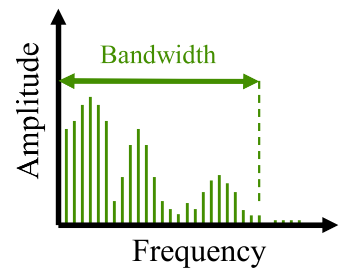
Outline

- Challenges in Wireless Networking
- RF introduction
- Modulation and multiplexing
- Channel capacity
- Antennas and signal propagation
- Modulation
- Diversity and coding
- OFDM and MIMO

From Previous Lecture: 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)
- Our focus here is on the <u>baseband</u> signal



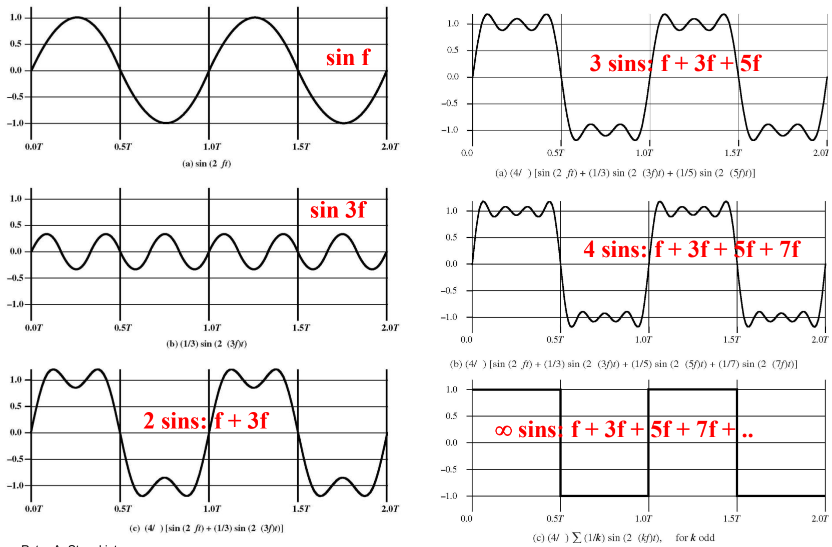


Relationship between Data Rate and Spectral Bandwidth

- The larger the (spectral) bandwidth is, 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 it can thus carry more more information
  - » 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 movie

- Can we make this more precise?

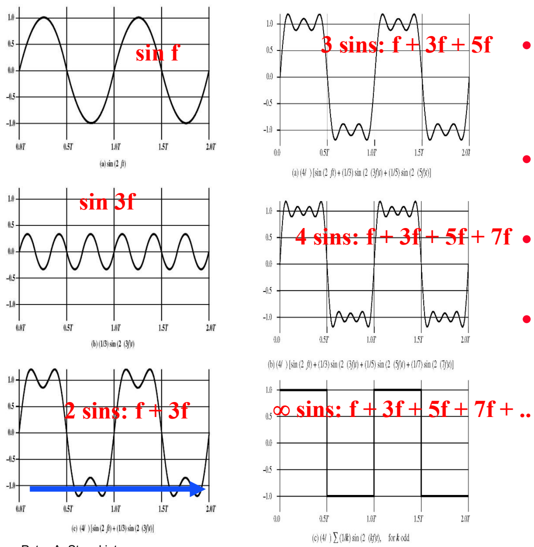
Adding Detail to the Signal



Some Intuition

- A signal that is smooth in the time domain has narrow frequency range
  - » Sine wave → pulse at exactly one frequency
- Adding detail widens the frequency range
  - » Need to add additional frequencies to represent details
  - » Very sharp edges are especially bad (many frequencies)
- The opposite is also true
  - » A ulse (very sharp edge!) in time domain has a very wide spectrum
  - » Same is true for random noise (“noise floor”)
- Implication: modulation has a big impact on how much (scarce) spectrum is used

What happens when I Double the Bandwidth?



- Shown here by scaling by two along time axis
- What happens to spectrum use?
- We have to double frequencies: f → 2f
- This means that we double the frequency range

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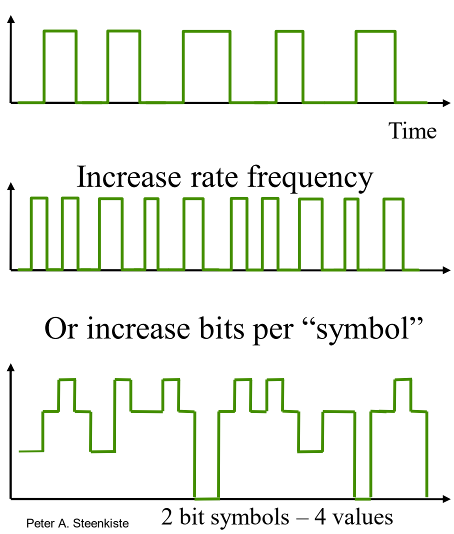
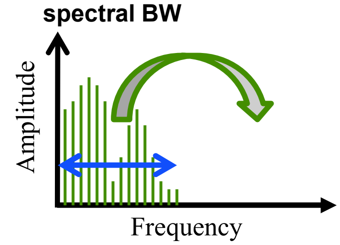
Increasing the Bit Rate



- Increases the rate at which the signal changes.
  » Proportionally increases all signals present, and thus the spectral bandwidth
- Increase the number of bits per change in the signal
  » Adds detail to the signal, which also increases the spectral BW



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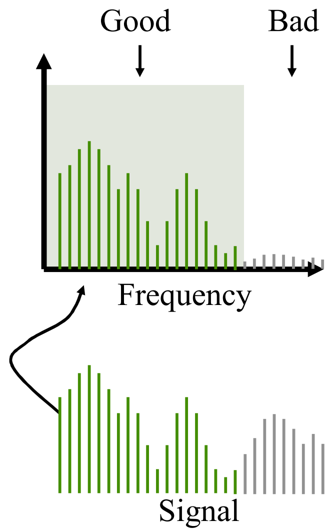
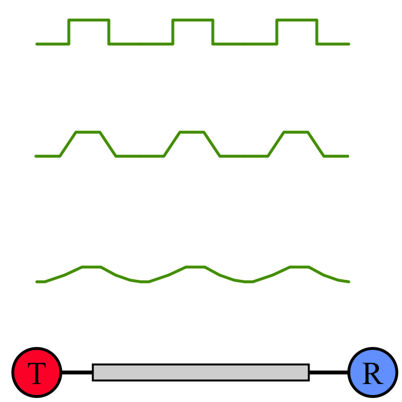
Transmission Channel Considerations

- Example: grey frequencies get attenuated significantly
- For wired networks, channel limits are an inherent property of the wires
  - Different types of fiber and copper have different properties
  - Capacity also depends on the radio and modulation used
  - Improves over time, even for same wire
- For wireless networks, limits are often imposed by policy
  - Can only use certain part of the spectrum
  - Radio uses filters to comply



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

- Wires only transmit signals in certain frequency ranges
  - » Stronger attenuation and distortion outside of range
- Wireless radios are only allowed to use certain parts of the spectrum
  - » The radios are optimized for that frequency band
- Attenuation and distortion makes it hard for receiver to extract the information
  - » A major challenge in wireless



Propagation Degrades RF Signals

- Attenuation in free space: signal gets weaker as it travels over longer distances
  - » Radio signal spreads out – free space loss
  - » Refraction and absorption in the atmosphere
- Obstacles can weaken signal through absorption or reflection.
  - » Reflection redirects part of the signal's energy
- Multi-path effects: multiple copies of the signal interfere with each other at the receiver
  - » Similar to an unplanned directional antenna
- Mobility: moving the radios or other objects changes how signal copies add up
  - » Node moves ½ wavelength -> big change in signal strength

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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 channel under given conditions
- Bandwidth - the bandwidth of the signal as constrained by the transmitter and the nature of the transmission medium (Hertz)
  - » Confusing term – network people use the term bandwidth for data rate (in Mbps)
- Noise – amount of noise in the spectrum band used by the communications channel
- Error rate - rate at which errors occur
  - » Error = transmit 1 and receive 0; transmit 0 and receive 1

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Decibels

- Decibels: ratio between signal powers

  decibels (db) = $10\log_{10}(P_1 / P_2)$
- Term is used in many contexts:
  - » The loss of a wireless channel, gain of an amplifier, …
  - » Useful when doing a lot of multiplication/division
- Note that dB is a relative value.
- Absolute value requires a reference point.
  - » Decibel-milliwatt – power relative to 1 milliwatt (dbm)
- Some example values (WiFi):
  - » Noise floor -90 dbm
  - » Received signal strength: -70 to -65 dbm
  - » Transmit power (2.4 GHz): 20 dbm

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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)

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

- A high SNR means a high-quality signal
- Low SNR means that it may be hard to “extract” the signal from the noise
- SNR sets upper bound on achievable data rate

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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
- More aggressive encoding can increase the actual channel bandwidth
  - » More bits per symbol
- *For M levels:* $C = 2B \log_2 M$
  - » M discrete signal levels
- Factors such as noise can reduce the capacity

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Shannon Capacity Formula

- Equation: $$C = B\log_2(1+\mathrm{SNR})$$
- Represents error free capacity
  - » It is possible to design a suitable signal code that will achieve error free transmission (you design the code)
- This 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 data rate over a channel

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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 accounted for by a gap parameter**
  - » **Gap depends on error rate, coding, modulation, etc.**

$$C = B\log_2\left(1+\mathrm{SNR}/\Gamma\right)$$

  - » **Over time, the gap has been shrinking due to technology improvements**

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Example of Nyquist and Shannon Formulations

- **Spectrum of a channel between 3 MHz and 4 MHz ; $\mathbf{SNR_{dB}}$ = 24 dB**

$$B = 4\ \mathrm{MHz} - 3\ \mathrm{MHz} = 1\ \mathrm{MHz}$$

$$\mathrm{SNR}_{\mathrm{dB}} = 24\ \mathrm{dB} = 10\log_{10}\left(\mathrm{SNR}\right)$$

$$\mathrm{SNR} = 251$$

- **Using Shannon's formula**

$$C = 10^6 \times \log_2\left(1+251\right) \approx 10^6 \times 8 = 8\mathrm{Mbps}$$

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Example of Nyquist and Shannon Formulations

- How many signaling levels are required using Nyquist?

$$C = 2B\log_2 M$$
$$8\times10^6 = 2\times\left(10^6\right)\times\log_2 M$$
$$4 = \log_2 M$$
$$M = 16$$

- Look out for: dB versus linear values and $\log_2$ versus $\log_{10}$

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- Challenges in Wireless Networking
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- Modulation and multiplexing
- Channel capacity
- Antennas and signal propagation
  - » How do antennas work
  - » Propagation properties of RF signals
  - » Modeling the channel
- Modulation
- Diversity and coding
- OFDM and MIMO

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What is an Antenna?

- Conductor that carries an electrical signal and radiates an RF signal.
  - » The RF signal "is a copy of" the electrical signal in the conductor
- Also the inverse process: RF signals are "captured" by the antenna and create an electrical signal in the conductor.
  - » This signal can be interpreted (i.e. decoded)
- Efficiency of the antenna when transmitting or receiving depends on its size and orientation
  - » Transmitting: How much energy does it radiate?
  - » Receiving: How much of the energy radiated by the transmitter does it capture?

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Types of Antennas

- Abstract view: antenna is a point source that radiates with the same power level in all directions – omni-directional or isotropic.
  - » In practice, the shape of the conductor creates a specific radiation pattern
  - » Note that isotropic antennas are not very efficient!!
    - – Unless you have a very large number of receivers
- A common shape is a straight conductor.
  - » Creates a "disk" pattern, e.g. dipole
- Shaped antennas can be used to direct the energy in a certain direction.
  - » Well-known case: a parabolic antenna

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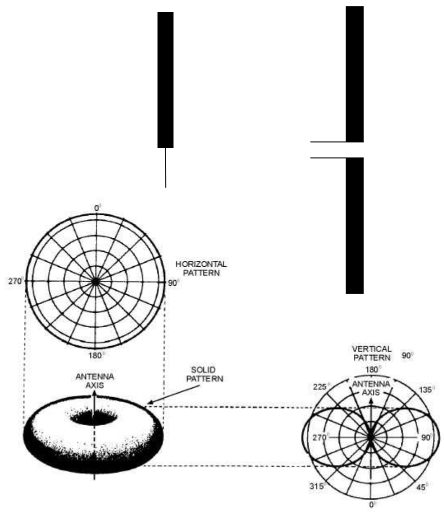
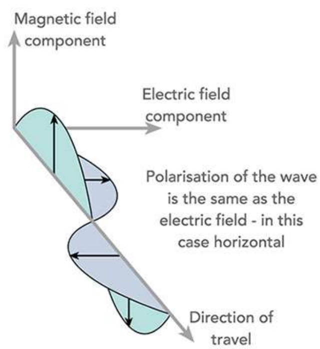
Antenna Types: Dipoles

- General rule: length of the antenna should be ~half a wavelength
  - » Length depends on the carrier frequency!
  - » Wavelength at 900MHz: ~1 foot
- Simplest antenna: half wave, quarter wave or dipole antenna
  - » Very simple and very common
  - » Quarter wavelength is replicated using a reflective surface
  - » Donut shape radiation



What about Antenna Orientation? Polarization?

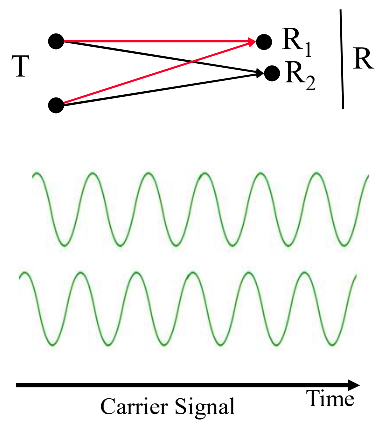


- A "wireless" signal consists of an electric and magnetic field
  - » "electro magnetic" signal
- They can both be viewed as sine waves traveling in orthogonal planes
- The orientation of the electric field is called "polarization" of the signal
- The polarization of the signal is determined by the sending antenna
- In order for reception to be effective, the signal and receiving antenna must have the same polarization
  - » But reflections, ... can change polarization

Figure from: https://www.digikey.com/en/blog/antenna-polarization-what-it-is-and-why-it-matters

Preview: Multi-element Antennas

- Multi-element antennas have multiple, independently controlled conductors.
  - » Signal is the sum of the individual signals transmitted (or received) by each element
- Can electronically direct the RF signal by sending different versions of the signal to each element.
  - » For example, change the phase in a two-element array.
- There are many variants of multi-element antennas
  - » Number of elements, relative position of the elements, control over the signals, …



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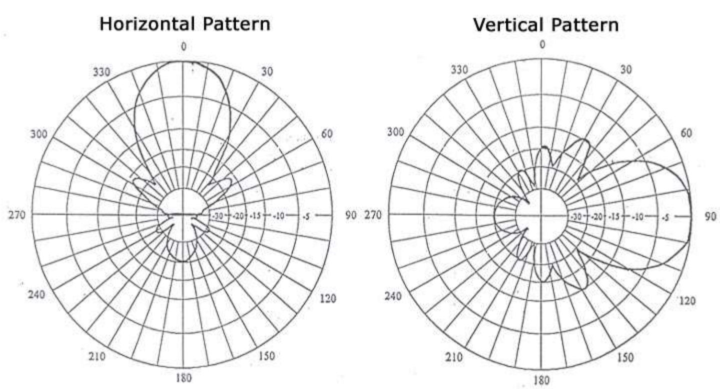
Directional Antenna Properties



- dBi: antenna gain in dB relative to an isotropic antenna with the same transmit power
  - » Example: an 8 dBi Yagi antenna has a gain of a factor of 6.3 (8 db = 10 log 6.3)

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Examples 2.4 GHz

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Summary

- **The maximum capacity of a channel depends on the SINR**
  - » **How close you get to this maximum depends on the sophistication of the radios**
  - » **Distortion of the signal also plays a role – next lecture**
- **Antennas are responsible for transmitting and receiving the EM signals**
  - » **The “ideal” isotropic antenna is a point source that radiates energy in a sphere**
  - » **Practical antennas are directional in nature, as a result of the antenna shape or the use of multi-element antennas**
  - » **The antenna gain is expressed in dBi**

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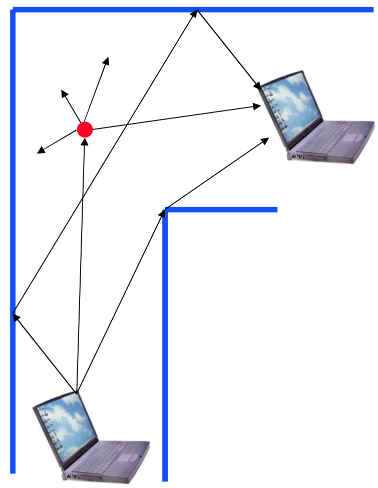
Propagation Modes

- Line-of-sight (LOS) propagation.
  - » Most common form of propagation
  - » Happens above ~ 30 MHz
  - » Subject to many forms of degradation (next set of slides)
- Obstacles can redirect the signal and create multiple copies that all reach the receiver
  - » Creates multi-path effects
- Refraction changes direction of the signal due to changes in density
  - » E.g., changes in air temperature, humidity, …
  - » If the change in density is gradual, the signal bends!

Impact of Obstacles

- Besides line of sight, signal can reach receiver in three "indirect" ways.
- Reflection: signal is reflected from a large object.
  - » Large: relative to the wavelength
- Scattering: signal is scattered by an object that is small
- Diffraction: signal is scattered by the edge of a large object – "bends".



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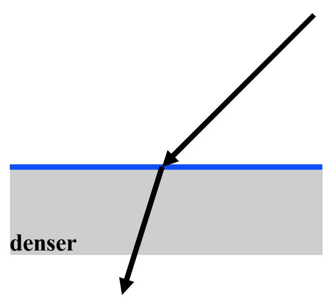
Refraction

- Speed of EM signals depends on the density of the material
  - » Vacuum: 3×10^8 m/sec
  - » Denser: slower
- Density is captured by refractive index
- Explains "bending" of signals in some environments
  - » E.g. sky wave propagation: Signal "bounces" off the ionosphere back to earth – can go very long distances
  - » But also local, small scale differences in the air density, temperature, etc.



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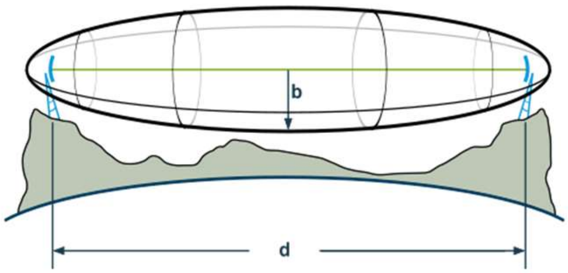
Fresnel Zones

- Sequence of ellipsoids centered around the LOS path between a transmitter and receiver
- The zones identify areas in which obstacles will have different impact on the signal propagation
  - » Capture the constructive and destructive interference due to multipath caused by obstacles



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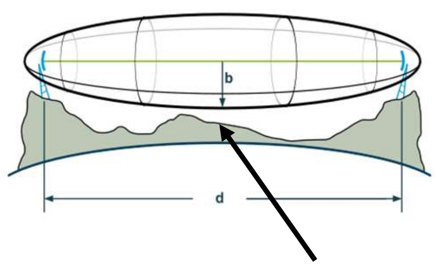
Fresnel Zones

- Zones create different phase differences between paths
  - » First zone: 0-90
  - » Second zone: 90-270
  - » Third zone: 270-450
  - » Etc.
- Odd zones create constructive interference, even zones destructive
- Also want clear path in most of the first Fresnel zone, e.g. 60%
- The radius F_n of the nth Fresnel zone depends on the distances d_1 and d_2 to the transmitter and receiver and the wavelength



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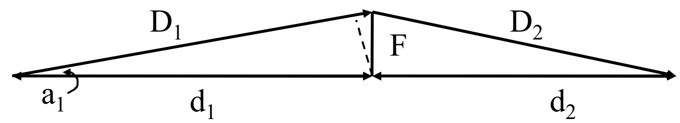
Sketch of Calculation: Difference in Path Length

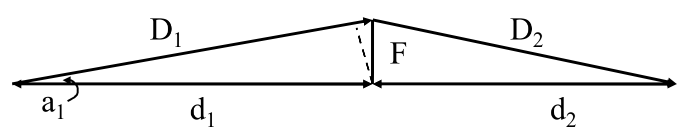
FYI only



- Goal is to calculate F
- Difference in path length (a_1 is small)
  - » $D_1 - d_1 \approx F * \sin a_1$
- But for small a_1 we also have
  - » $\sin a_1 = \tan a_1 = F / d_1$
- So $D_1 - d_1 = F^2 / d_1$

Sketch of Calculation Fresnel Radios

FYI only



- Given $D_1 - d_1 = F^2 / d_1$

So, the difference in path length is:

- $(D_1 + D_2) - (d_1 + d_1) = \lambda * n$
- Or $(D_1 - d_1) + (D_2 - d_2) = F^2 / d_1 + F^2 / d_2$
- or

$$F_n = \sqrt{\frac{n\lambda d_1 d_2}{d_1 + d_2}}$$