Basic Radio Physics

Network Startup Resource Center
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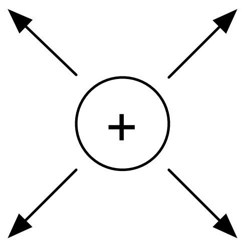
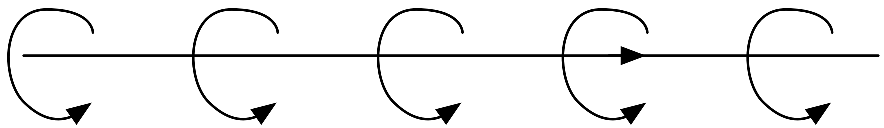
Electromagnetism

A Positive Charge in Space Creates an Electric Field (E)

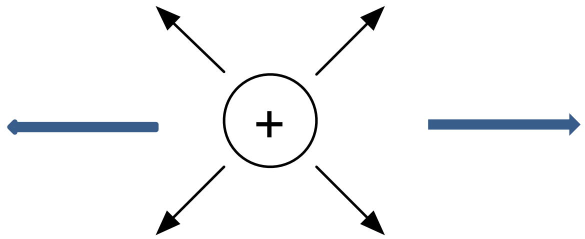


Current in Wires Creates a Magnetic Field (B)

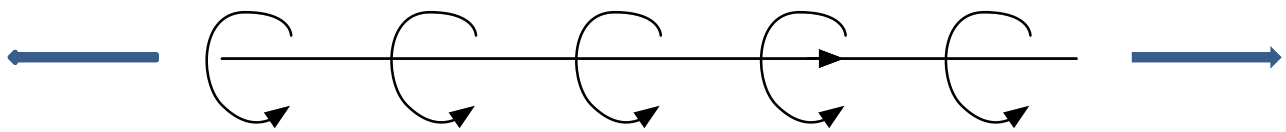


Electromagnetism

Change an Electric Field, you create a Magnetic Field (B)

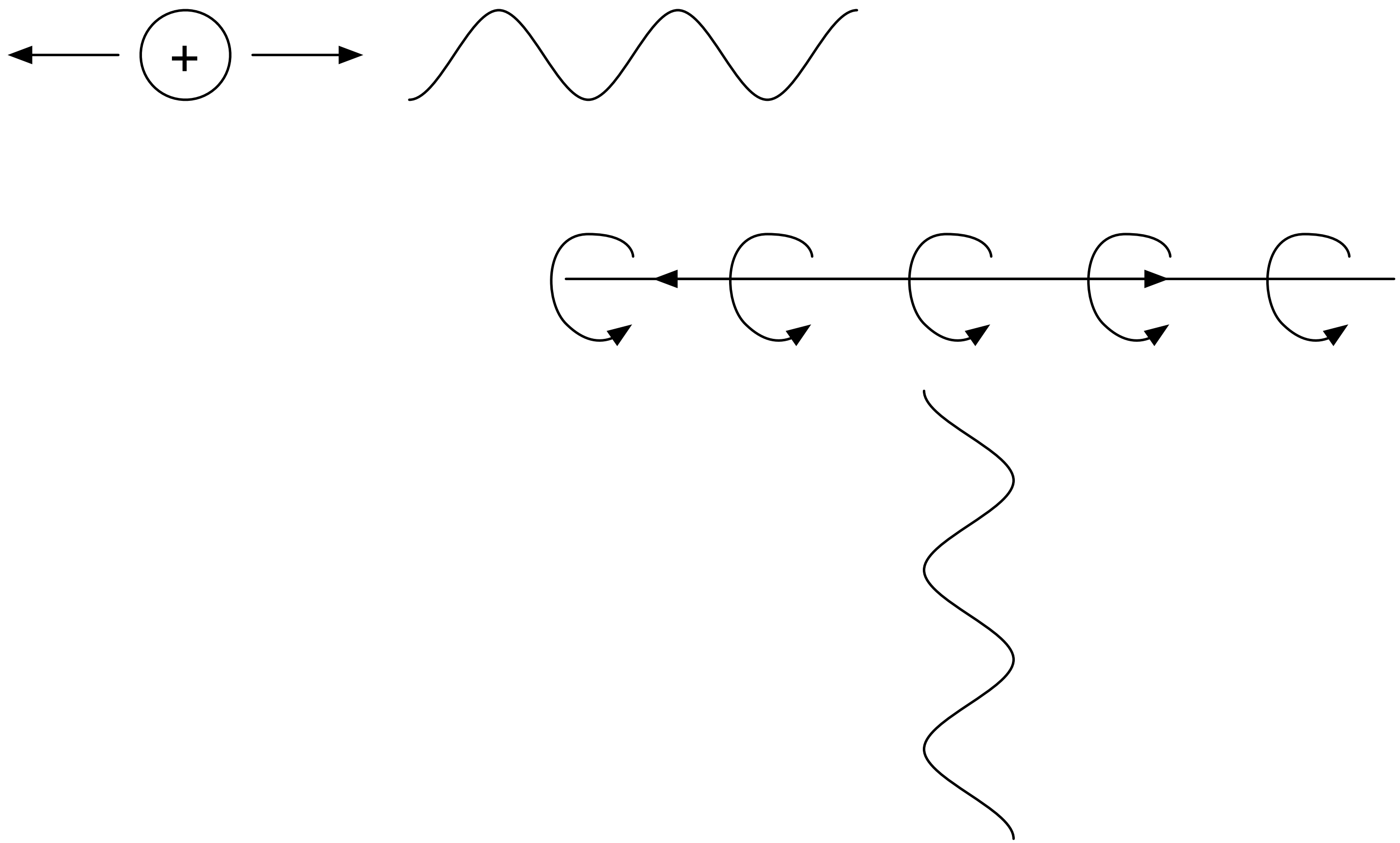


Change a Magnetic Field, you create an Electric Field (E)



Electromagnetic Waves

Changing Electromagnetic Fields propagate outwards in waves.




waves

Waves

- Oscillation + Transfer of Energy
- Mechanical Waves:
  - Sound, Water
  - Require a physical medium
- Electromagnetic Waves:
  - Light, Radio Microwave, Infrared, X-Ray, Gamma Ray
  - No Physical Medium Required
  - Radio can propagate through metal
  - Light can propagate through glass

Electromagnetic Waves

$c = \lambda * \nu$

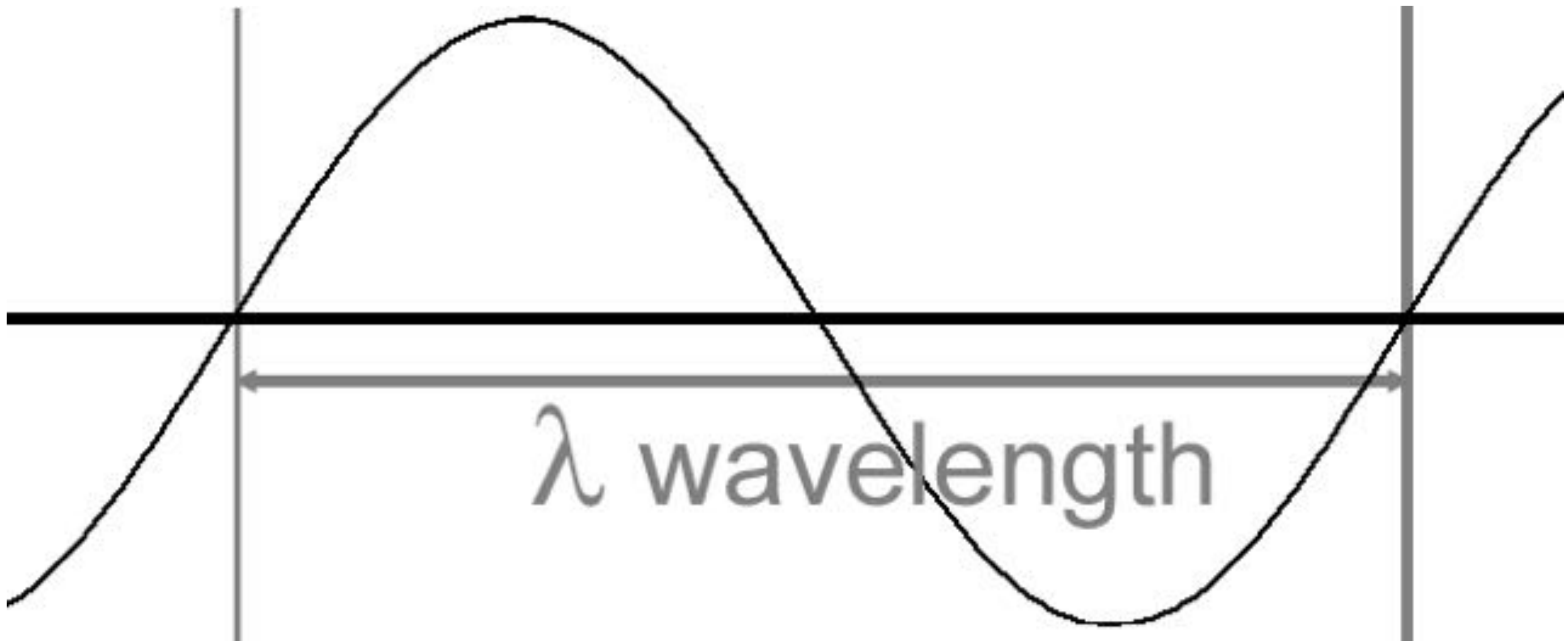
c is the speed of light (in vacuum) 3×10^8 m/s

λ Lambda is the wavelength [m]

ν Nu is the frequency [1/s = Hz]

- Light takes 8 minutes from Sun to Earth
- How long does it take to go 100km?
- Does it go as fast in a cable?

A Wave

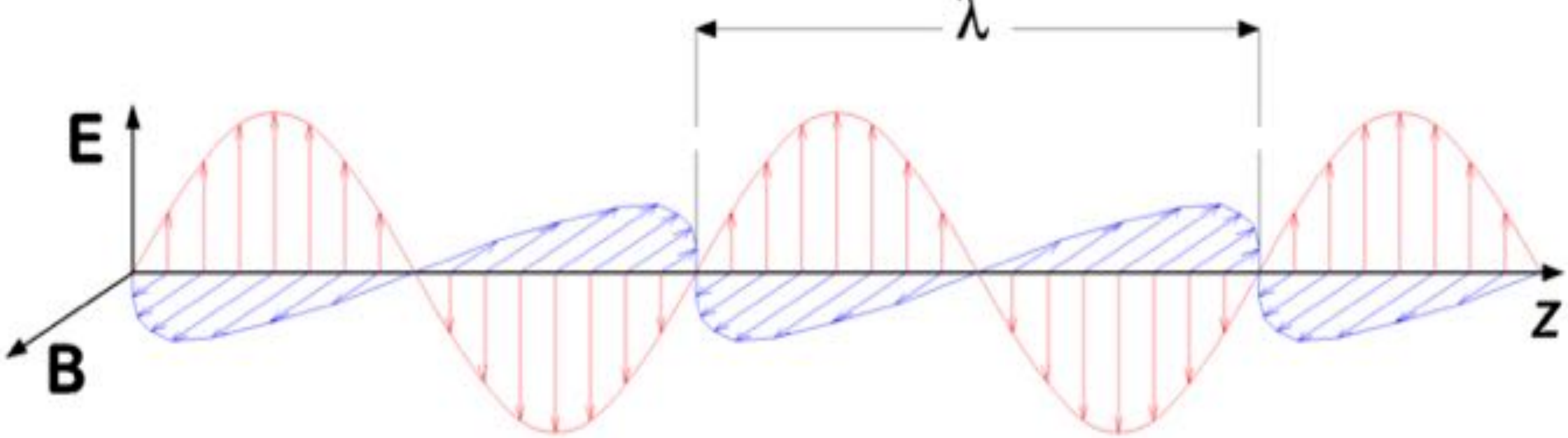


Wavelength Calculations

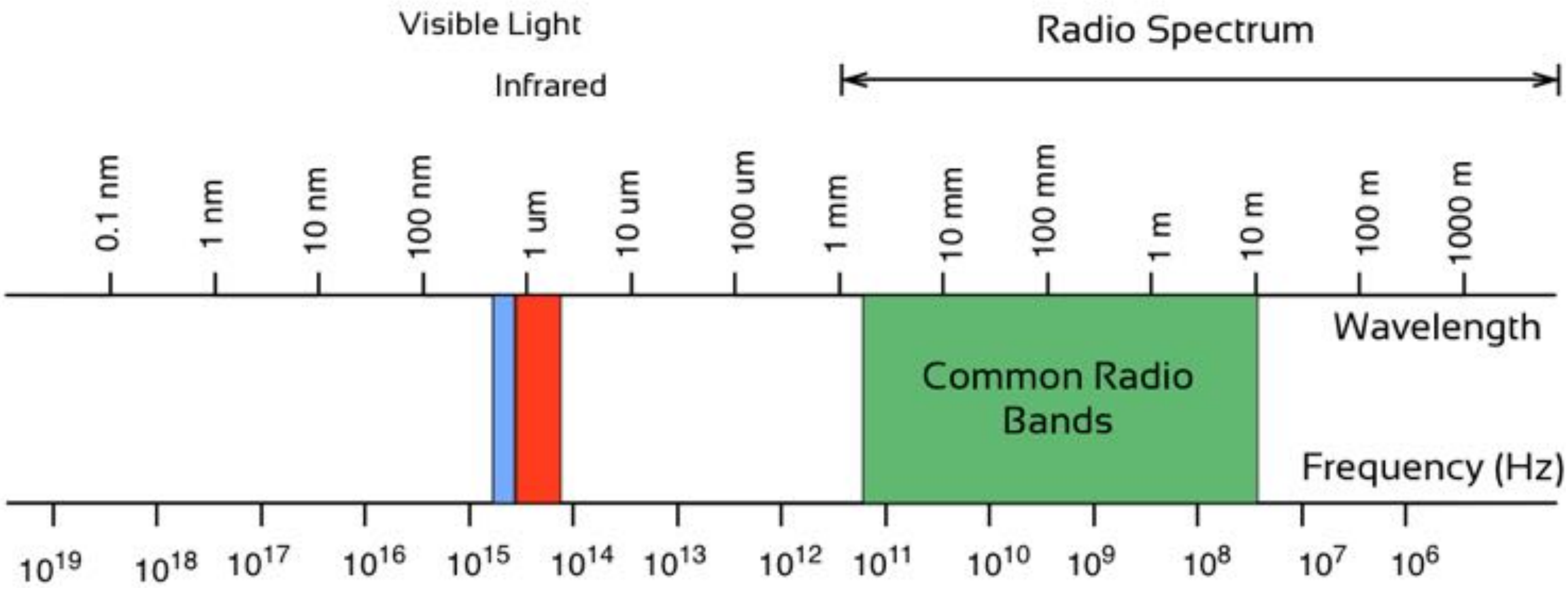
- Speed of Light = Wavelength * Frequency
- Frequency = Speed of Light / Wavelength
- Wavelength = Speed of Light / Frequency
- What's the frequency of 3.5 mm waves?
- What's the wavelength at 2400 MHz?

EM Wave Polarization

Direction of the electric field vector
Linear, elliptic, circular polarization



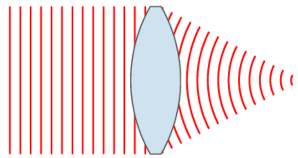
Electromagnetic spectrum



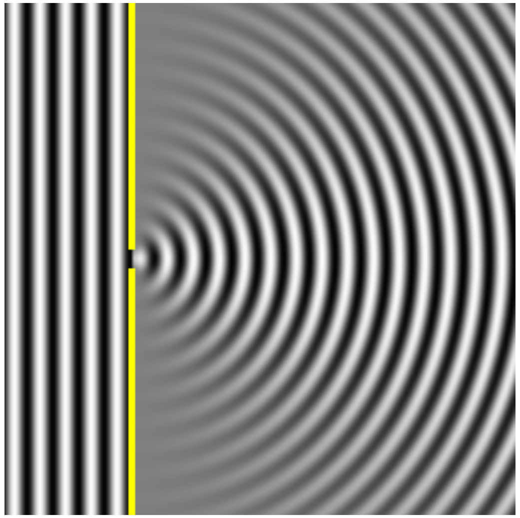
Wireless Networking Frequencies

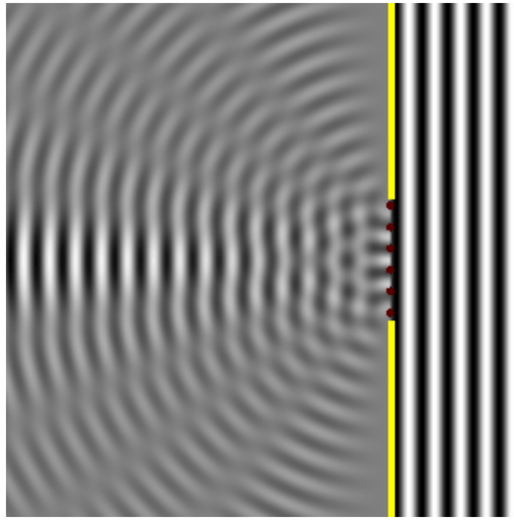
- Wi-Fi is typically used in:
  - 2.4 GHz – 802.11b/g/n
  - 5.x GHz – 802.11a/n
- Other bands interesting to us
  - 415/433 MHz
  - 868 MHz
  - 915 MHz
  - 3.5 GHz
  - 24 GHz
  - 60-80 GHz

Propagation of Radio waves

- Wave Fronts: planar & spherical 
- Huygens principle:
    - Spherical waves start at any disturbance
- Waves do not propagate as a straight line
    - Not even light!
- Behavior scales with wavelength

Huygens principle





Animated images thanks to Fu-Kwun Hwang and author of Easy Java Simulation = Francisco Esquembre

http://commons.wikimedia.org/wiki/File:Wavelength%3Dslitwidth.gif#/media/File:Wavelength%3Dslitwidth.gif

Radio Waves are Affected By

- Absorption
- Reflection
- Diffraction
- Interference

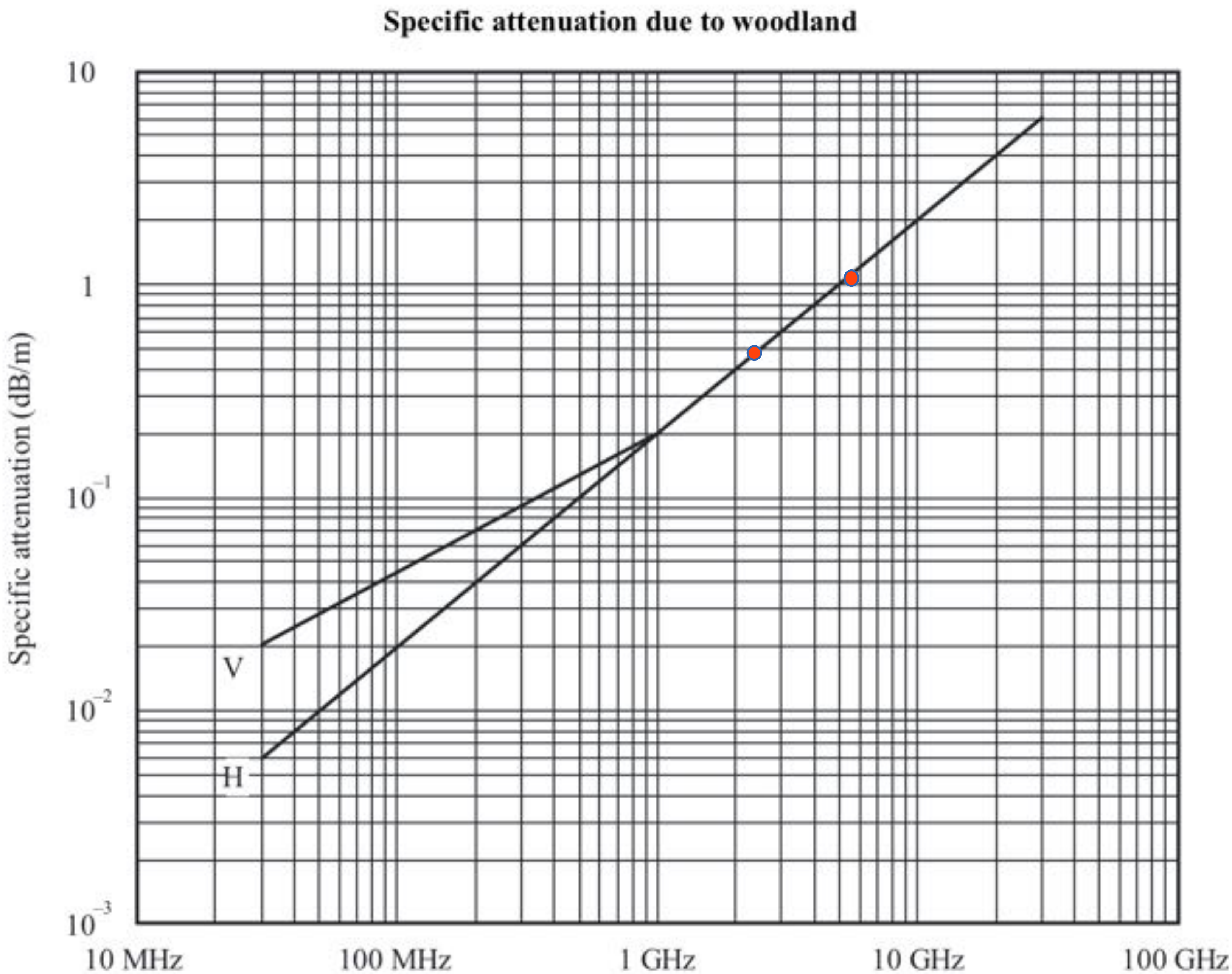
Radio waves: Absorption

- Converts energy into heat
- Decreases power exponentially
  - this is a linear decrease in dB
- Water, Metal, Oxygen
- Stones, Bricks, Concrete
- Wood, Trees

Radio waves: Absorption

- Plasterboard / Drywall Wall: 3-5dB
- Metal Door: 6-10dB
- Window: 3dB
- Concrete Wall: 6-15dB
- Block Wall: 4-6dB

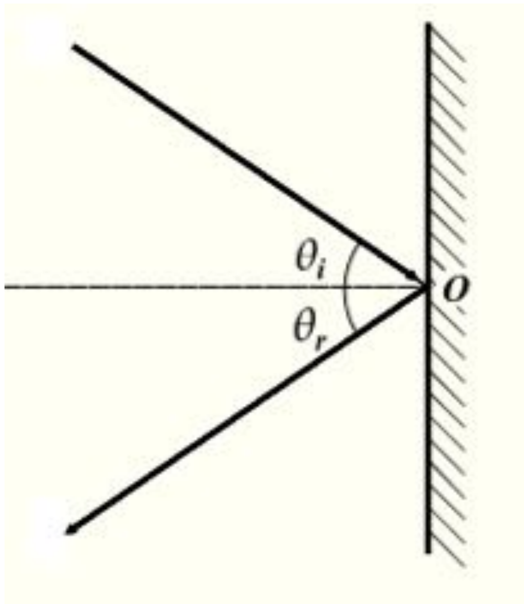

Image: https://www.flickr.com/photos/19622227@N00/2591612352/



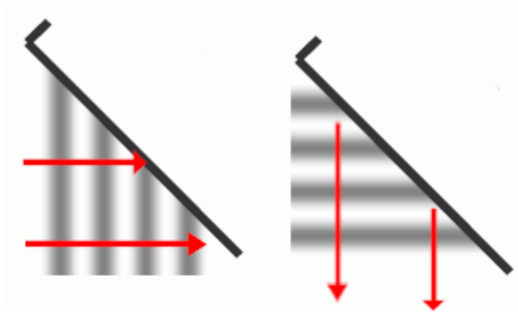
Specific attenuation due to woodland
Specific attenuation (dB/m)
10
1
10^{-1}
10^{-2}
10^{-3}
V
H
10 MHz
100 MHz
1 GHz
10 GHz
100 GHz

Radio waves: Reflection

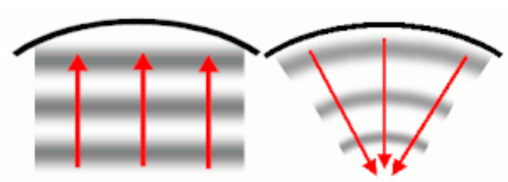
e.g. on Metal
angle in = angle out



plane

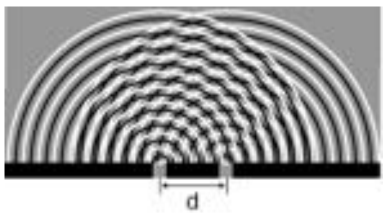


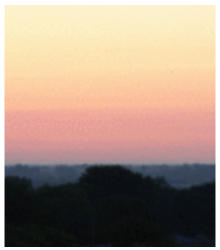
parabole

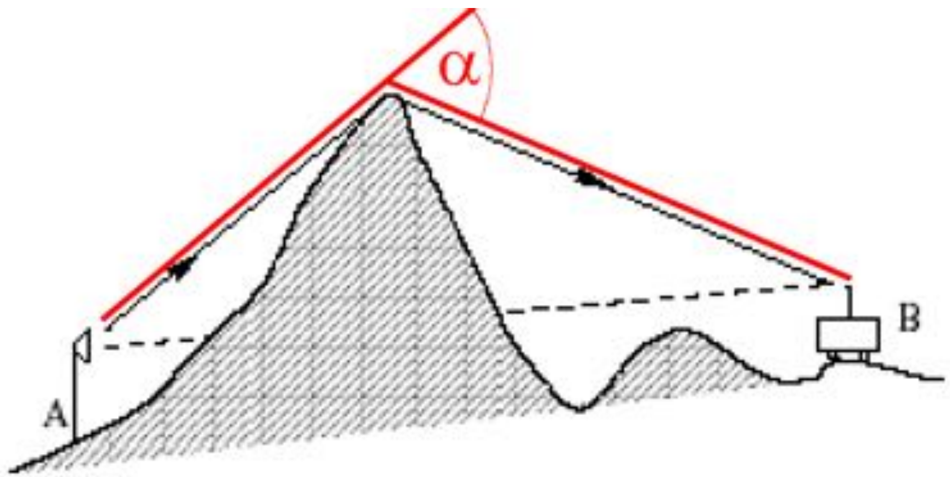


Radio waves: Diffraction

Diffraction is the apparent bending and spreading of waves when they meet an obstruction. Scales roughly with wavelength.







Radio waves: Interference

Interference is **misunderstood**
Is it really interference?
Or are too lazy to find the real problem?
Maybe we don't care!

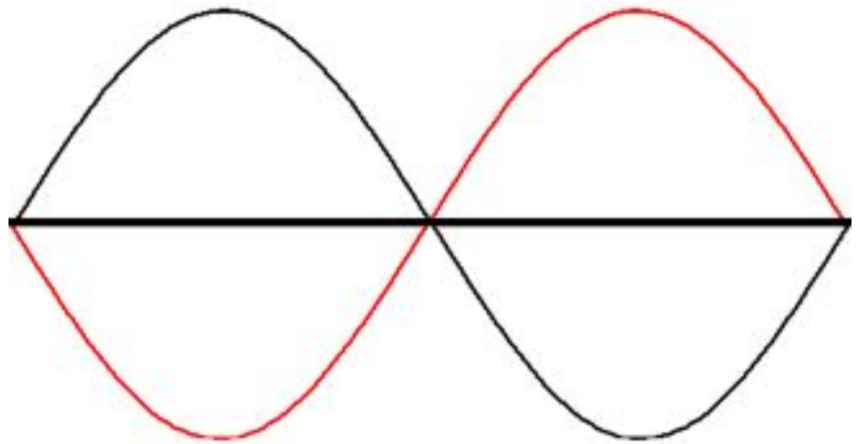
Two Meanings of Interference

- Physicists View:
  - The behavior of waves
- Engineer's View:
  - Noise that causes problems
- Both are important for Wireless
  - In different ways!

Interference: Physicist's View

Waves can annihilate each other

$1 + 1 = 0$



...when they have fixed **frequency and phase relation**

Waves can also enhance each other

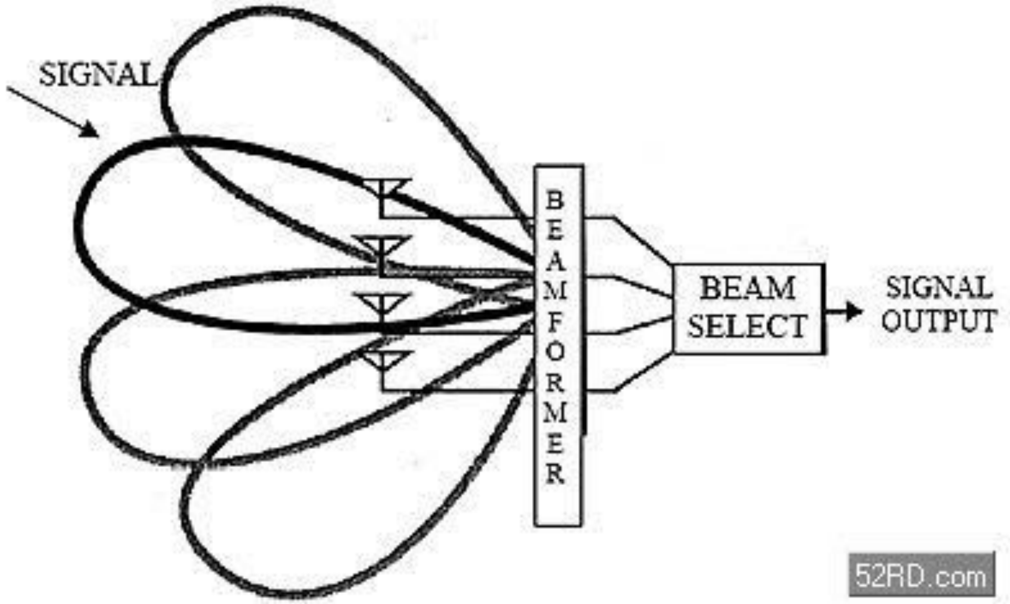
Interference: an Experiment

- Take two laser pointers – one green, one red
- Cross the beams – will one change the other?
- Point them in the same direction, will one change the other?
- If you give signals with them, both in the same direction, would you be able to read them?
- Now use two lasers of the same color – what happens?

Interference: MIMO, Beam Shaping

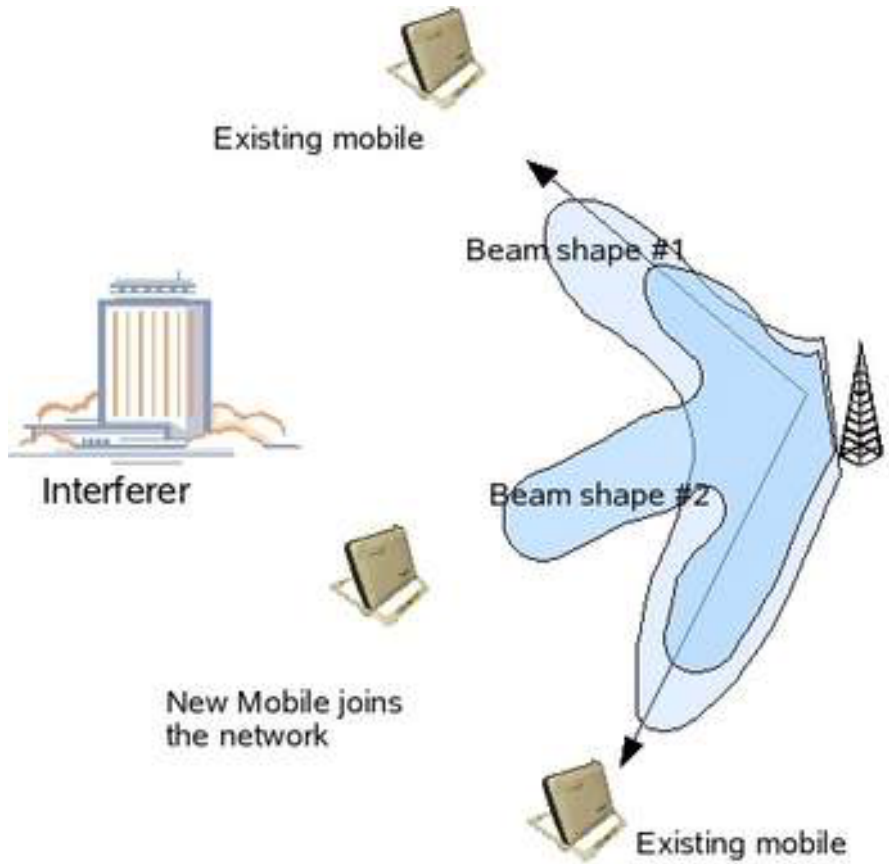
- Interference is used for good in:
  beam-shaping, smart antennas, MIMO

  Modern MIMO techniques use interference to optimize antennas, allow for full multiplexing on same frequency



MU-MIMO, Dynamic Beam Shaping

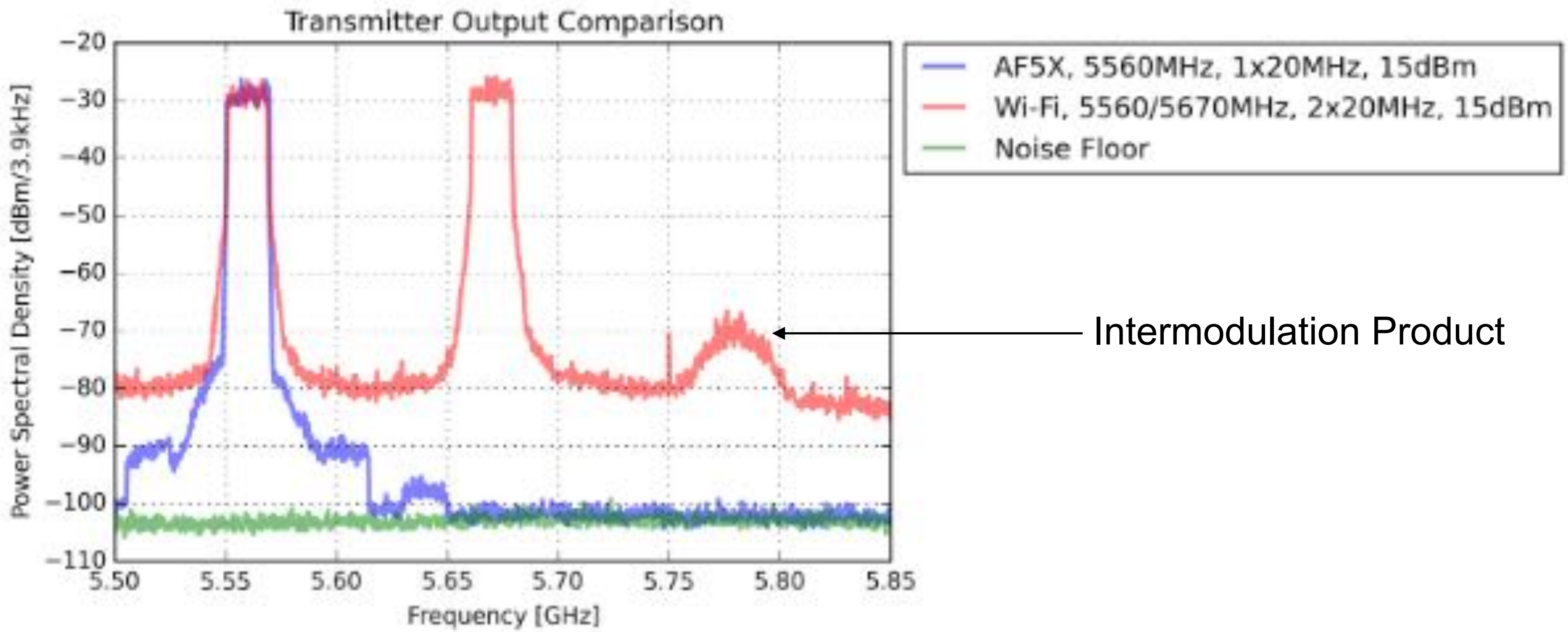
- In multi-antenna arrays, possibilities are virtually unlimited
- Fast processors use interference for good



Interference

- The Engineering View:
  - “any noise that gets in the way”
- High Noise Floor From Busy Spectrum
- Co-Channel Interference
- Adjacent-Channel Interference
  - Next frequency, overloading your receiver
    - Use a better receiver!
  - Next frequency, leaking into your channel
    - Time to talk to the interferer

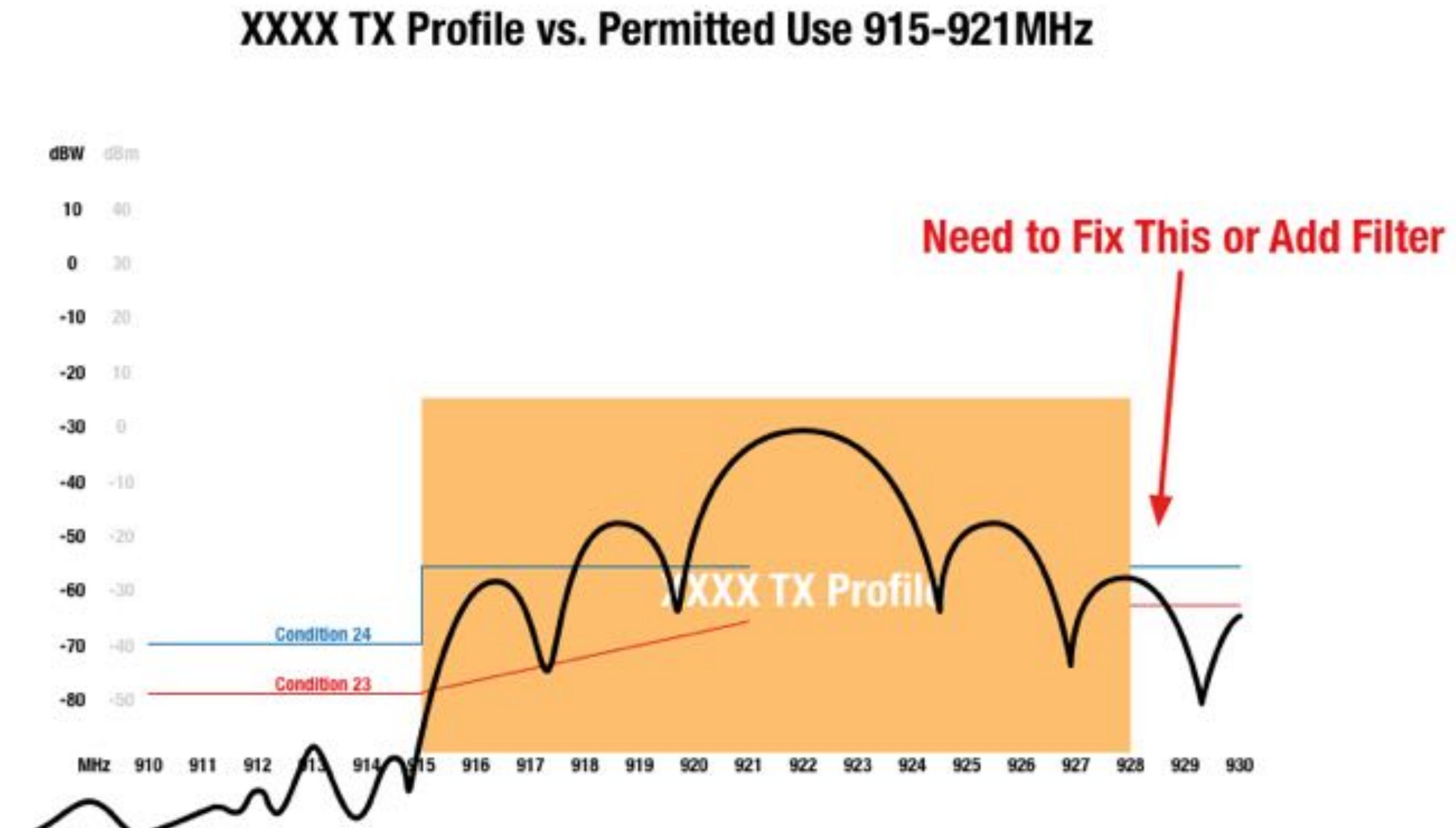
Some Transmitters Interfere



Intermodulation Product

Image: http://community.ubnt.com/t5/airFiber-Stories/AF5X-Why-you-owe-it-to-yourself-to-use-these-radios-for-backhaul/cns-p/1239600

Some Transmitters Interfere



Actual Transmission Sample from a Spectrum Analyzer
Compared to New Zealand 921MHz License Conditions

Frequency Dependent Behavior

- Longer wavelengths
  - Go further
  - Travel through obstacles
  - Bend around obstacles
  - Need bigger antennas
- Shorter wavelengths
  - Can transport more data
  - Need smaller antennas

Not All Spectrum is Created Equal

Capacity ↑

5GHz Wi-Fi
2.4GHz: Wi-Fi
2.1GHz: 3G
1.8GHz: 2G & LTE
900MHz: 3G
700MHz: LTE
500-700MHz: UHF Television
100MHz: Radio

Antenna Size ↓

Better Propagation ↓

Radio Propagation in Free Space

Free space loss
Fresnel zones
Line of Sight

Free Space Loss

Proportional to square of the distance

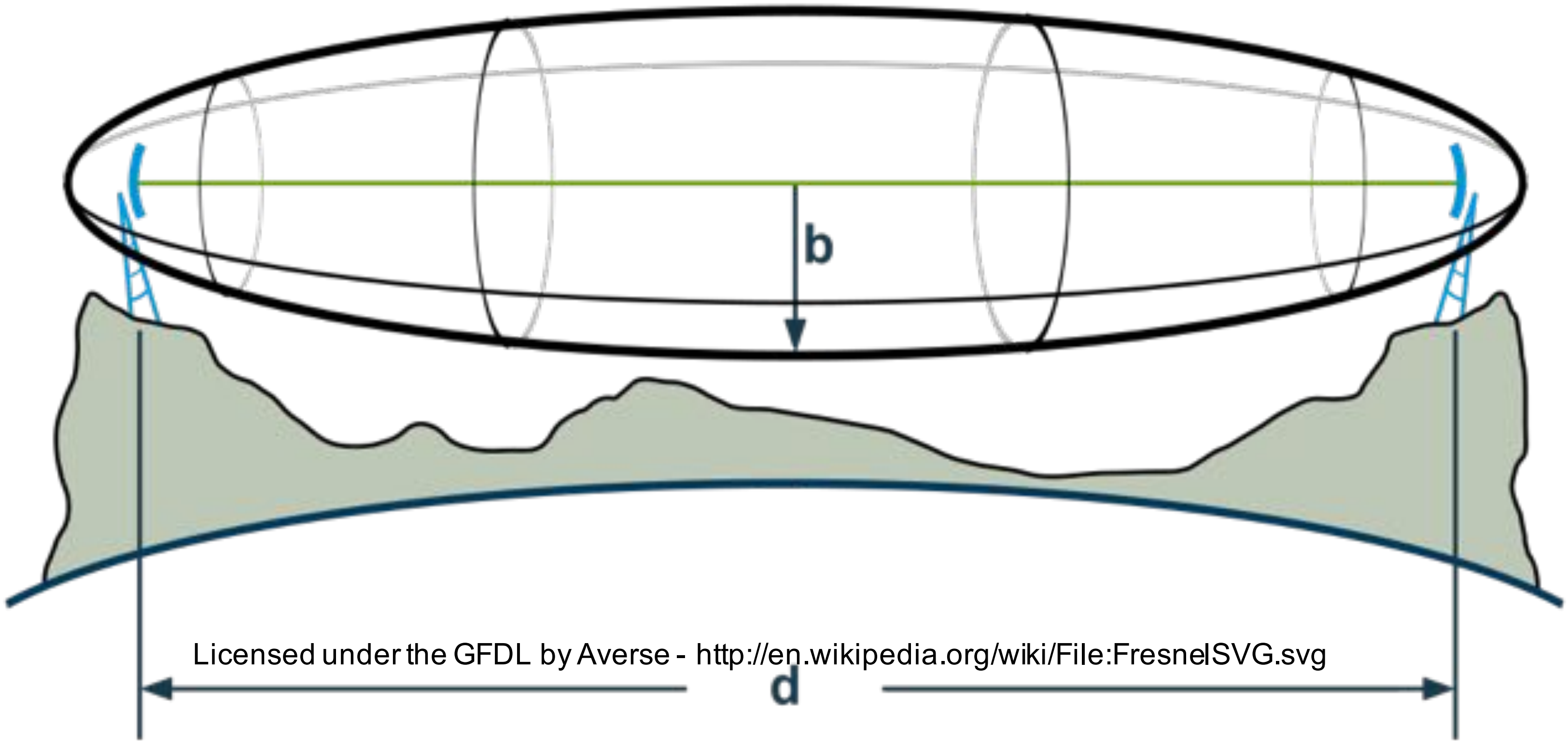
Proportional to square of the radio frequency

L_{FS} *(dB) = 20*log[4*π*distance/wavelength]*

where distance and wavelength are in the same units

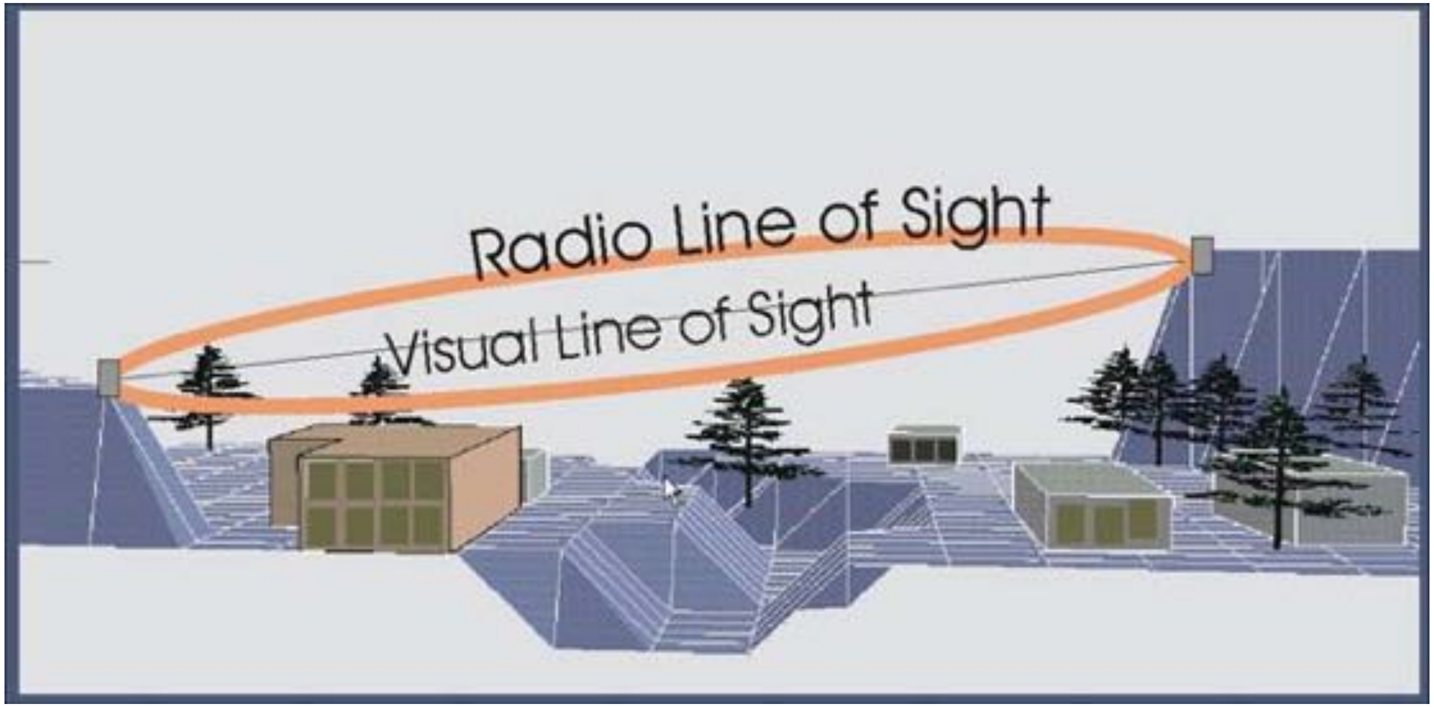
Fresnel zones

Zone where reflections are bad
Reflected waves = (good/bad) interference



Line of sight

Required for Higher Frequencies (> 1GHz)
Less Absorption / Reflection = Better Links



The dB

- Definition: $10 * \text{Log} (P_1 / P_0)$
- 3 dB = double power
- 10 dB = order of magnitude = x 10
- Calculating in dBs
- Relative dBs
  - dBm = relative to 1 mW
  - dBi = relative to ideal isotropic antenna

The dB: Examples

1 mW = 0 dBm
100 mW = 20 dBm
1 W = 30 dBm
An omni antenna with 6 dBi gain
A parabolic dish with 29dBi gain
A cable (RG213) with 0.5 dB/m loss

dB to measure Transmit Power

Example from a 802.11a/b card:

Output Power:

802.11b: 18 dBm (65 mW) peak power
802.11a: 20 dBm (100 mW) peak power

dB to Measure Receive Sensitivity

Example from a Senao 802.11b card

Receive Sensitivity:

1 Mbps:	-95 dBm;
2 Mbps:	-93 dBm;
5.5 Mbps:	-91 dBm
11 Mbps:	-89 dBm

Radio Physics Matter

Always! ... and especially ...

when an AP or 3G modem is under a desk
 or in a metal cabinet.

when winter turns to springtime

when it is rush hour in the city

with long distance links (speed of light!)

Examples: Office network

Offices typically have massive multi-path conditions cause by reflections
Reflections: metal infrastructure (computers, radiators, desks, even CDs!)
Absorbtion: from People, Plants, Books
Choice of locations and antennas essential

Changing Seasons: Absorption

Vegetation, humidity, rain and change with the seasons!

Dry trees might be radio transparent

Wet green trees are not radio transparent

Rush Hour: Reflection/Diffraction

Urban conditions change with the day

They change with the hour

- People, Vans, Cars
- Electromagnetic Interference (Noise Floor)

Test Monday what you measure Sunday

In the Afternoon.... In the Morning

The Speed of Light

Some 802.11_ standards set time-out windows: PCF, DIFS, SIFS

For long links, travel time of the signal might lead to timeout and performance losses

We have to hack the MAC layer to go long distance … see e.g. TIER group, Berkeley

Antennas & Transmission Lines

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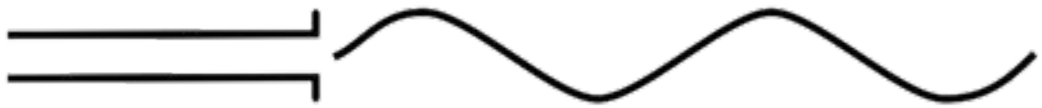
Objectives

- This unit will help you to understand
  - How an antenna works
  - How to read a radiation pattern
  - How to choose the right antenna
  - How transmission lines work
  - How to choose the right transmission line

What's An Antenna?

An antenna couples electrical current to radio waves

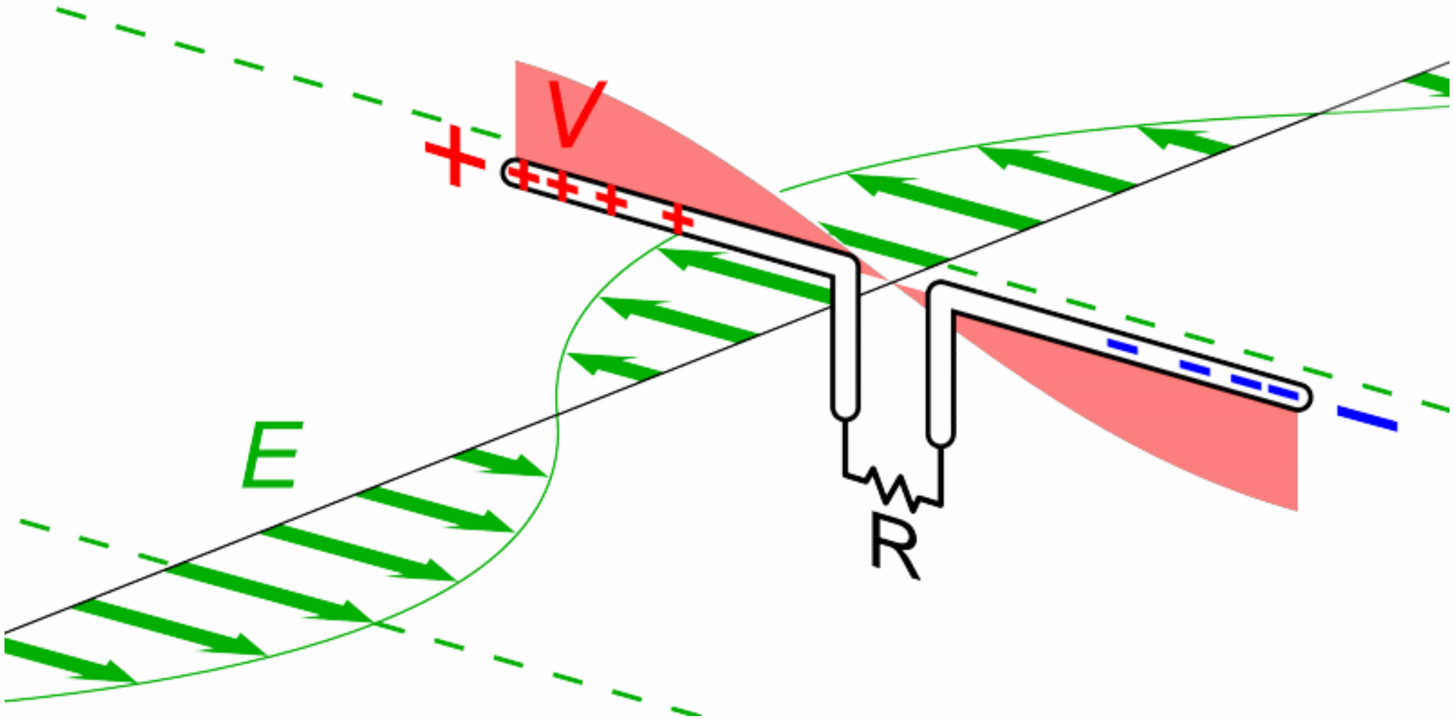


And it couples radio waves back to electrical current

It's the interface between guided waves from a cable and unguided waves in space

Radio Waves to Electrical Current

This antenna is receiving energy from radio waves

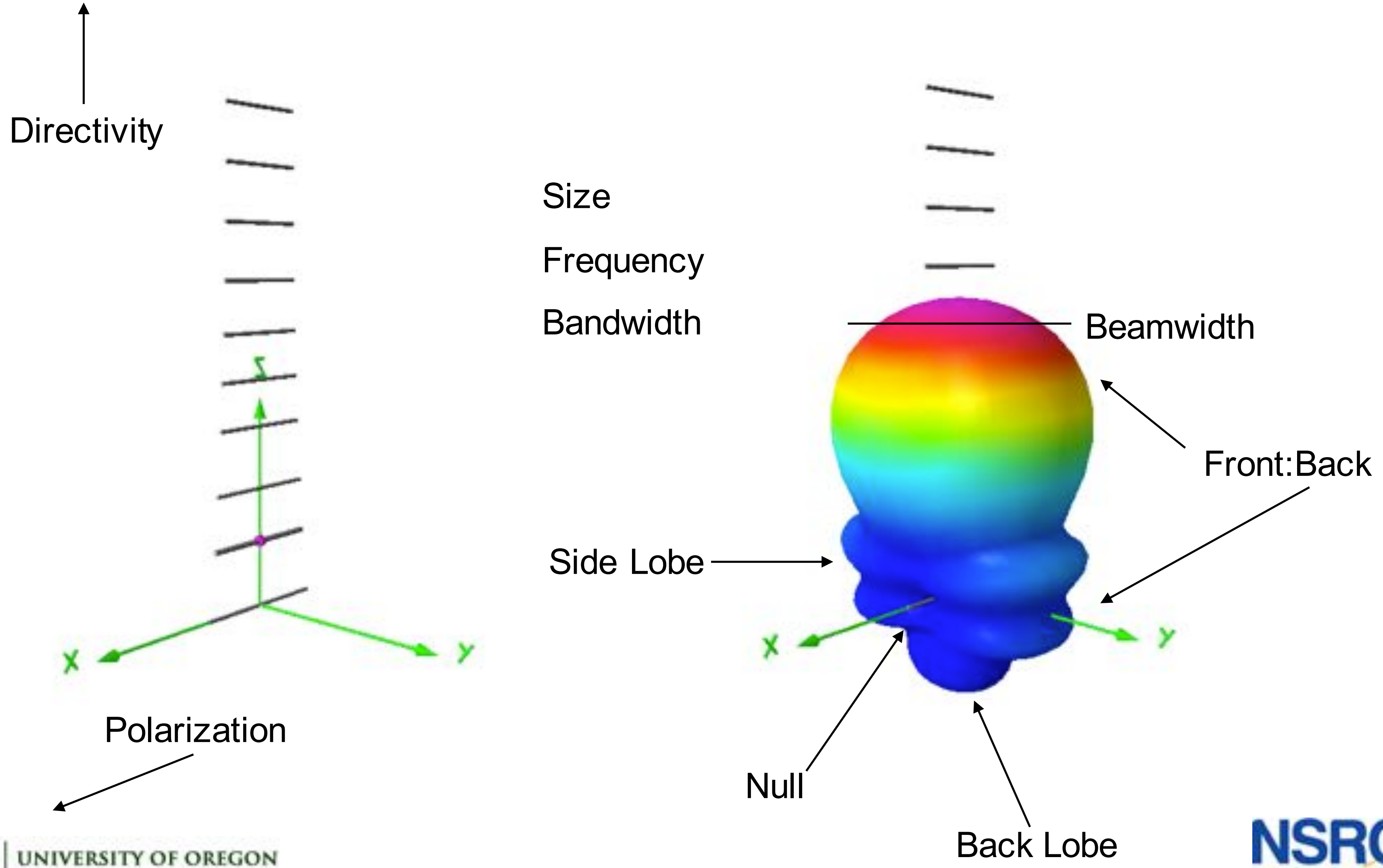


https://commons.wikimedia.org/wiki/File:Dipole_receiving_antenna_animation_6_800x394x150ms.gif

General Antenna Properties

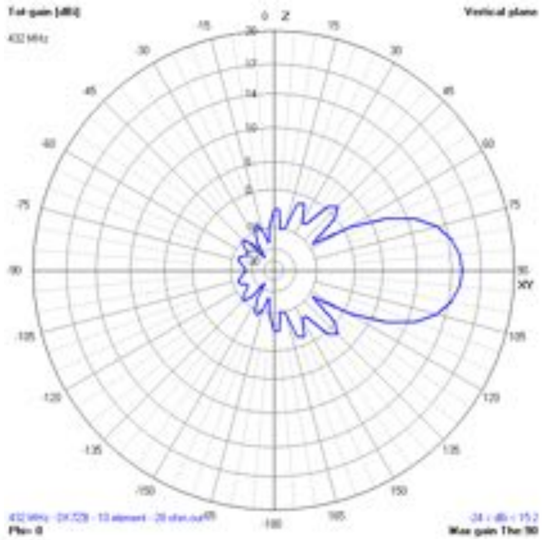
- Directivity
  - Gain, shown by Radiation Patterns
    - Beamwidth, Lobes, Sidelobes, Nulls
    - Front to Back Ratios
- Polarization
- Center Frequency
- Bandwidth (How far ⬆ & ⬇ below center Frequency?)
- Physical Size
- Impedance & Return Loss

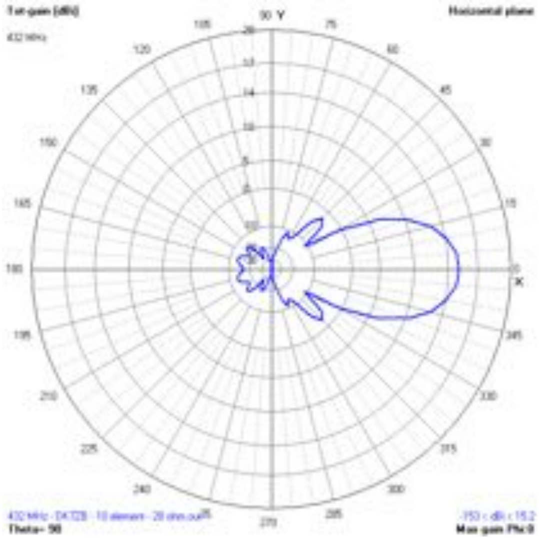
General Antenna Properties



Radiation Patterns

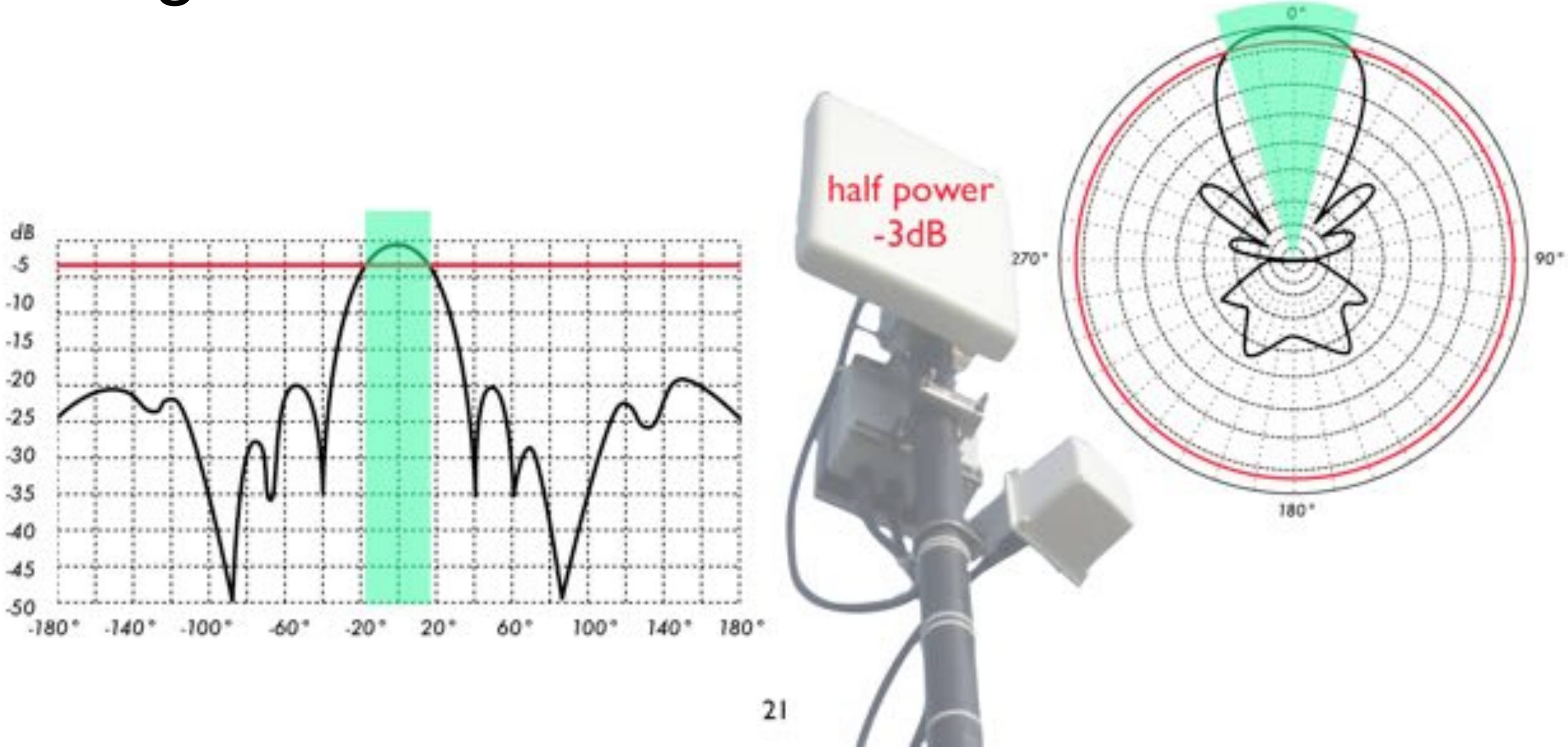
- Distribution of power radiated from or received by the antenna
- Shown as a function of direction angles from the antenna
- Patterns usually use a polar projection
- Directional antennas have differing Vertical & Horizontal gain





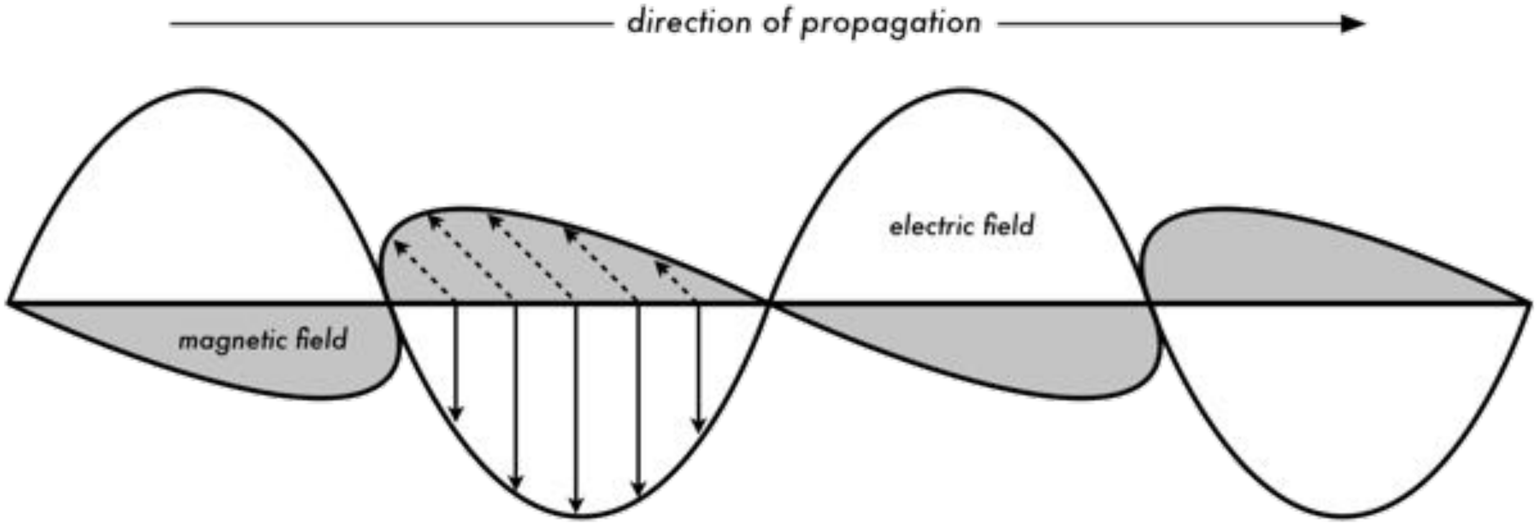
Beamwidth

Angular measure where radiated power is equal or greater than half its maximum value



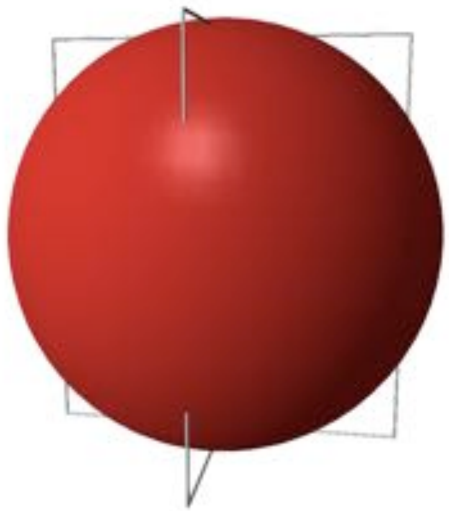
Polarization

- Electromagnetic waves are polarized
- Mismatched-polarization reduces gain
- Waves can be linear (H/V) or circular (RH/LH) polarized
- Many new antennas have multiple polarizations



Isotropic Antenna

- Theoretically radiates energy equally
- Used as a basis of measurement
- dBi: decibels relative to an isotropic antenna
- EIRP: Equivalent Isotropic Radiated Power
- Is a candle an isotropic radiator?
- Is the sun an isotropic radiator?

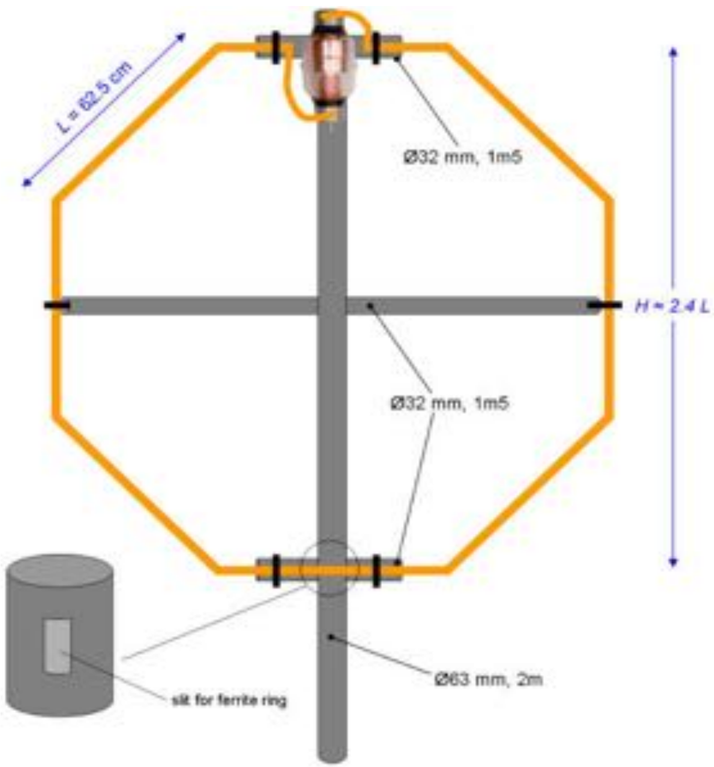


Directivity, Polarization, Lobes? No
Front to Back Ratio? 1:1

Loop Antenna

- Discovered in the 1830s by Michael Faraday
- to detect magnetic waves
- Used by Hertz to detect radio waves in 1887
- Small Loops (1/10 λ) receive magnetic waves
- Large Loops (1 λ) act like a folded dipole
- Loops are directional, not isotropic
- Small Loops have very low gain
- Do you have any Loop Antennas with you?

Loop Antenna

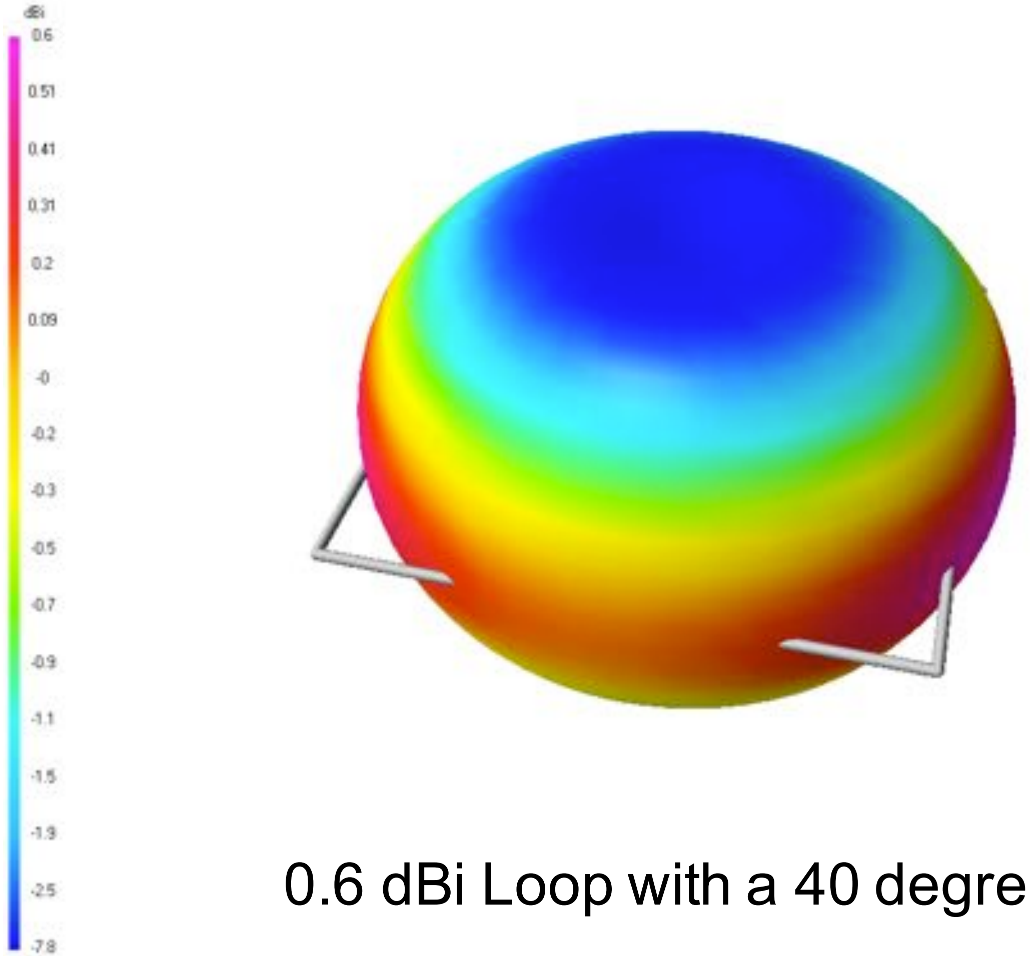


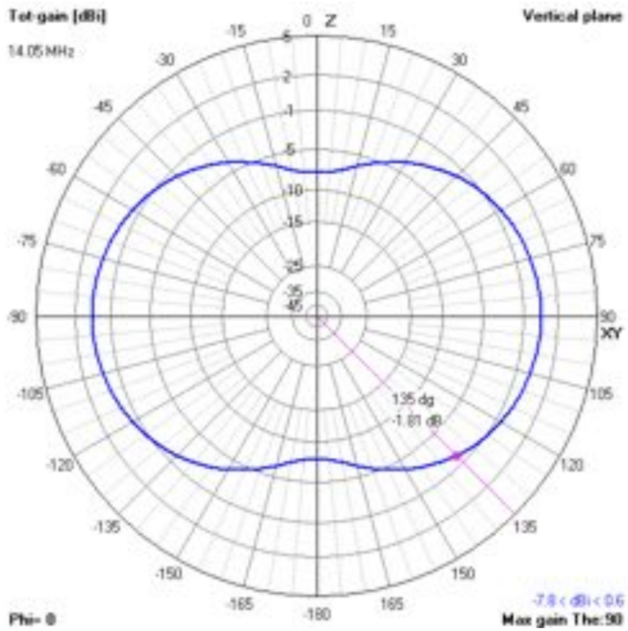
13.56 MHz Smartlabel photo by Wikimedia user Kalinko
https://commons.wikimedia.org/wiki/File:Transponder2.jpg

Magnetic Loop Antenna for 3.75MHz / 80m band, Design by Frank N4SPP
http://www.nonstopsystems.com/radio/frank_radio_antenna_magloop.htm

Loop Antennas: Dr. Michael Gebhart
rfid-systems.at/03_Loop_Antennas.pdf

Loop Antenna

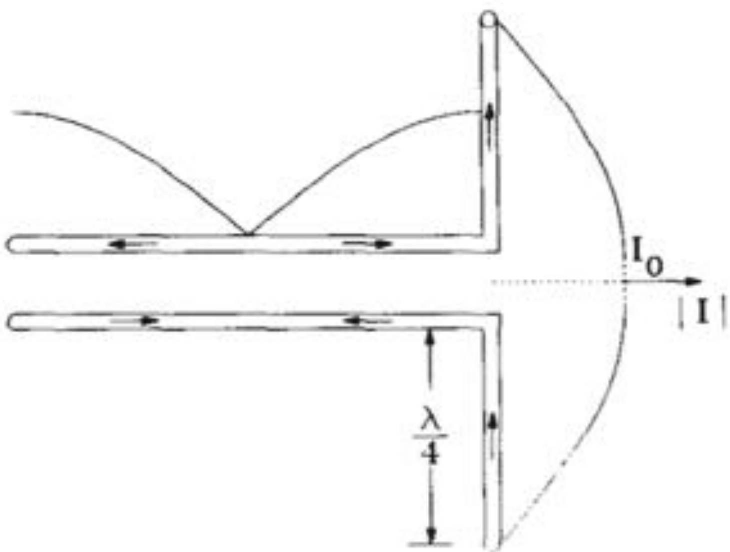




0.6 dBi Loop with a 40 degree omnidirectional beam

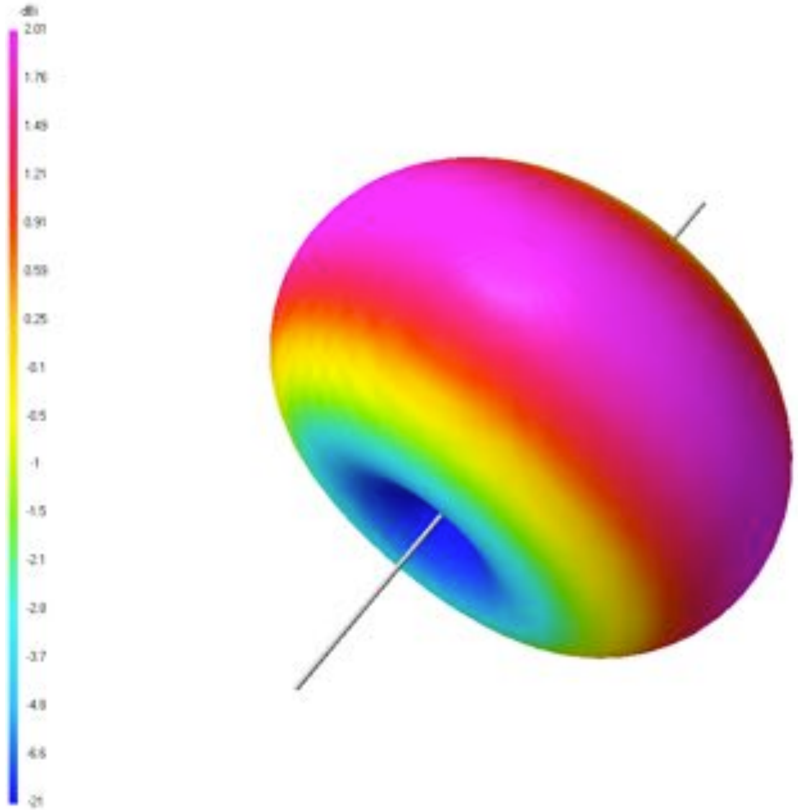
Dipole Antenna

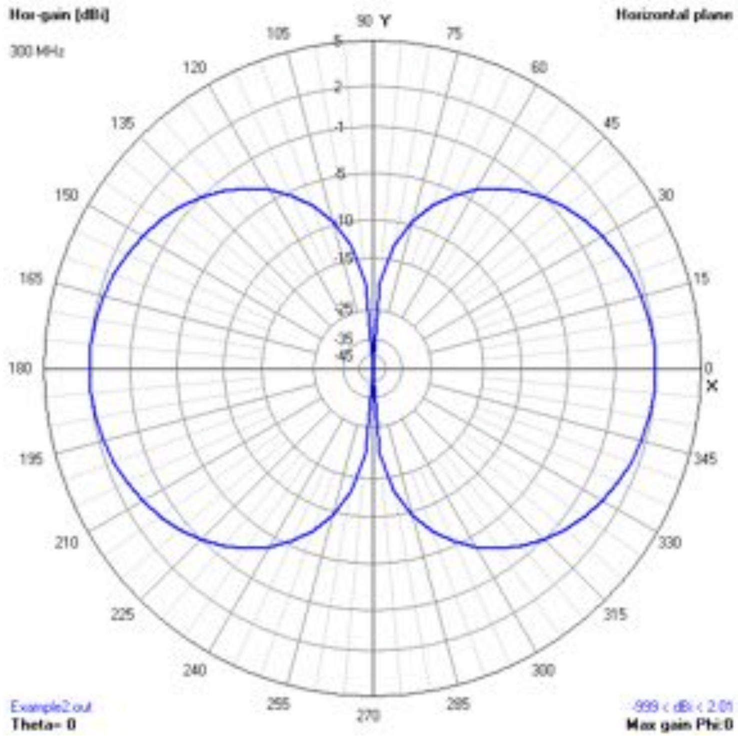
Discovered in 1886 by Heinrich Hertz
Typically has two ¼ λ elements & 2.1dBi gain



"Half – Wave Dipole" by Schwarzbeck Mess-Elektronik
Own work. Licensed under CC BY-SA 3.0 via Commons
https://commons.wikimedia.org/wiki/File:Half_%E2%80%93_Wave_Dipole.jpg

Dipole Antenna

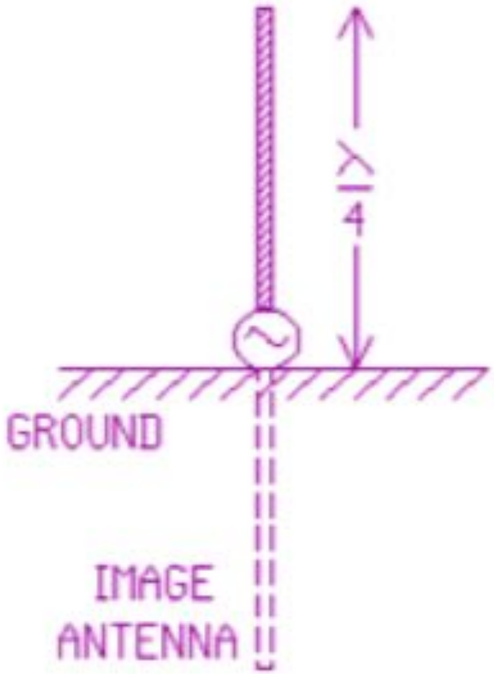


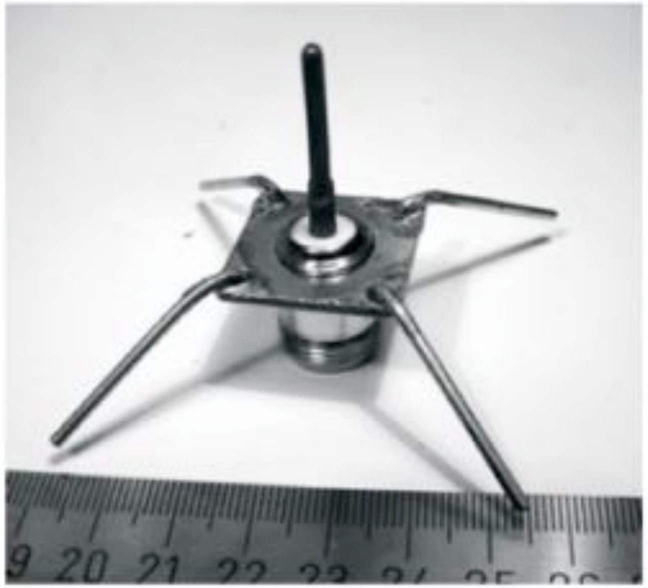


2 dBi Dipole with a 60 degree omnidirectional beam

Monopole Antenna

Discovered in 1895 by Guglielmo Marconi
¼ λ vertical element over a ground plane
Provides 5.14 dBi gain





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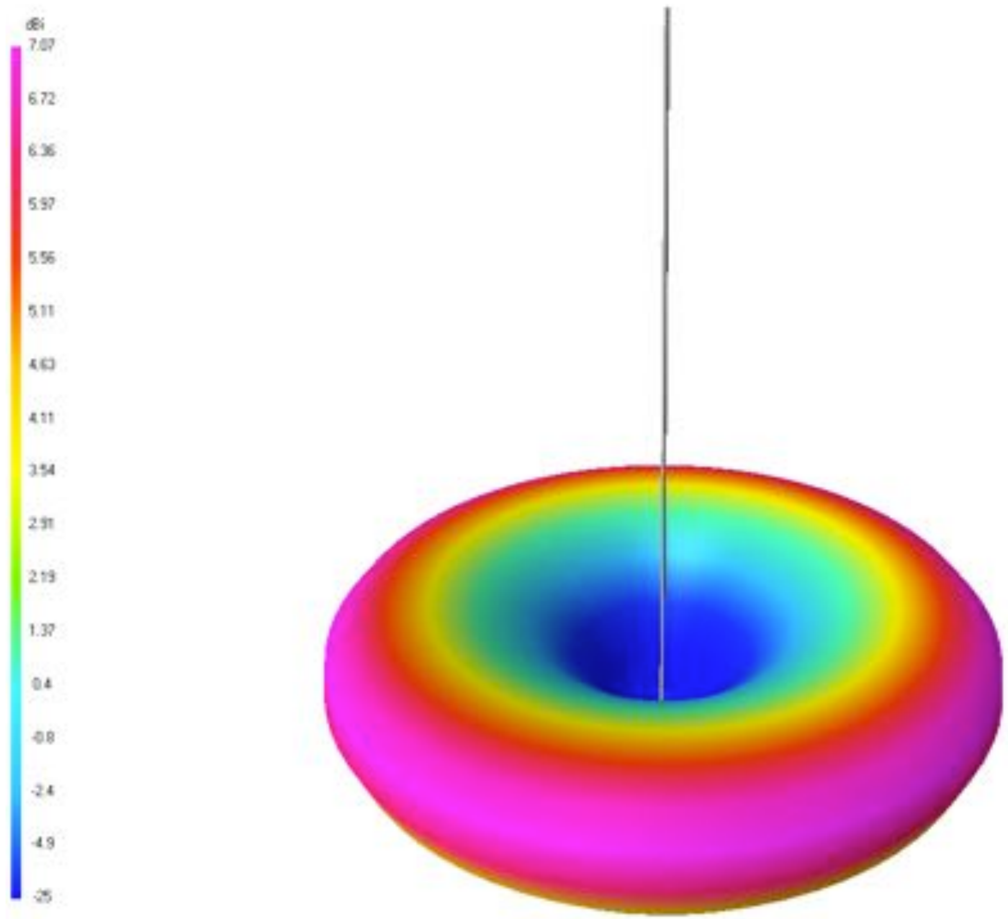
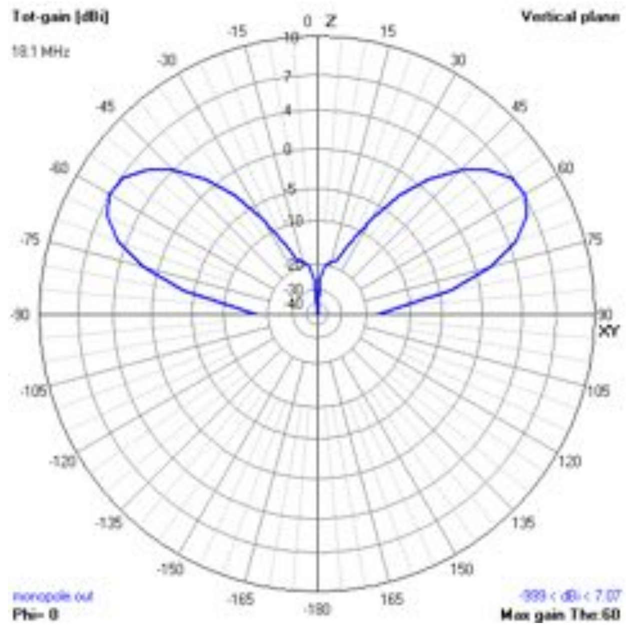
Monopole Antenna

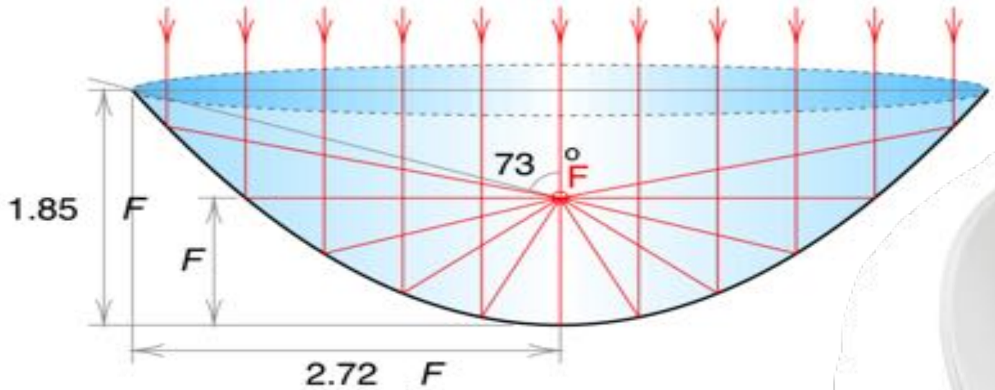




7 dBi Monopole with a tilted 30 degree omnidirectional beam

Parabolic Reflector

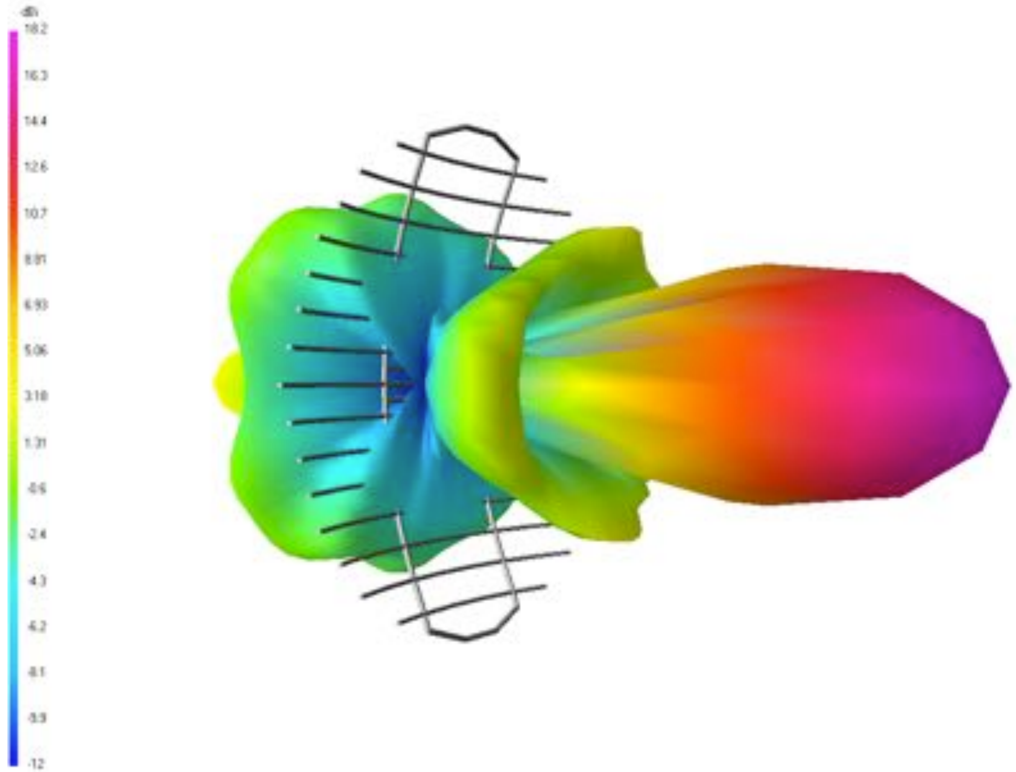
Discovered around 200 BC by Diocles
Used for Radio in 1887 by Heinrich Hertz

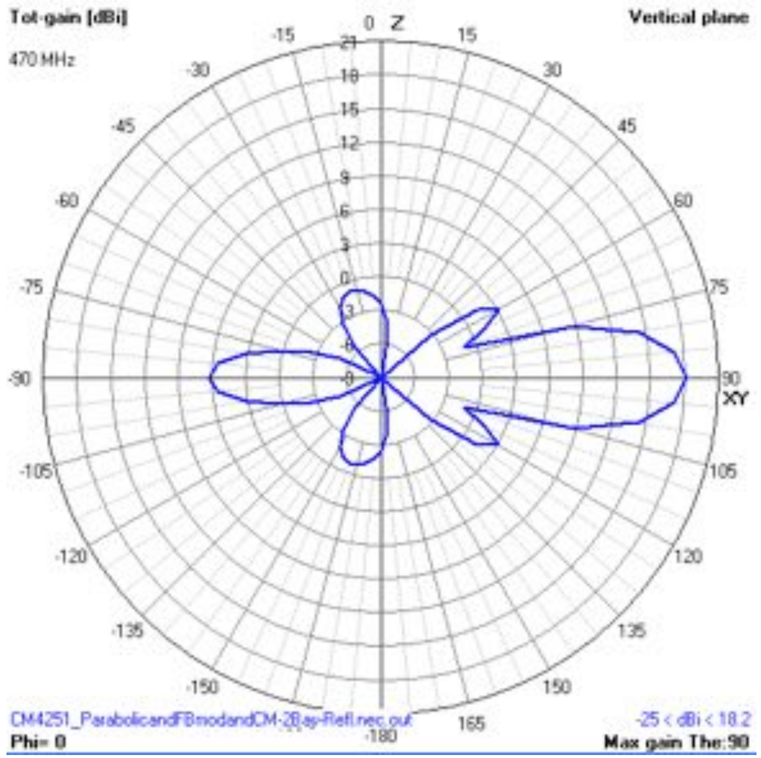


Parabola illustrated by Wikimedia Commons User CMGlee
https://commons.wikimedia.org/wiki/File:Focus-balanced_parabolic_reflector.svg

Ubiquiti Nanobeam Dishes: https://www.ubnt.com/

Parabolic Reflector



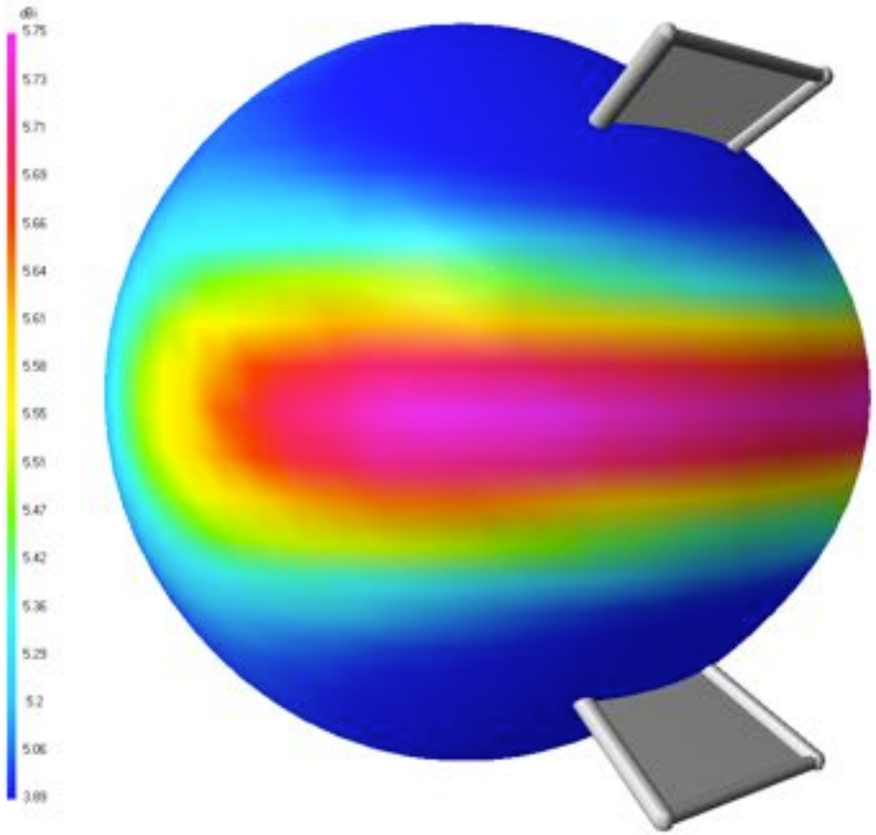


Antenna in front of a Parabolic Reflector
yields 18dBi with a 40 degree H+E beamwidth

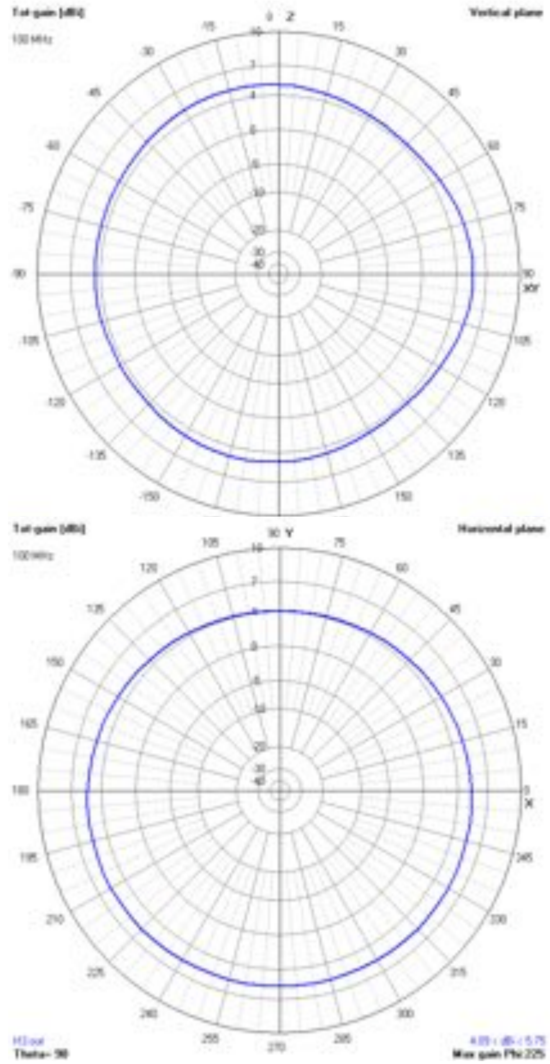
Horn Antennas

- Lens Discovered ~ 700 BC in Assyria
- Horns in use since Prehistoric times
- First used for radio in 1897 by Sir Jagadish Chandra Bose
- Often coupled with a lens to focus waves

Horn Antenna

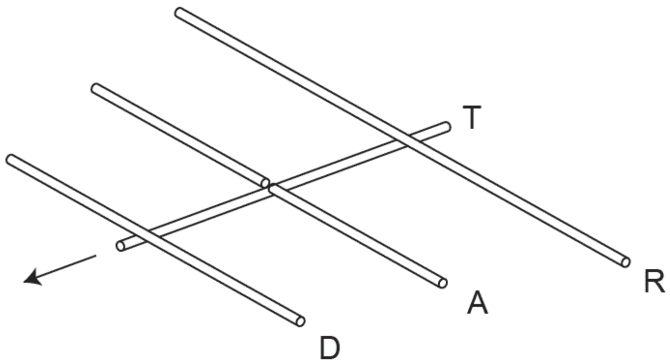


5.75 dBi Directional Horn
(approx) 60 degree E, 180 degree H

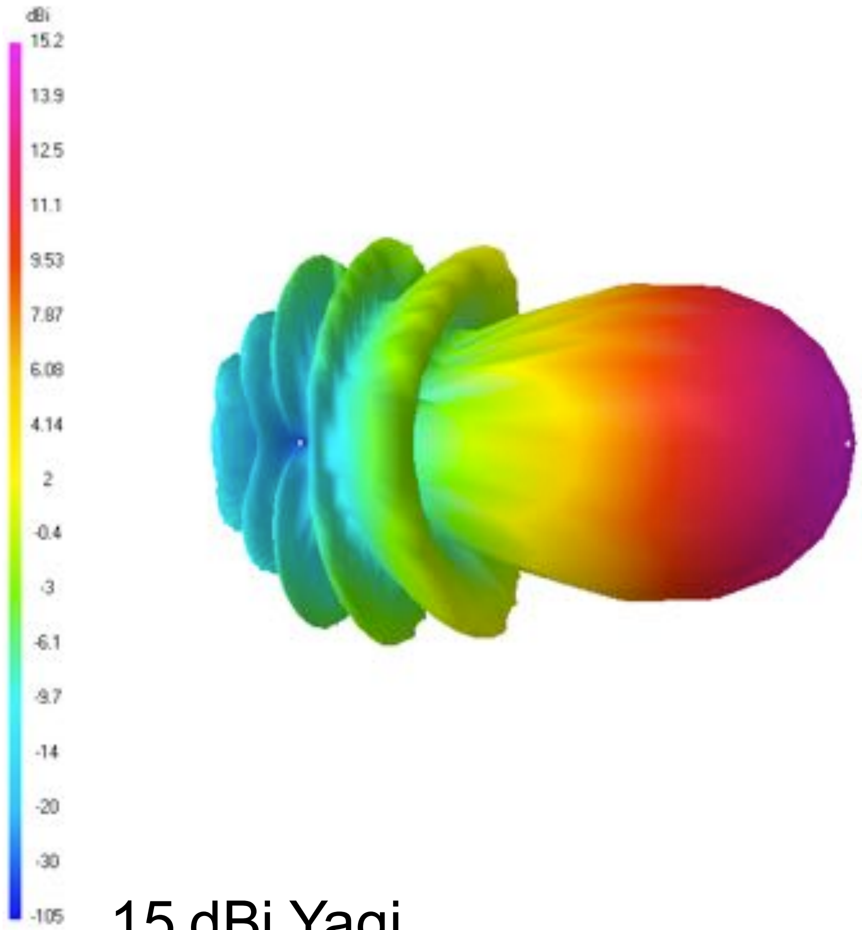


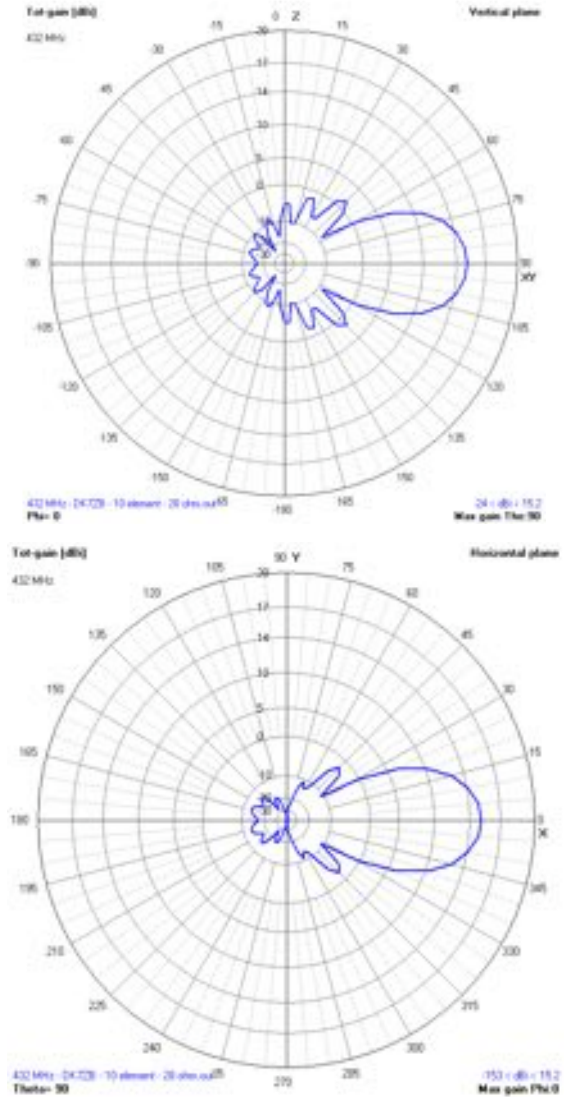
Yagi-Uda (Yagi) Antenna

Invented 1926 by Shintaro Uda & Hidetsugu Yagi
Common from VHF up to 3 GHz
Low cost, light weight, durable, and high gain



Yagi Antenna

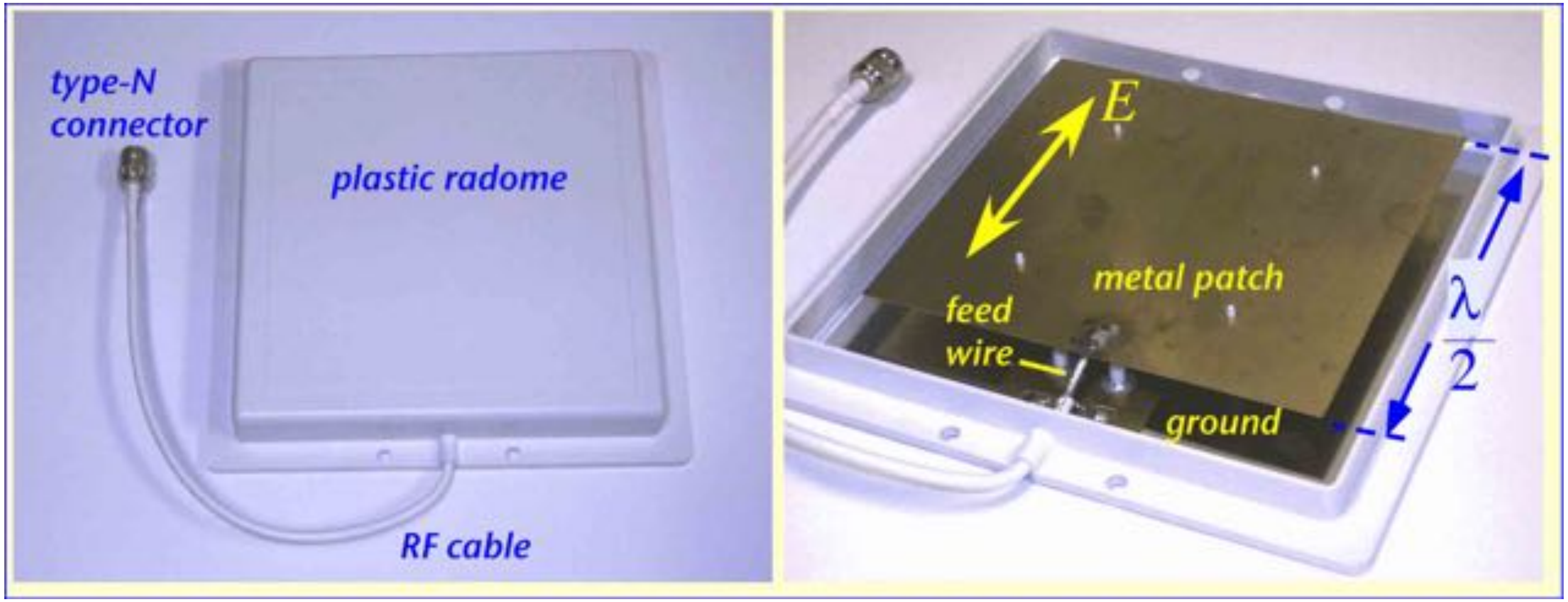




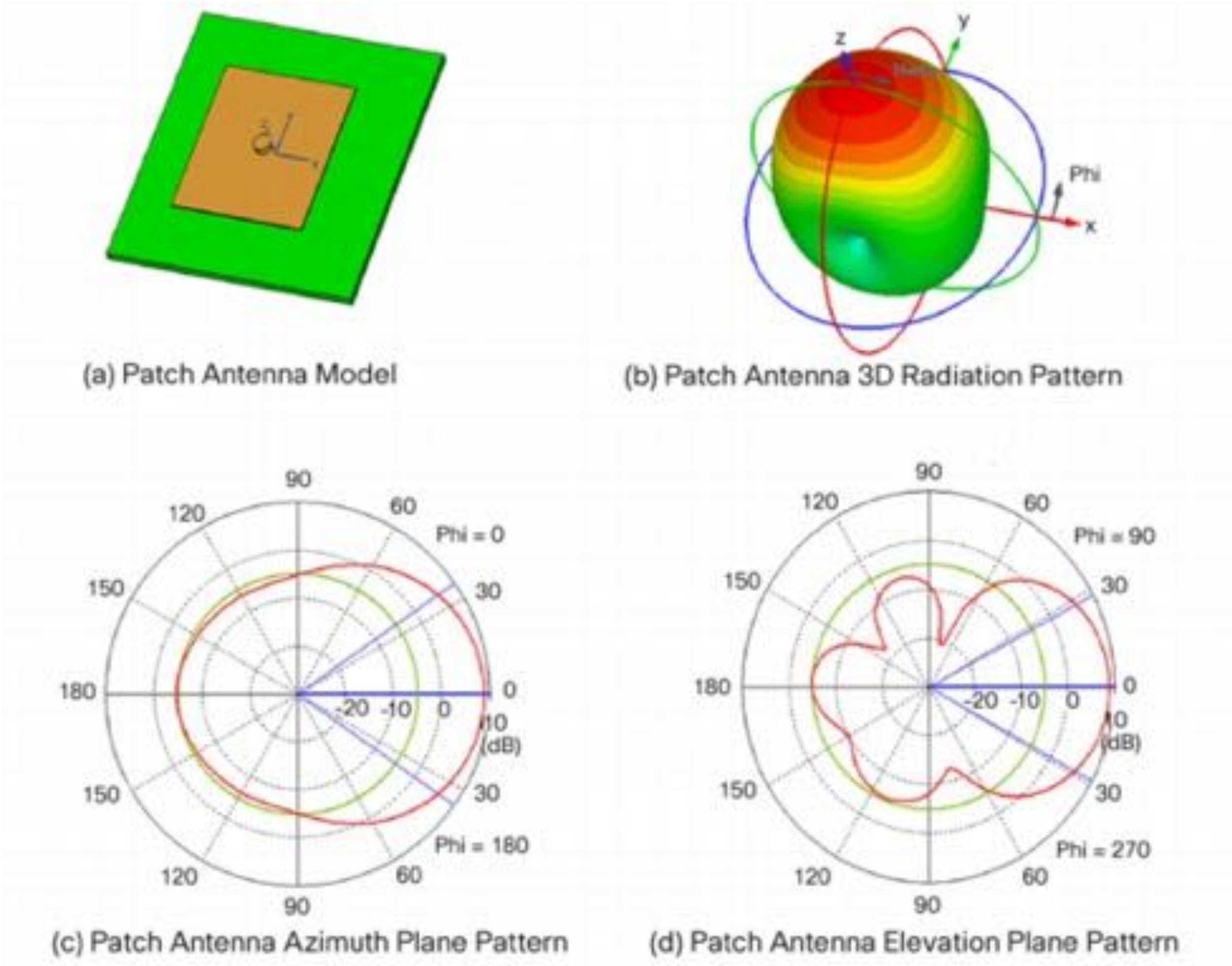
15 dBi Yagi
(approx) 30 degree E, 30 degree H

Microstrip (Patch) Antennas

Invented in 1972 by J.Q. Howell at NASA
Very common in electronics and Wi-Fi



Microstrip (Patch) Antennas

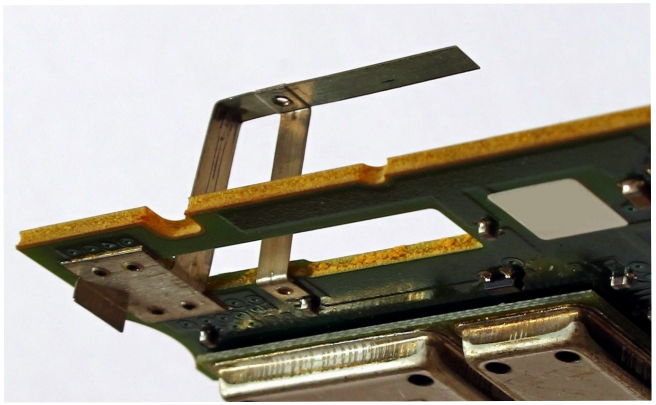


(a) Patch Antenna Model
(b) Patch Antenna 3D Radiation Pattern
(c) Patch Antenna Azimuth Plane Pattern
(d) Patch Antenna Elevation Plane Pattern

http://www.cisco.com/c/en/us/products/collateral/wireless/aironet-antennas-accessories/prod_white_paper0900aecd806a1a3e.html

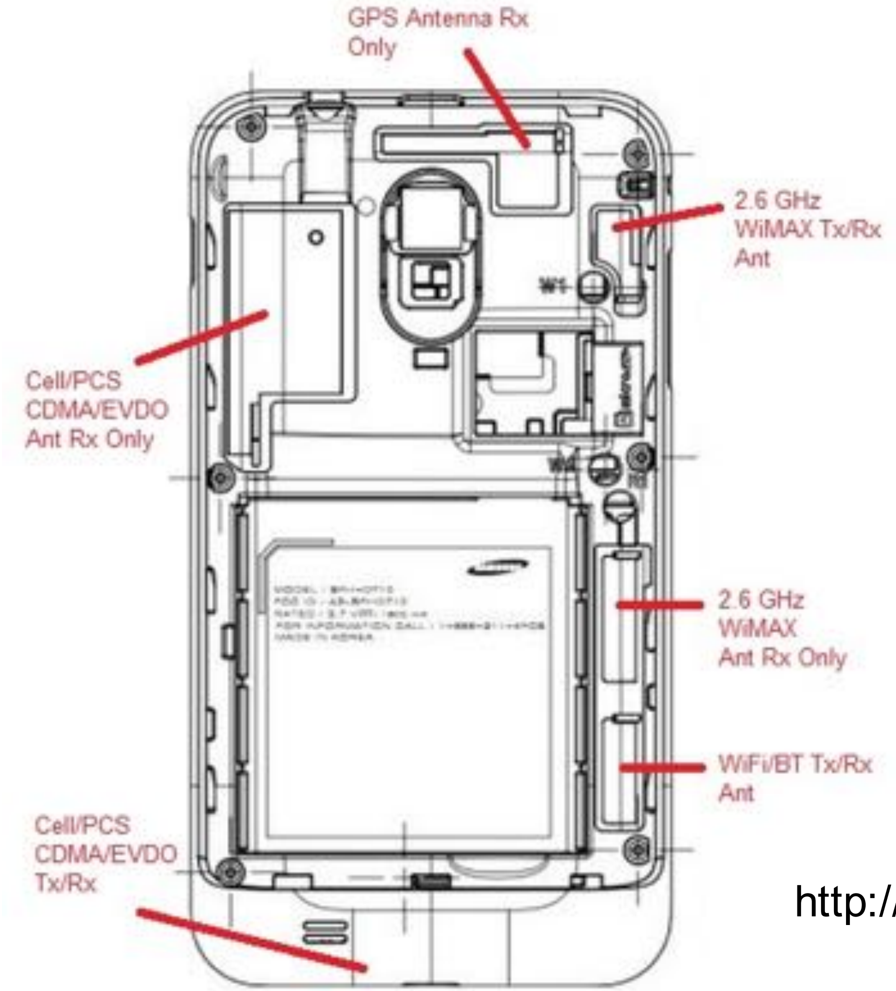
Planar Inverted F-Antenna (PIFA)

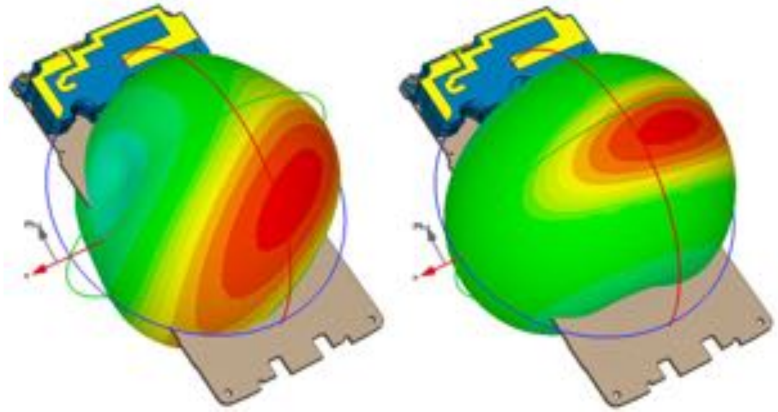
- Invented in 1987 by Taga & Tsunekawa at NTT
- Allows for a very small antenna
- Width + Height can be around ¼ λ
- A ¼ λ dipole at 750 MHz is 100mm: Phone size!
- PIFA allows for good antennas less than ¼ λ long
- There are also multi-band PIFA designs



https://commons.wikimedia.org/wiki/File:
Planar_Inverted_F-Shaped_DECT_Antenna.jpg

Planar Inverted F-Antenna (PIFA)



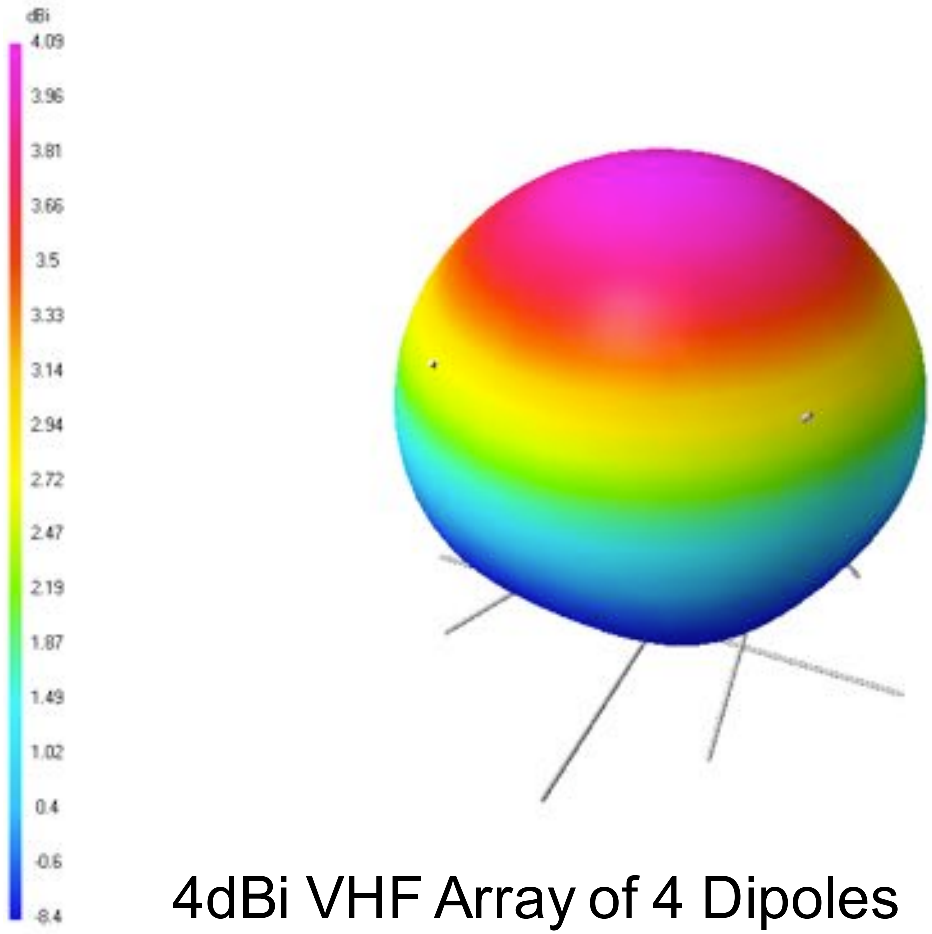


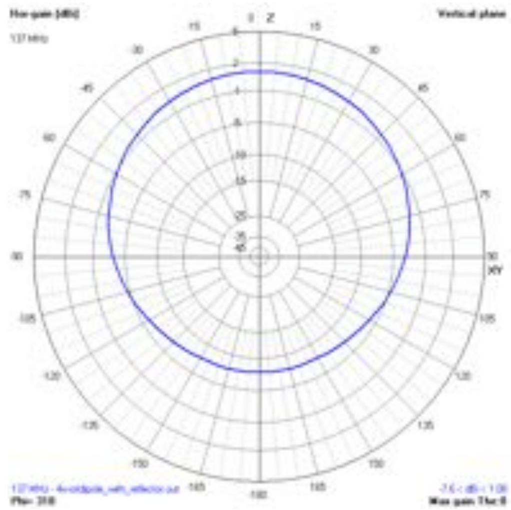
http://www.raymaps.com/index.php/tag/antenna/

Antenna Arrays

- Two or more antennas
- Signals combined for multiple purposes
  - increase gain
  - provide diversity receive
  - cancel interference
  - steer the direction of highest gain
  - locate the direction of received signals
- Most WiFi Sector Antennas are Arrays

Antenna Arrays





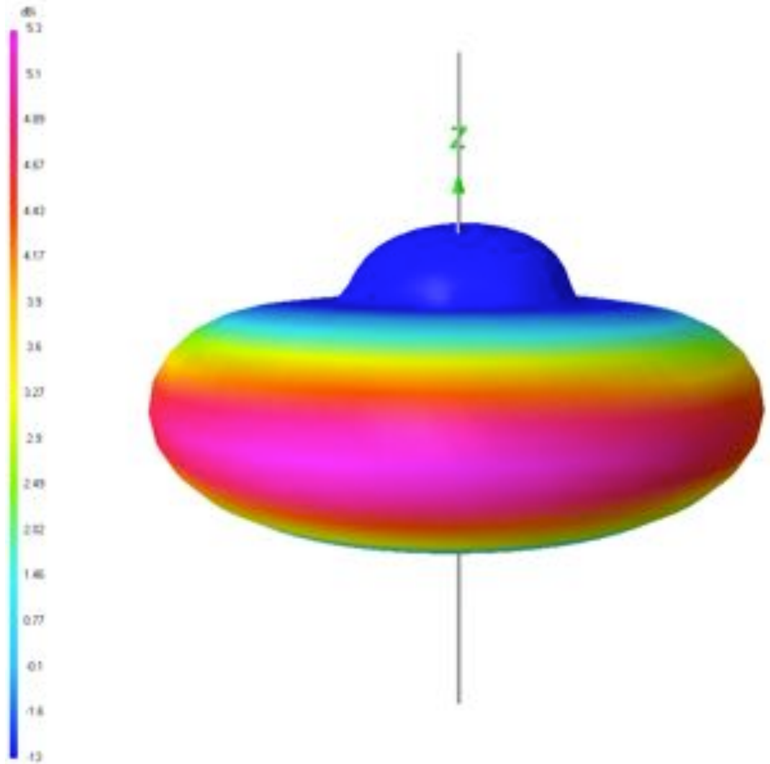
4dBi VHF Array of 4 Dipoles
(approx) 120 degree E, 90 degree H

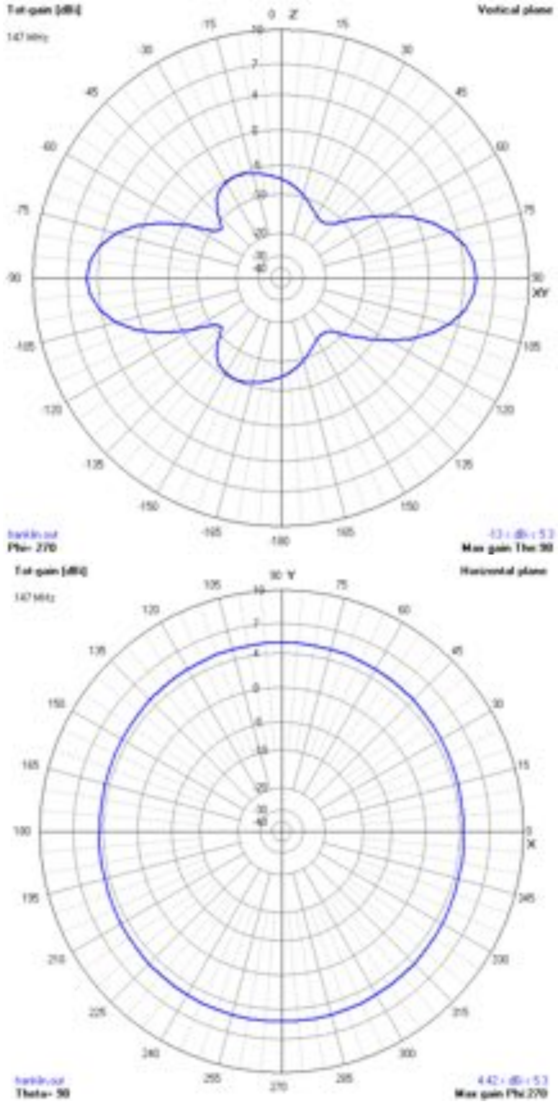
Collinear (Omni) Antenna

- Invented 1925 by Charles Franklin
- Made of an array of stacked dipoles
- Common from VHF up to 6 GHz
- Low cost, light weight, durable, and high gain

https://commons.wikimedia.org/wiki/File:
Antennes_VHF_UHF_01.JPG

Collinear (Omni) Antenna





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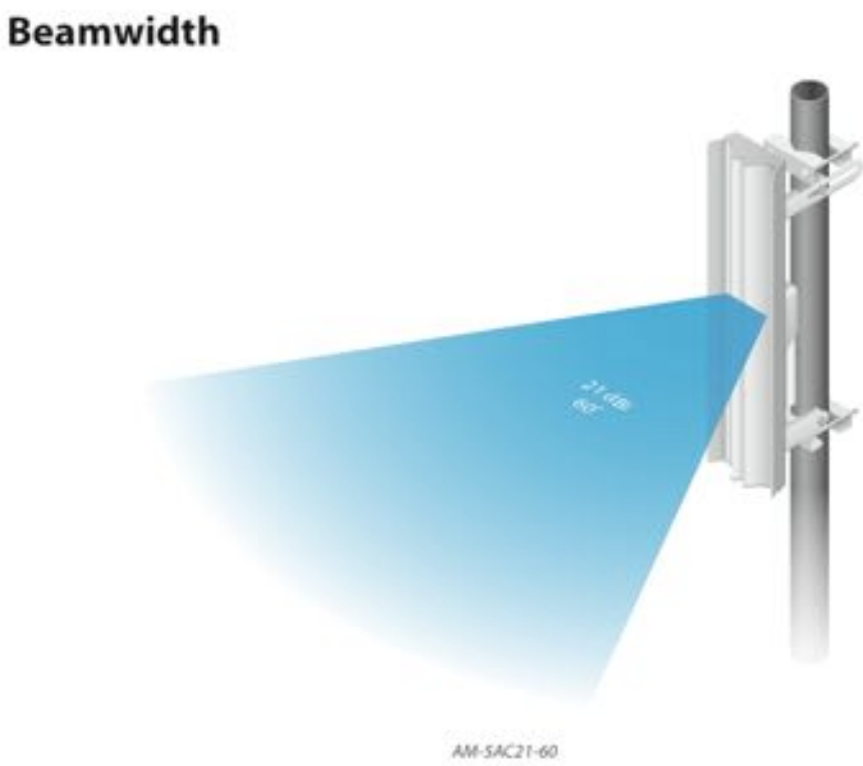
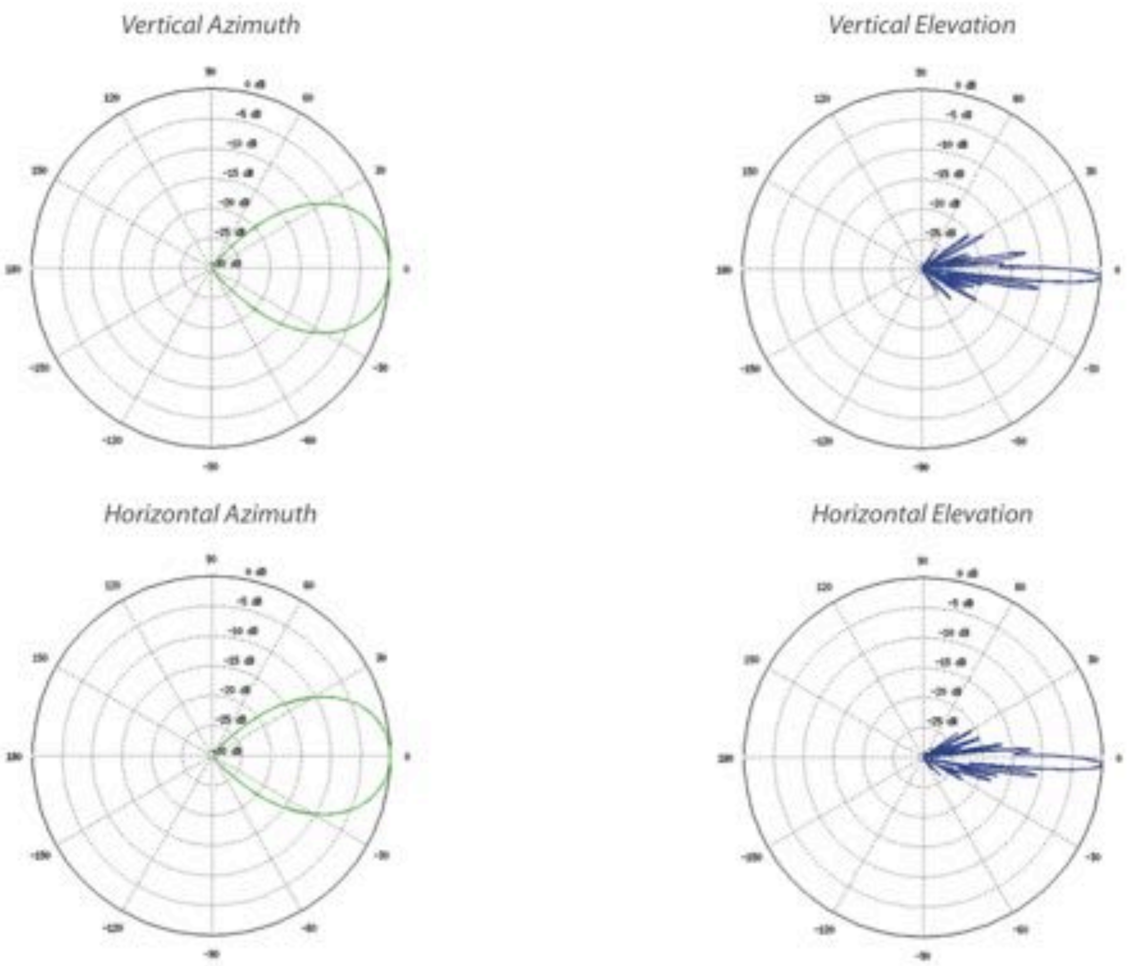
Choosing an Antenna

- What frequency and bandwidth?
- What coverage do you need?
- Does physical size matter?
  - Is your mast strong enough for a big antenna?
- Are aesthetics important?
- Is the environment windy?
  - Maybe use a grid antenna with low surface area
- Is there ice?
  - Use a dish with a plastic cover to keep the ice off

A Commercial Sector (Array of Patches)



A Commercial Sector Antenna

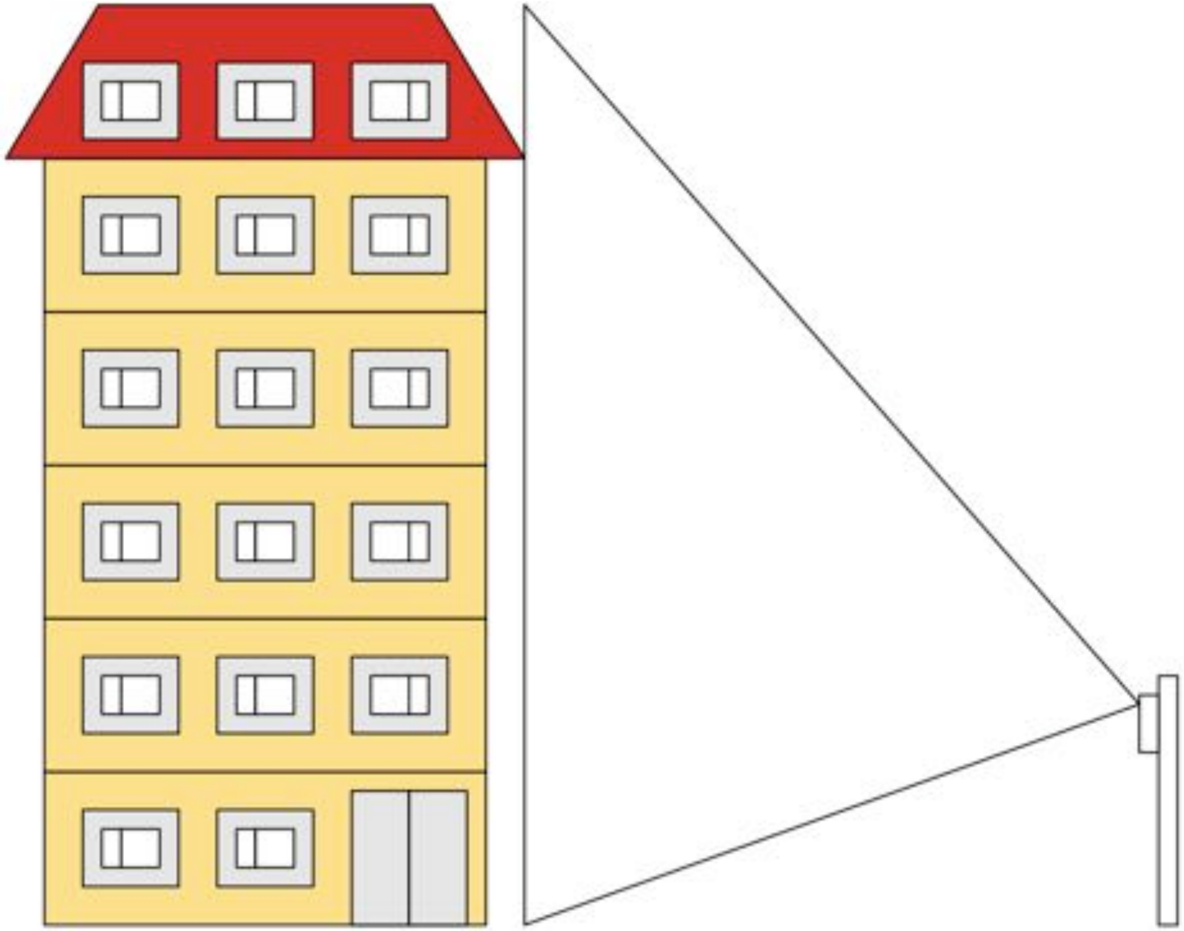


A Commercial Sector Antenna

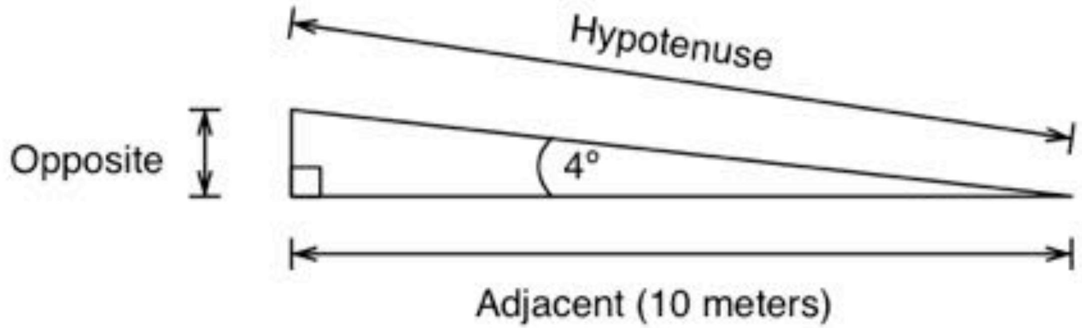
60 degree H, 4 degree E, 10m from a 18m Building

Is this going to work?

A Commercial Sector Antenna



A Commercial Sector Antenna



$\tan(\theta)$ = Opposite / Adjacent

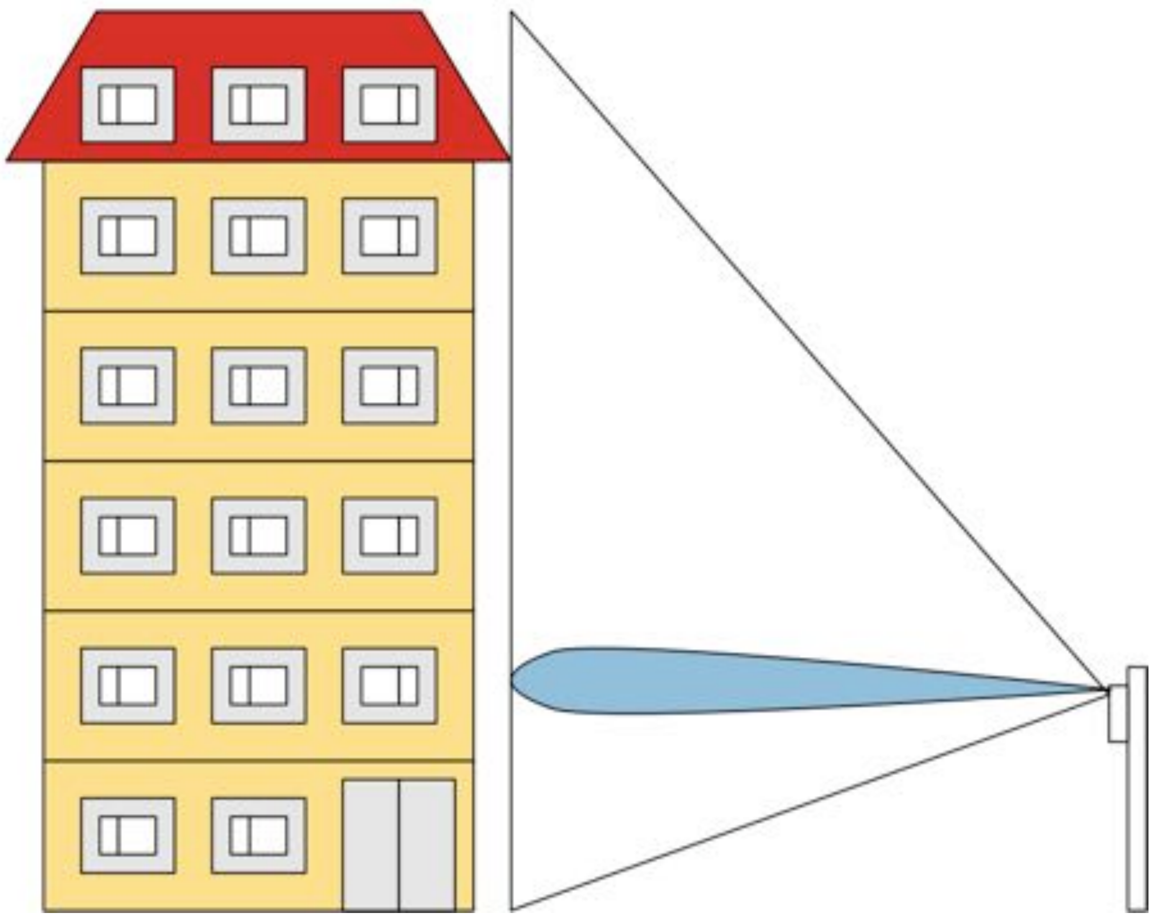
$\tan(4) = 0.07$

0.07 = Opposite / 10

Opposite = 0.07 * 10

Opposite = 0.7 meters

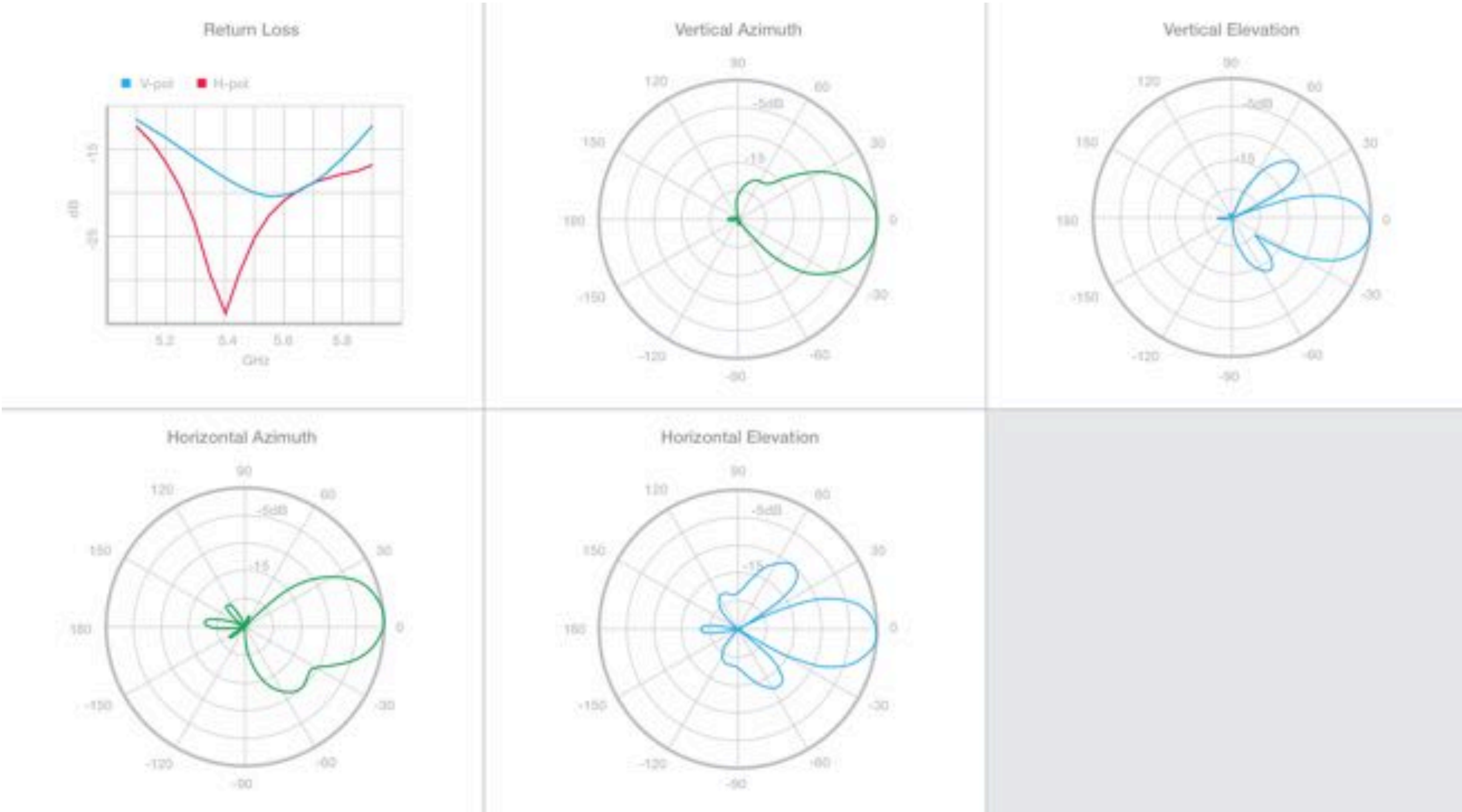
A Commercial Sector Antenna



A Commercial Sector Antenna

This array of patch antennas has an access point built-in!

A Commercial Sector Antenna



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A Commercial Sector Antenna

45 degree H, 45 degree E, 10m from a 18m Building

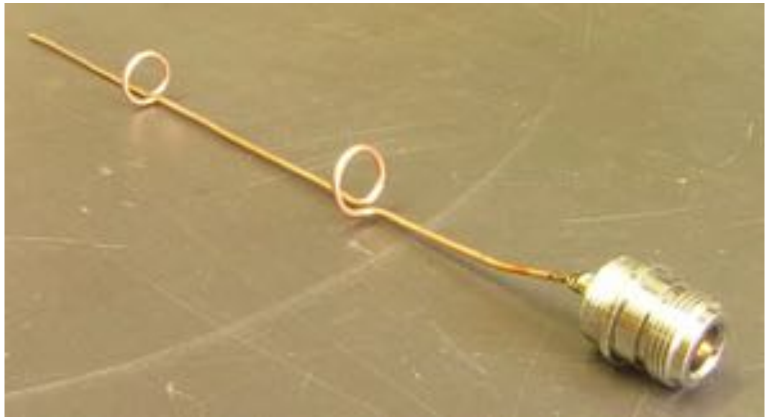
Is this going to work?

Making Your Own Antennas

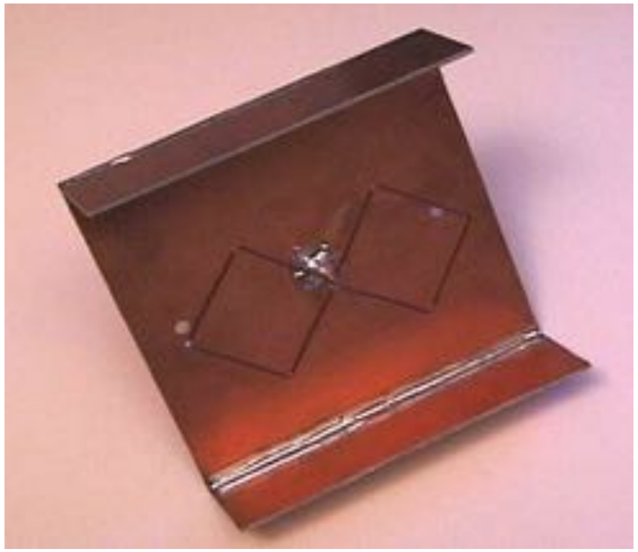
- Free, Open Source Designs Available
- Combine with Reflectors (Satellite Dishes) for high gain
- Learn Collinear & Cantenna with WNDW (multiple languages)
  - http://wndw.net/book.html
- Make a BiQuad with Trevor Marshall (English)
  - http://www.trevormarshall.com/biquad.htm
- Make a Parabolic Reflector & More with M. Erskine (English)
  - http://www.freeantennas.com/projects/template/index.html
- Make a Collinear with Marty Bugs (English)
  - http://martybugs.net/wireless/collinear.cgi

Making Your Own Antennas

http://www.dslreports.com/forum/remark,5605782~root=wlan~mode=flat



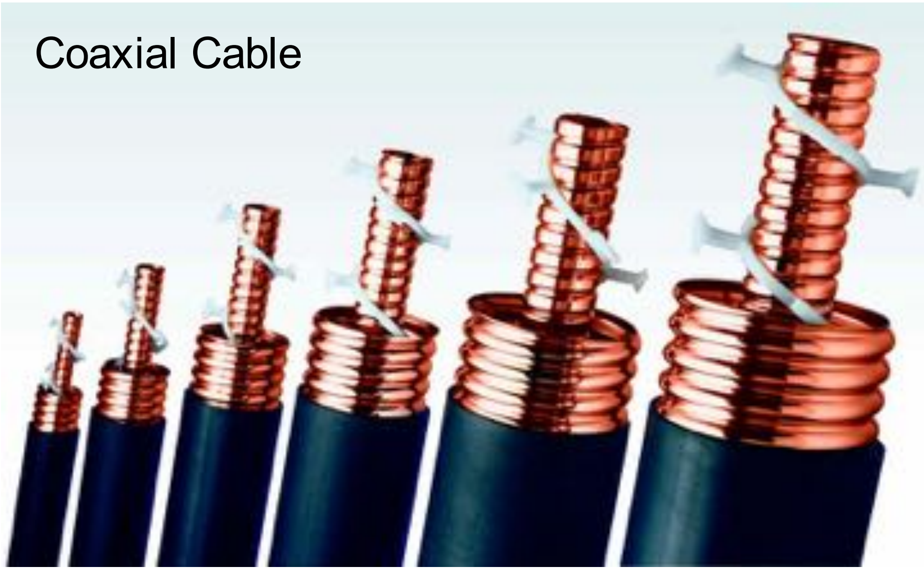
http://martybugs.net/wireless/collinear.cgi



http://www.trevormarshall.com/biquad.htm

What's A Transmission Line?

A device to guide waves that are not in free space

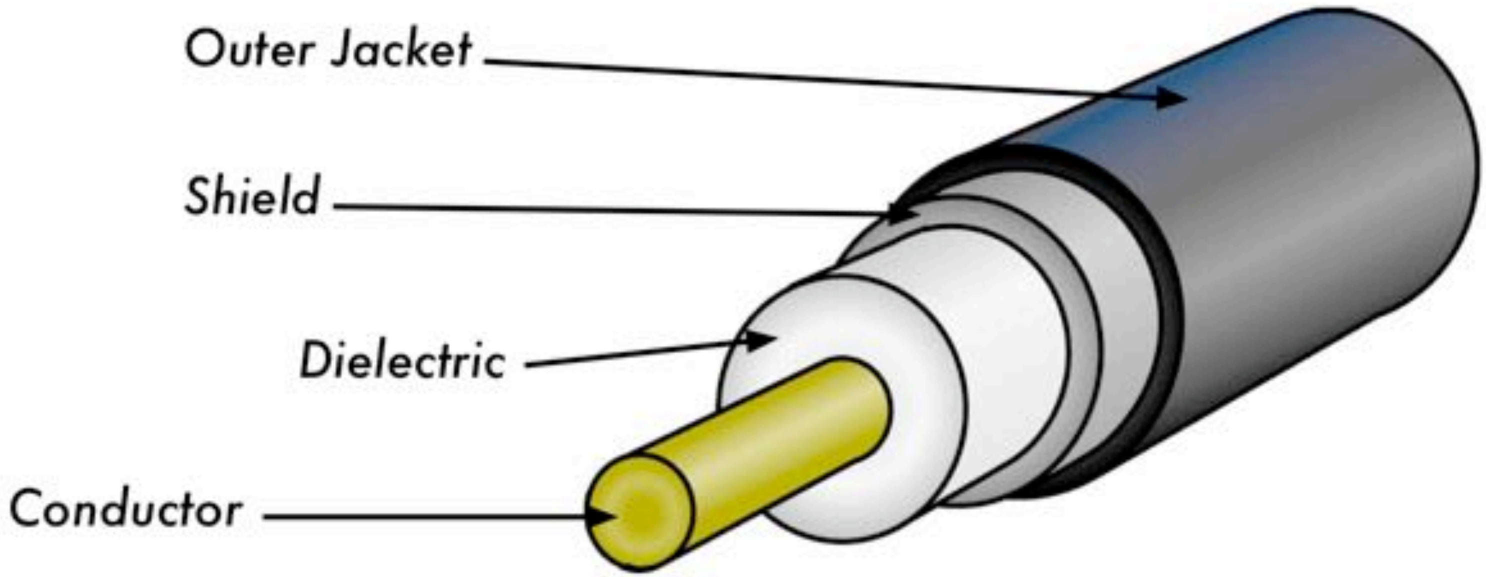


https://commons.wikimedia.org/wiki/File:Air_Cables.jpg

https://commons.wikimedia.org/wiki/File:
Waveguide-flange-with-threaded-collar.jpg

Coaxial Transmission Lines

The most common cables for use with Wi-Fi



Coaxial Transmission Lines

The loss (or attenuation) of a coaxial cable depends on cable construction and operating frequency

Loss is proportional to cable length

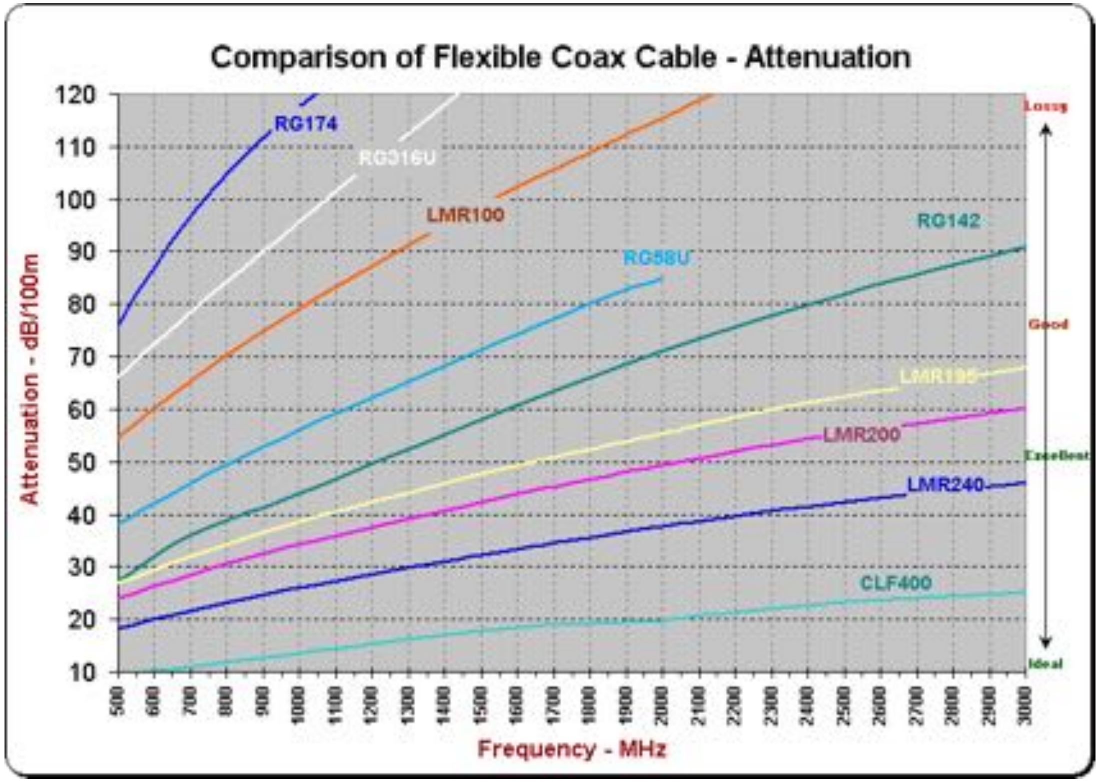
Thicker cable = less loss, harder to work with

Cable Type	Diameter	Attenuation @ 2.4 GHz	Attenuation @ 5.3 GHz
RG-58	4.95 mm	0.846 dB/m	1.472 dB/m
RG-213	10.29 mm	0.475 dB/m	0.829 dB/m
LMR-400	10.29 mm	0.217 dB/m	0.314 dB/m
LDF4-50A	16 mm	0.118 dB/m	0.187 dB/m

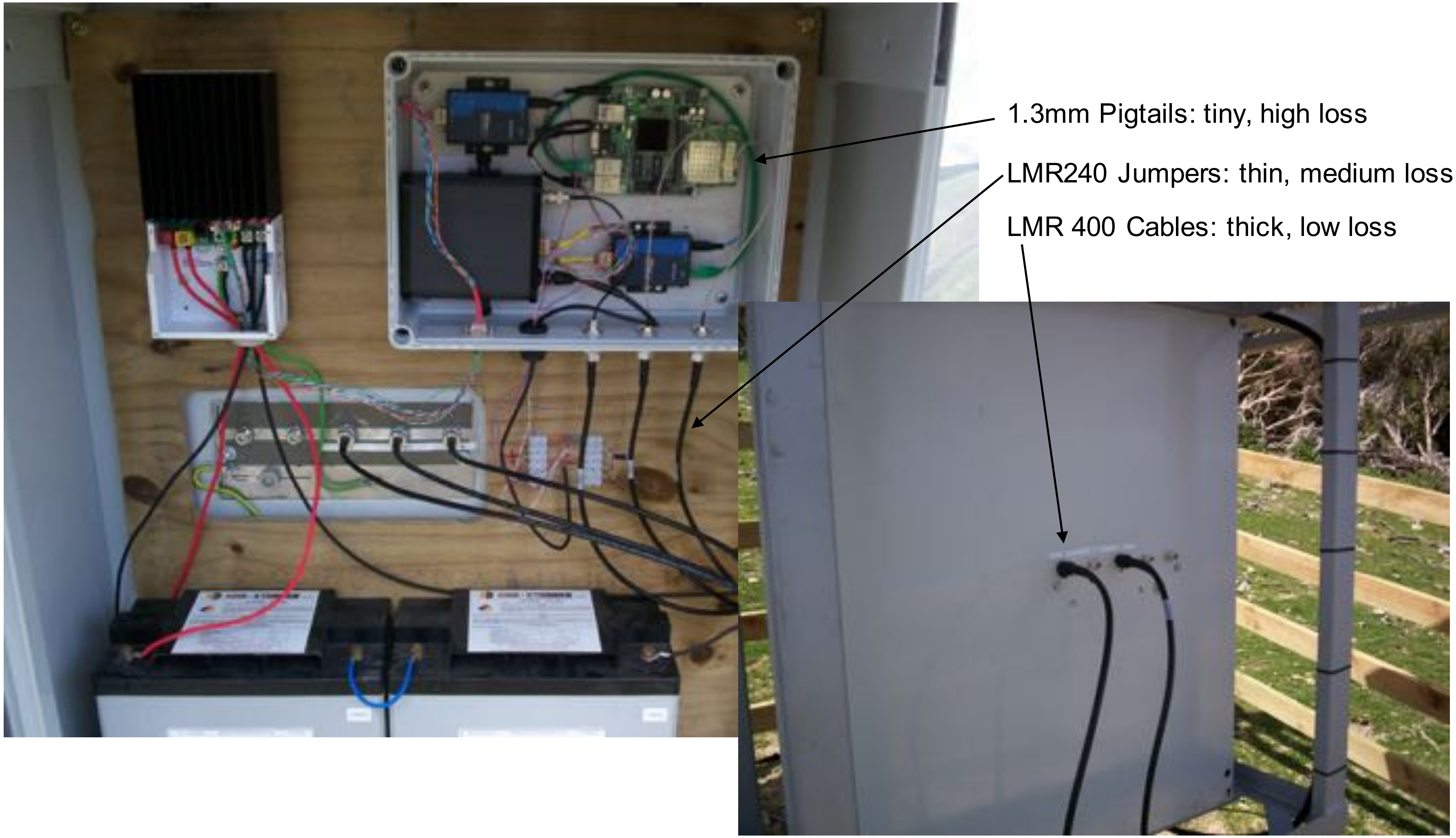
http://www.ocarc.ca/coax.htm

Cable Loss Chart

Cable manufacturers publish charts per product
Always understand: frequency, distance, loss



Why Use Different Cables? Flexibility



1.3mm Pigtails: tiny, high loss

LMR240 Jumpers: thin, medium loss

LMR 400 Cables: thick, low loss

Choosing Transmission Line

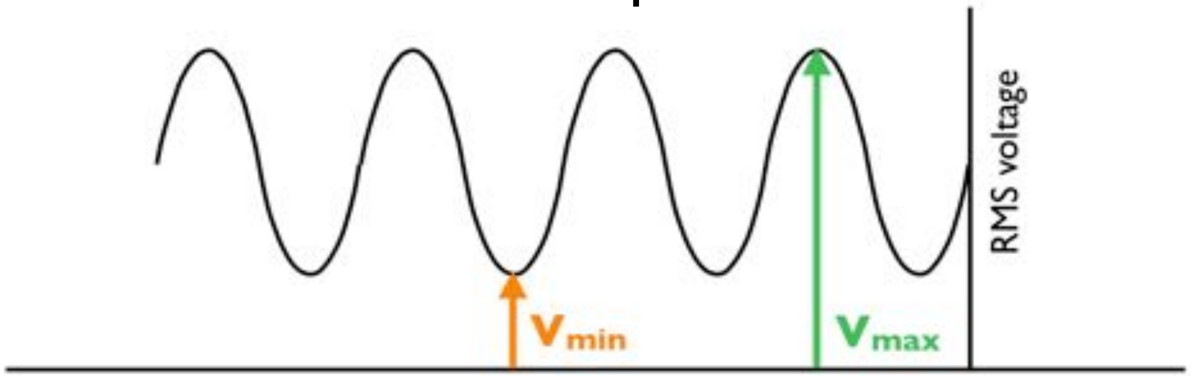
- What frequencies do you need?
- How much loss can your system tolerate?
- Does size matter? Flexibility?
- Using multiple types of line is ok!

Impedance

- All materials oppose the flow of current
  - This opposition is called impedance
  - It's analogous to resistance in DC circuits
- Comms cable & antennas are usually 50 Ohms
- TV cable & antennas are usually 75 Ohms
- Always match impedance of cable & antennas
  - Mis-match will cause reflections & high VSWR

Voltage Standing Wave Ratio

- Impedance mismatch will result reflections
- VSWR is a function of the reflection coefficient
- Higher VSWR = less power from tx to antenna
- Lower VSWR = more power from tx to antenna



$$\text{Voltage Standing Wave Ratio VSWR} = \frac{V_{max}}{V_{min}}$$

How could you Mismatch Impedance?

- UHF Television antennas are 75 Ohm
- UHF Television antennas cover 500-800 MHz
- RG-6 Cable is ideal for 500-800MHz. It's 75 Ohm
- All these things are inexpensive & available
- New LTE services use 700-800 MHz
- LTE radios are 50 Ohm
- Use TV equipment for LTE? Impedance Mismatch

Review

- How does an antenna work?
- What's a radiation pattern?
- How do you choose the right antenna?
- What does a transmission line do?
- How do you choose a transmission line?

Wireless Standards & Protocols

Network Startup Resource Center
www.nsrc.org

Original Slides: Sebastian Büttrich, NSRC/ITU/wire.less.dk Edit: June 2012

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NSRC

Objectives

- Introduce Core Concepts & Terminology
  - Shared Radio Spectrum Bands
  - Wi-Fi & 802.11 radio channels
  - Channel Access
  - Wireless network topologies
  - Wi-Fi modes of operation
  - Basic wireless routing

What is Shared Spectrum?

- Licenses give an exclusive right to use a frequency
  - Radio & TV Stations, Cellular Operators
- Wi-Fi typically operates in shared spectrum
  - Many networks on the same frequencies
- Use of shared spectrum is free in most countries
- Free does not always mean unregulated or unlicensed
  - “Type Approved Devices”
  - Maximum Power Limits & Radar Detect
  - General User Radio Licenses

Is Shared Spectrum Important?

- Innovation happens in shared spectrum
- The market size is greater
- No country-specific frequencies to develop for
- Wi-Fi is often faster than cellular
- Wi-Fi is usually cheaper than cellular

Industrial, Scientific, Medical (ISM) Bands

- Spectrum originally set aside for ISM equipment
- Opened for use in the US in the 1990s
- Wi-Fi works in 2.4 GHz and 5.8 GHz ISM spectrum
- ISM bands also exist at:
  - 433 MHz
  - 915 MHz
  - 24 Ghz

ISM bands

Frequency range		Bandwidth	Center frequency	Availability
6.765 MHz	6.795 MHz	30 kHz	6.780 MHz	Subject to local acceptance
13.553 MHz	13.567 MHz	14 kHz	13.560 MHz	Worldwide
26.957 MHz	27.283 MHz	326 kHz	27.120 MHz	Worldwide
40.660 MHz	40.700 MHz	40 kHz	40.680 MHz	Worldwide
433.050 MHz	434.790 MHz	1.74 MHz	433.920 MHz	Region 1 only and subject to local acceptance
902.000 MHz	928.000 MHz	26 MHz	915.000 MHz	Region 2 only (with some exceptions)
2.400 GHz	2.500 GHz	100 MHz	2.450 GHz	Worldwide
5.725 GHz	5.875 GHz	150 MHz	5.800 GHz	Worldwide
24.000 GHz	24.250 GHz	250 MHz	24.125 GHz	Worldwide
61.000 GHz	61.500 GHz	500 MHz	61.250 GHz	Subject to local acceptance
122.000 GHz	123.000 GHz	1 GHz	122.500 GHz	Subject to local acceptance
244.000 GHz	246.000 GHz	2 GHz	245.000 GHz	Subject to local acceptance

Table: https://en.wikipedia.org/wiki/ISM_band

What is Wi-Fi?

- A Wi-Fi Alliance Trademark
  - Not a strict technical term
- Wi-Fi is commonly used to refer to the 802.11 family of wireless standards
- Wi-Fi can run in ISM bands
- Wi-Fi is designed for shared spectrum







WiFi™

WiFi can now be found almost anywhere.



Current 802.11 Standards

Standard	Data rate [Mbps]	Frequency [GHz]	Channel Access
802.11b	11	2.4	DSSS
802.11g	54	2.4	DSSS, OFDM
802.11a	54	5	OFDM
802.11n	150/300/600	2.4 / 5	DSSS, OFDM, MIMO
802.11ac	1300	5	OFDM, Mu-MIMO

Emerging 802.11 standards

Standard	Data rate [Mbps]	Frequency	Channel Access
802.11ad	>6000	60 GHz	Milimetre waves Very short range
802.11af	10-100	2.4	TV White Spaces Non Line of Sight

The Speed of Wi-Fi

- Wi-Fi Data Rates – 11, 54, 1300mbps
  - Peak raw radio symbol rates
  - Half-duplex, not full duplex!
  - Not actual TCP/IP throughput rates
  - Lower Speeds are realized due to:
    - Protocol overhead
    - Adaptive modulation
- Practical Wi-Fi advice, on a perfect link:
  - TCP/IP throughput is ½ Wi-Fi data rate

Spectrum Access Schemes

- Channel-based access schemes
  - Frequency Division Multiple Access (FDMA)
  - Time division multiple access (TDMA)
  - Code division multiple access (CDMA)
  - Space division multiple access (SDMA)
  - These can be combined!
- Packet-based access schemes
  - Carrier sense multiple access (CSMA)
- Important as they impact performance

802.11 Spectrum Access

WiMax	Dynamic TDMA
LTE	OFDMA / MIMO / SC-FDMA
3G mobile	CDMA
2G mobile	TDMA
Bluetooth	FHSS

802.11a	DSSS, FHSS
802.11b	DSSS, 20 MHz channel
802.11g	OFDM, DSSS
802.11n	OFDM, DSSS, MIMO, 40MHz channel
802.11ac	OFDM, MU-MIMO, 80MHz channel

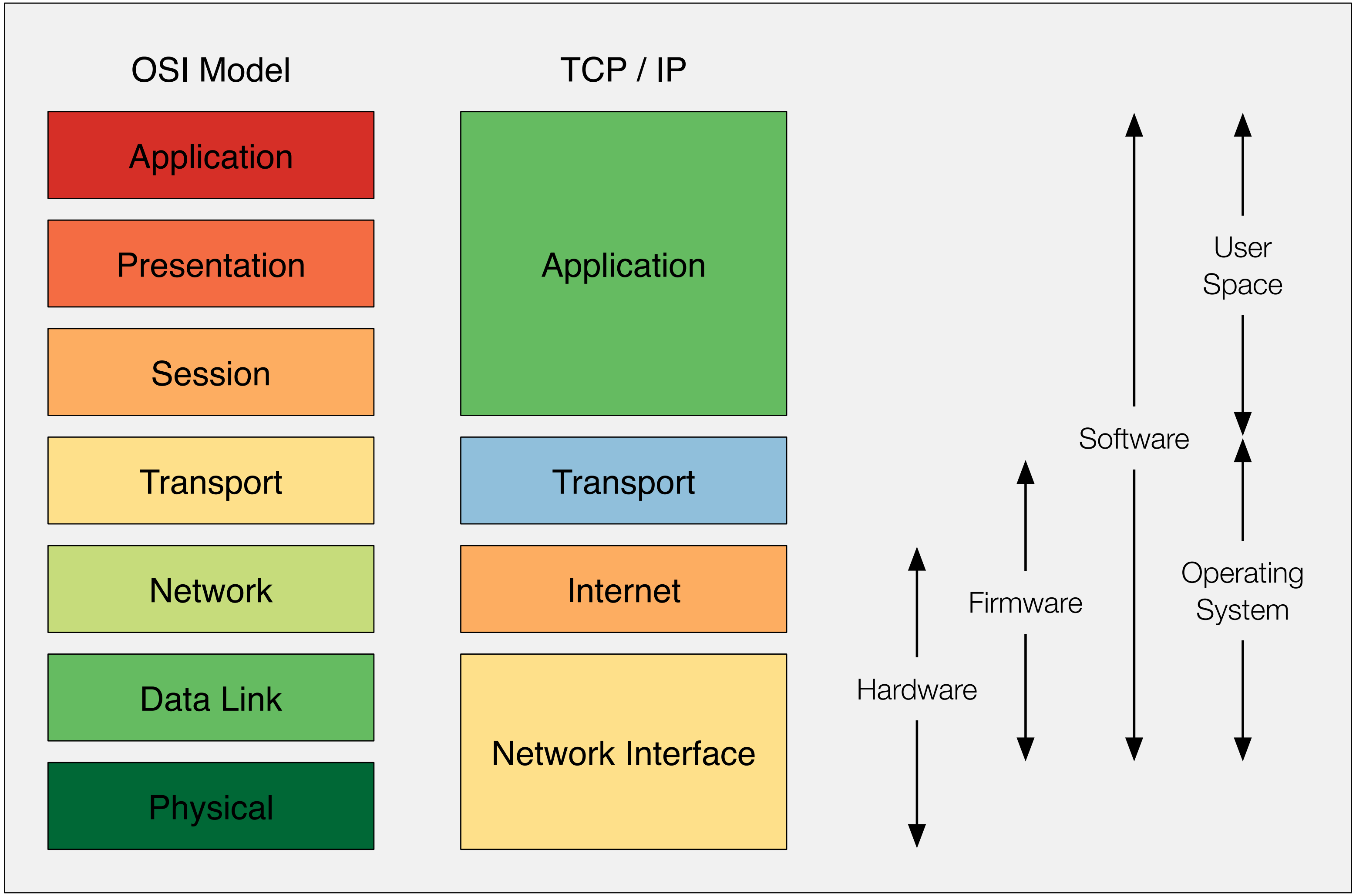
Compatibility of Standards

Access Point

Client

	802.11a	802.11b	802.11g	802.11n	802.11ac
802.11a	Yes			@5GHz	@5GHz
802.11b		Yes	(slower)	(slower)	
802.11g		(slower)	Yes	(slower)	
802.11n	@5GHz	@2.4GHz	@2.4GHz	Yes	(slower)
802.11ac	@5GHz			@5GHz	Yes

Think In Layers



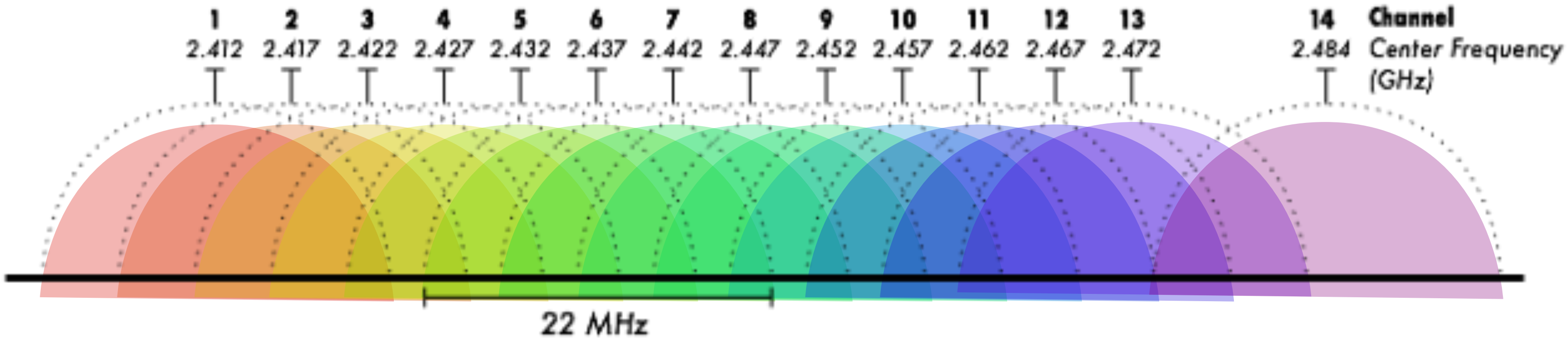
Layers 1 & 2

- WiFi devices must agree on several parameters
- Before they can communicate with each other!

TCP/IP Protocol Stack	
5	Application
4	Transport
3	Internet
2	Data Link
1	Physical

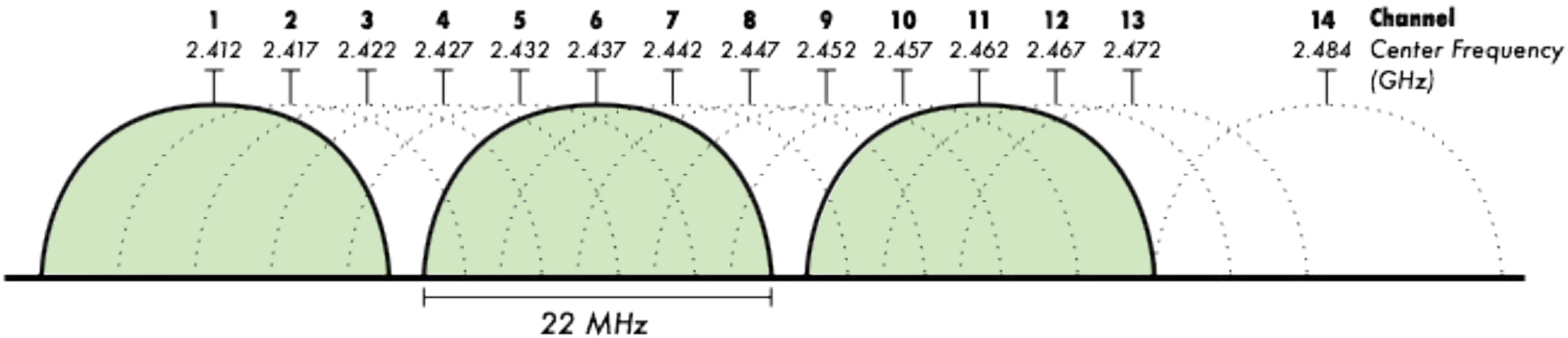
- Frequency:
  - Band, Center, Channel Size
- Radio operating mode:
  - Managed, Station/Client, Ad-Hoc
- Network name (SSID)
- Security features:
  - WPA, WPA2, EAP

802.11 Wi-Fi Channels



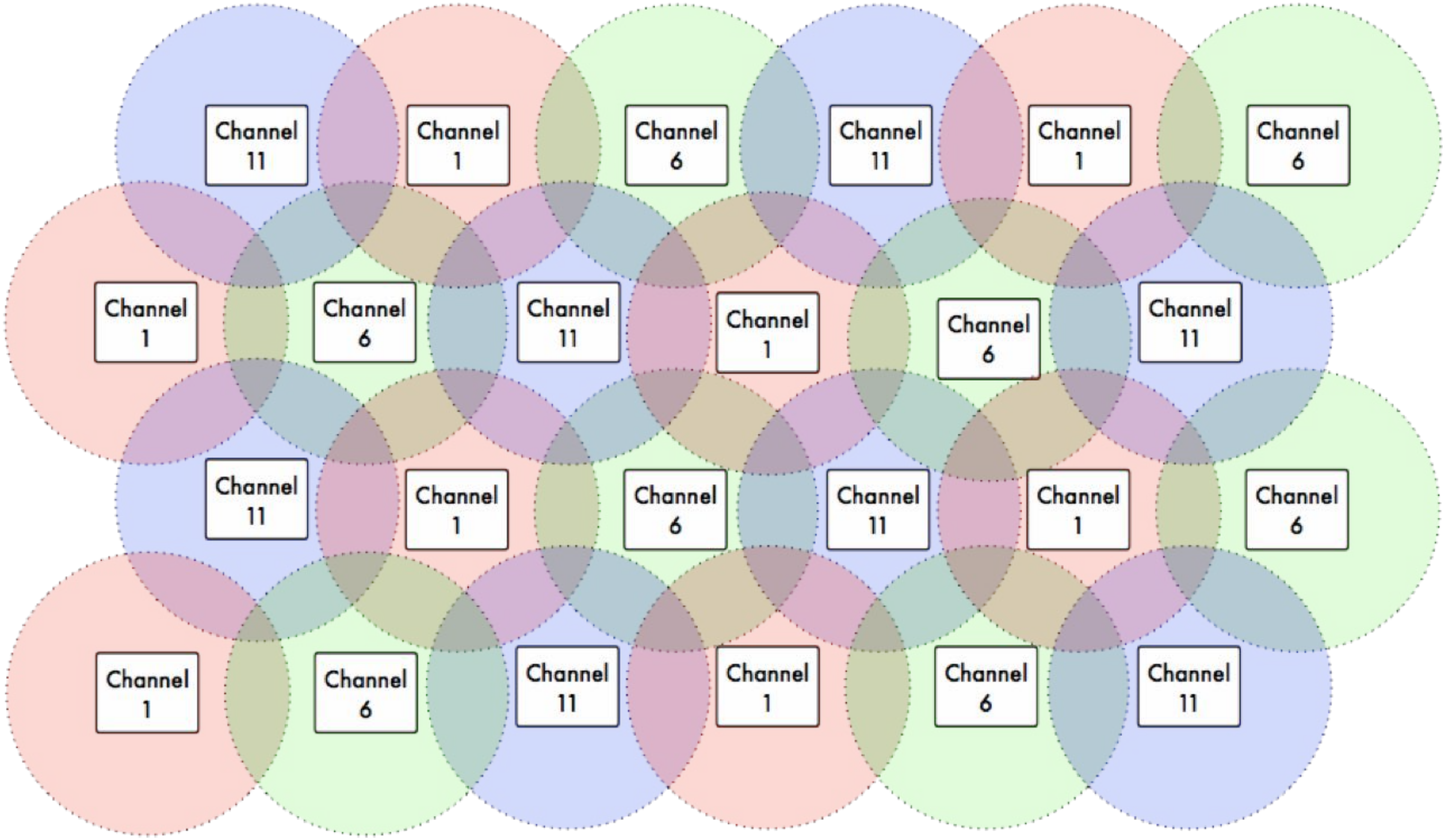
- Frequency bands are divided into channels
- 2.4 GHz has 14 overlapping channels of 22 MHz each
- 5.8 GHz has 5 non-overlapping channels of 20 MHz each
- Wi-Fi devices must use the same channel
- Wi-Fi devices send and receive on the same channel
    - This kind of connection is called ***half-duplex***.

Non-Overlapping Channels 1,6,11,14



- Not All Countries Allow All Channels!
- Channel 14 is not allowed in the USA

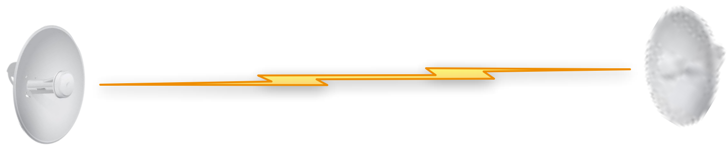
Three Channel Coverage Design



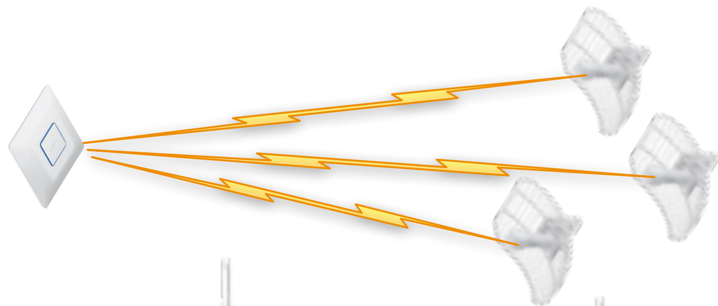
Remember this is theory!
Reality does not look this nice.

Wireless Network Topologies

- Point to Point



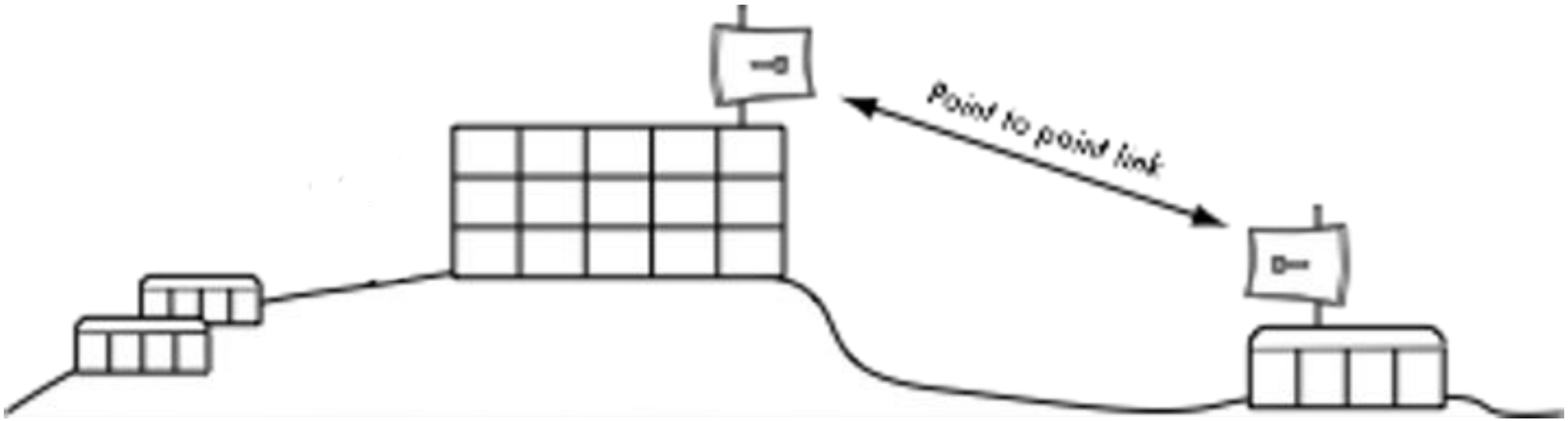
- Point to Multipoint



- Multipoint to Multipoint

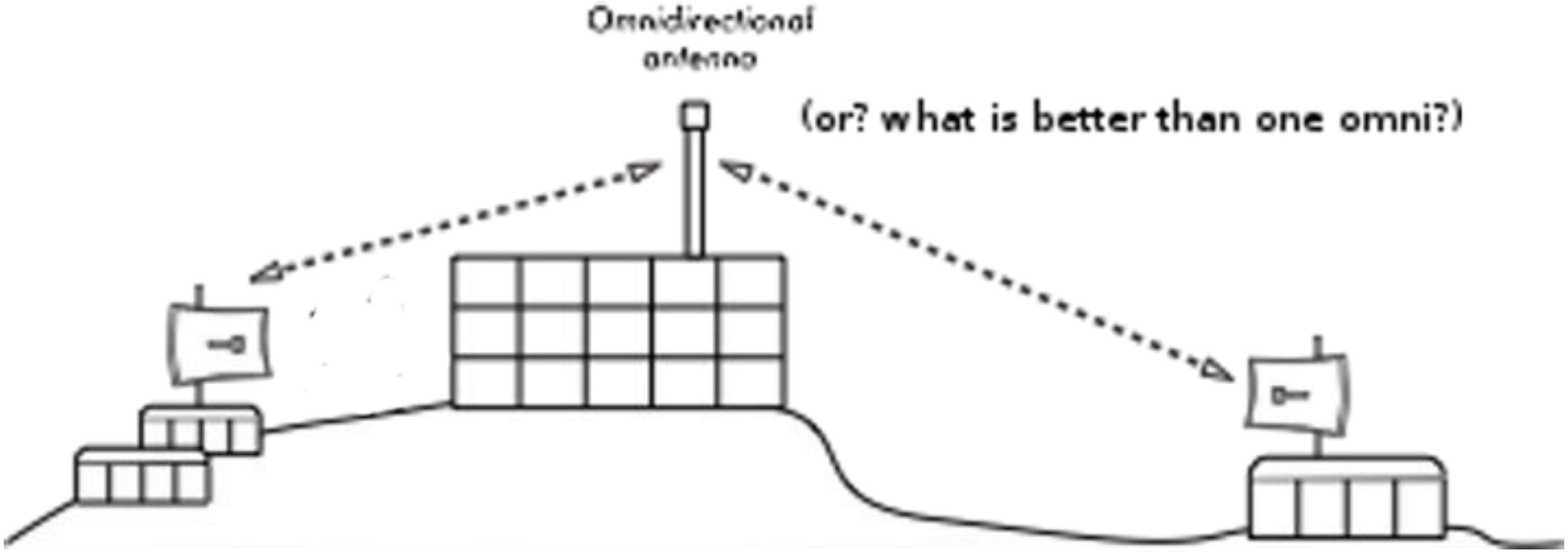
Point-to-Point

- The simplest connection is a ***point-to-point*** link
- These links can work over great distances



Point-to-Multipoint

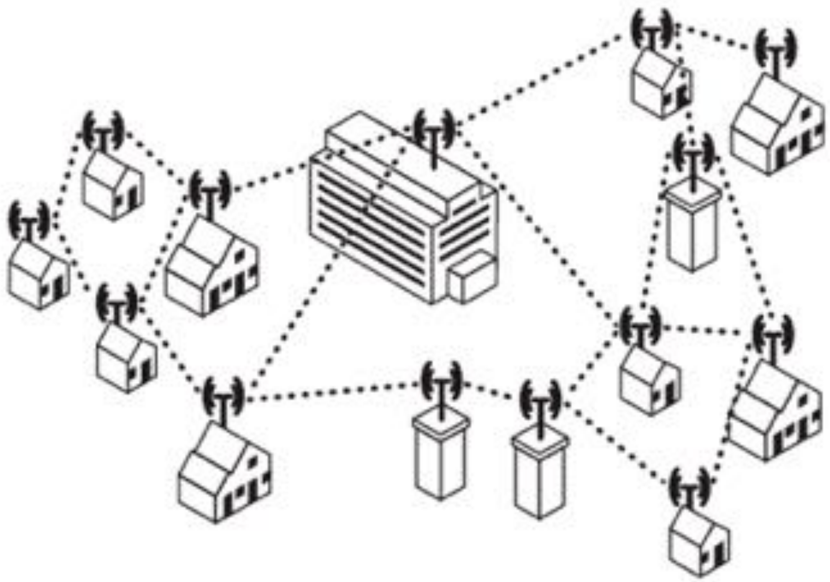
When more than one node communicates with a central point, this is a ***point-to-multipoint*** network.



Multipoint-to-Multipoint

Any node ***may*** communicate with any other

This can be an “ad-hoc” or a planned **mesh**



Wi-Fi Radio Modes

- Wi-Fi devices can operate in one of these modes
  - ***Master*** (access point)
  - ***Managed*** (also known as ***client*** or ***station***)
  - ***Ad-hoc*** (used for mesh networks)
  - ***Monitor*** (not normally used for communications)
- Only one mode is supported at a time

Master (Infrastructure) Mode

Master mode (also called AP or infrastructure mode) is used to provide an infrastructure with an access point connecting different clients. The access point creates a network with a specified name (called the ***SSID***) and channel, and offers network services on it.

WiFi devices in master mode can only communicate with devices that are associated with it in ***managed*** mode.

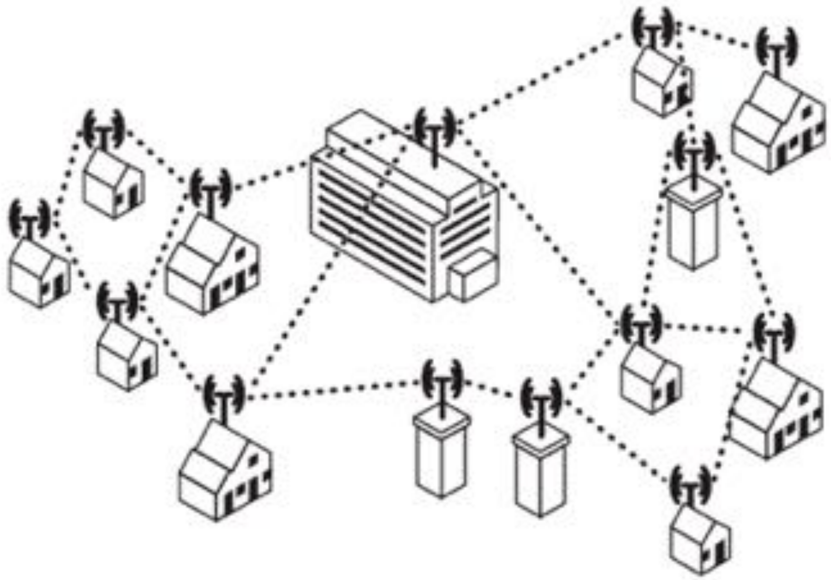
Managed Mode

Managed mode is sometimes also referred to as ***client mode***. Wireless devices in managed mode will join a network created by a master, and will automatically change their channel to match it.

Clients using a given access point are said to be ***associated*** with it. Managed mode radios do not communicate with each other directly, and will only communicate with an associated master (and only with one at a time).

Ad-Hoc Mode

Ad-hoc mode is used to create one to one connections and mesh networks.
In this case, there is no master and client.
Devices must must agree on a network name and channel.

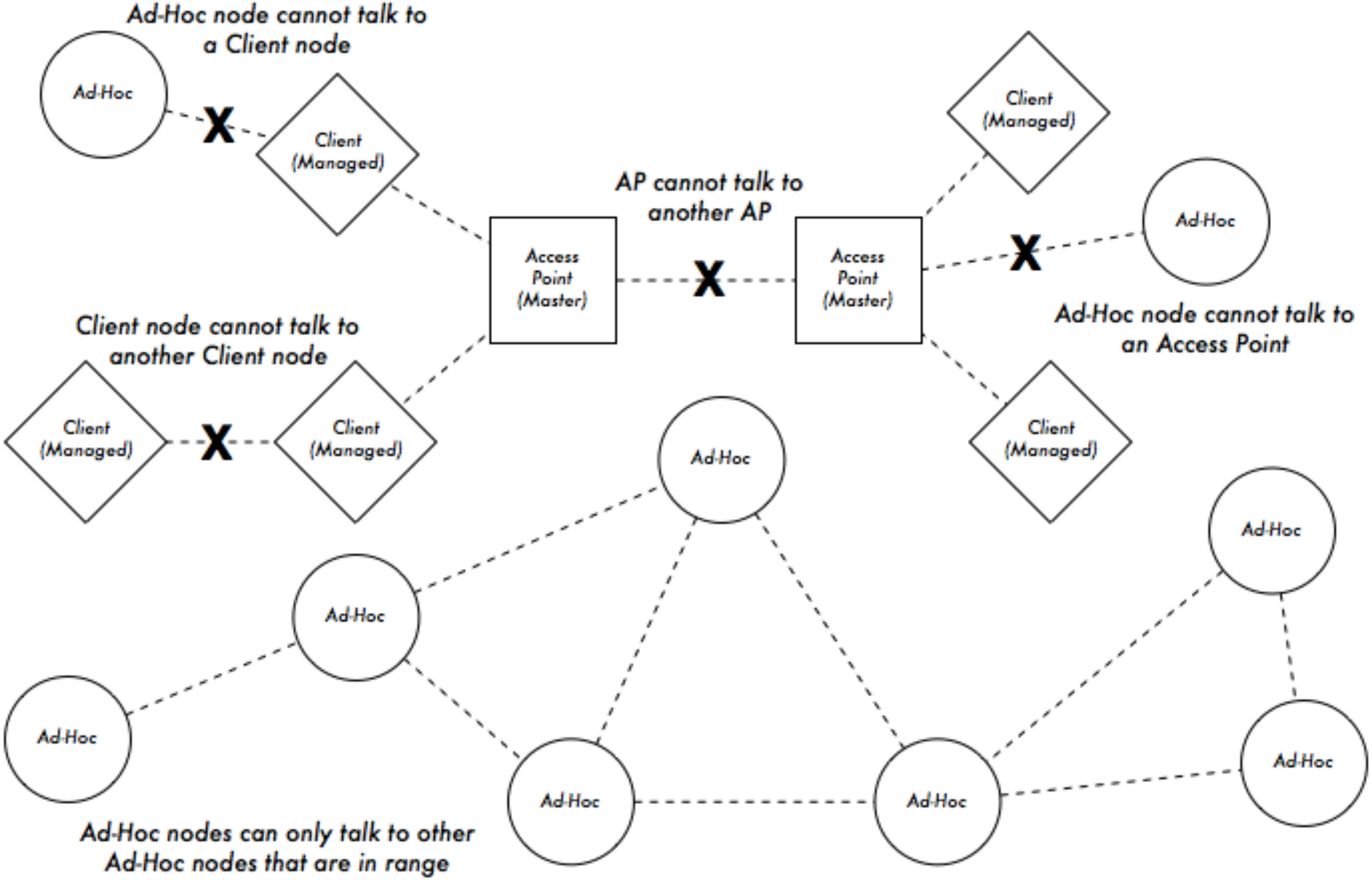


Monitor Mode

Monitor mode is used to passively listen to all radio traffic on a given channel. This is useful for:

- Analyzing wireless link problems
- Observing spectrum usage
- Security maintenance tasks

Wi-Fi Radio Modes In Action



Wireless Distribution System (WDS)

- Access Points can communicate with each other!
- But there can be many problems
  - Cross-vendor compatibility
  - Maximum throughput is halved at each hop
  - Typically supports only 5 APs at a time
- WDS is rarely needed and not recommended.

Wi-Fi Does Not Route Traffic

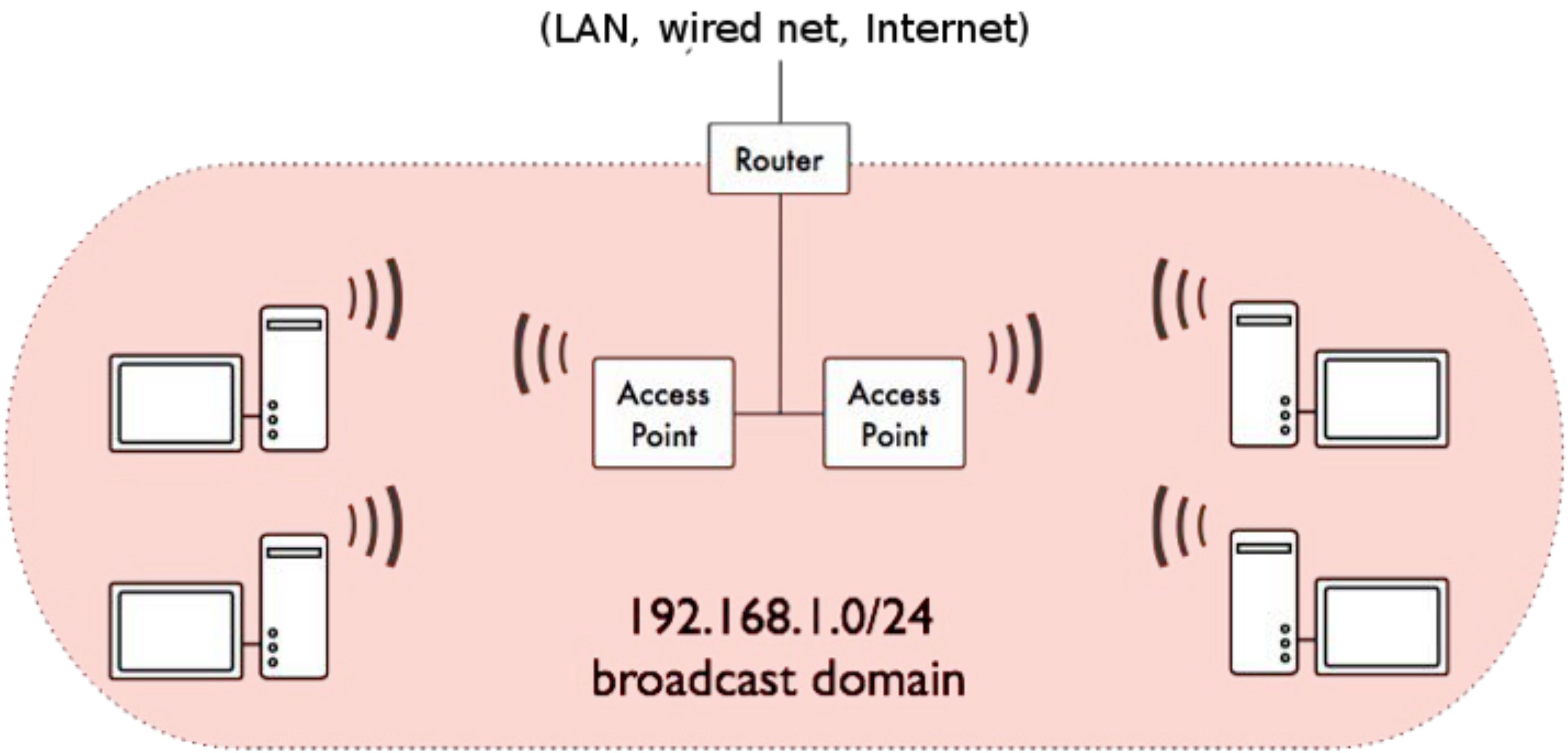
- 802.11 Wi-Fi provides a link-local connection.
- Wi-Fi does ***not*** provide any routing functionality!
- Routing is implemented by higher level protocols.

TCP/IP Protocol Stack	
5	Application
4	Transport
3	Internet
2	Data Link
1	Physical

Bridged Networking

- Appropriate for simple networks
- **Advantages**
  - Very simple configuration
  - Roaming works very well
- **Disadvantages**
  - Efficiency falls as nodes are added
  - All broadcast traffic is repeated
  - Unstable on larger networks

Bridged Access Points



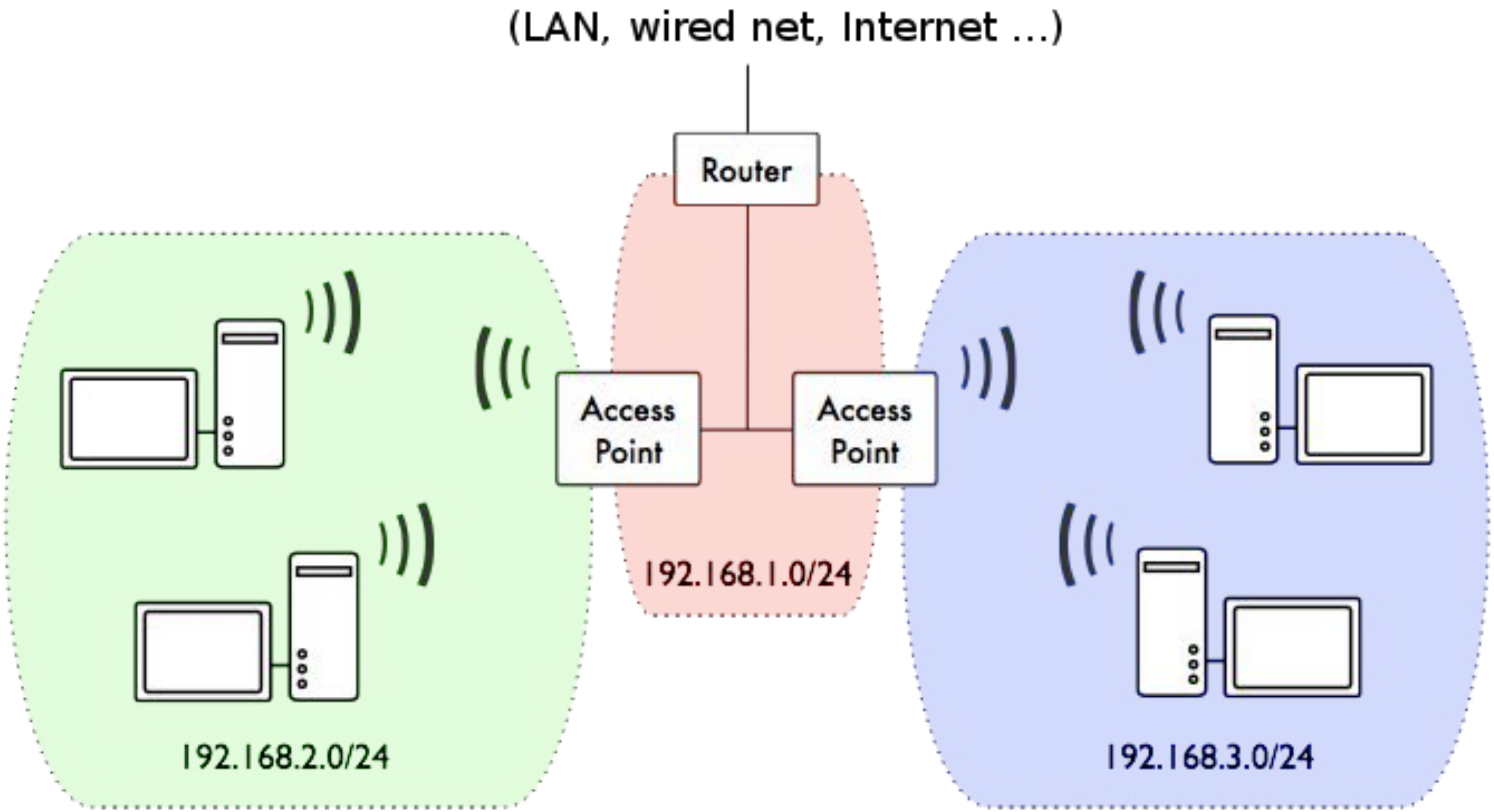
Routed Networking

- Route between nodes for large networks
- Static Routing
  - Point-to-point links
  - Simple networks
- Dynamic Routing
  - RIP is a very old protocol with many problems
  - OSPF is a modern protocol for dynamic routing
  - RIP and OSPF do not perform well on unstable backbones
- Mesh Routing
  - Standards & proprietary protocols available
  - Can perform better than OSPF on unstable networks

Routed Networking

- Appropriate for large, campus, or metro networks
- **Advantages**
  - Limited broadcast domains
  - More efficient use of radio bandwidth
  - Many protocols & bandwidth management tools
- **Disadvantages**
  - More complex configuration
  - Roaming between APs is more difficult

Routed Access Points



Frequently Asked Questions

Frequently Asked Questions

How fast?
How far?
How many clients?
Are all my devices compatible?
What should I buy?

What We Can Do Today

- 10 Mbps over 1 km for $100
- 300 Mbps over 5 km for $200
- 1 Gbps over 10 km for $2000
- Up to 100 km distance (and beyond)
- Simple hotspots for <$50 per AP
- Managed access networks for $100 per AP

How Many Clients?

- How many end users on one AP?
  - 100 moderate users
  - 10-30 heavy users
- Limitations
  - Radio Spectrum
  - Slowest Clients
  - Backhaul & Core Network
  - Access Point CPU / Packets Per Second

Problems For The Future

- Bring Your Own Device (BYOD) means 2-4 devices per person
- Power over Ethernet (PoE) at 100mbps is no longer enough
- 1gbps Ethernet is not enough for some 802.11ac access points
- Network security is difficult, and getting more difficult
- How will you manage your users?

Learning More

Network Startup Resource Center
http://nsrc.org
ICTP Wireless | T/ICT4D Lab
http://wireless.ictp.it/
Wireless Networking for the Developing World
http://wndw.net
ICTP UNESCO Wireless Training Kit
http://140.105.28.115/groups/wtkit/

Thank you!

Questions and comments?

Email your workshop mailing list!

Wireless Authentication

Network Startup Resource Center
www.nsrc.org

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Network Startup Resource Center

What is Authentication?

- Verifying the claim that an entity is allowed to act on behalf of a given known identity
- More simply:
  - Is this person says who they say they are?
  - Can they prove it
    - for example, with password, signature?
  - In our case, the entity is the software, acting on behalf of the user controlling the computer.

Why Is It So Complicated?

- I am on a computer. Am I its owner?
  - Device is not the same as person.
- I am a network administrator
  - Should I have access to the finance system?
- I am connecting to the network from home
  - Should I have access to all my work resources?

Authentication Core Concepts

- These are all different concepts:
  - Confidentiality
  - Access Control
  - Authentication
  - Authorization

Confidentiality

Ensure that only those who should have access to information can indeed do so (usually encryption)

Authorization

Authorization defines what an entity *(a user, a device)* is authorized *(allowed)*, to access

- Which networks (ACLs/filters)
- Which systems, which files ? (FS ACLs, permissions)
- When can they do that (time policies) ?
- Can they run an application or access a service ?

Access Control

Access control is the mechanisms by which rights &restrictions are controlled & enforced

Why Do We Authenticate?

- We want to know: WHO, WHERE(*), WHEN
  - Which user?
  - What AP did they associate with?
  - When did they log on ?
  - What IP number did they have?
- PSK (Pre-Shared Key) cannot tell us this.
  - Keys can be shared between users
  - We can’t know who, where, or when.

Authentication Solutions

- We recommended two ways to do this:
  - Captive portal
  - 802.1X (EAPoL and EAP-TLS) (Preferred)
- Your choice depends on
  - The size of your organization
  - The maturity of your IT systems
  - Your human resources
  - Available user stores, databases
    - For example, Active Directory or LDAP

Captive Portals: Positive

- Popular (public areas, airports, hotels…)
- Flexible
- Self-explanatory (web page), can enforce AUP (Acceptable Use Policy) validation
- Relatively easy to implement

Captive Portals: Negative

- Not transparent
- Depend on browser
- Not standardized (different looks, different credentials, …)
- Requires regular re-authentication (disruptive)
- Often unreliable and easy to break

Captive Portals: Redirection

- Any of the following methods can be used:
  - HTTP silent redirection
  - HTTP 30x redirect
  - IP hijacking
  - DNS hijacking
  - Certain URLs may be allowed
    - e.g. Information, help, use policies pages

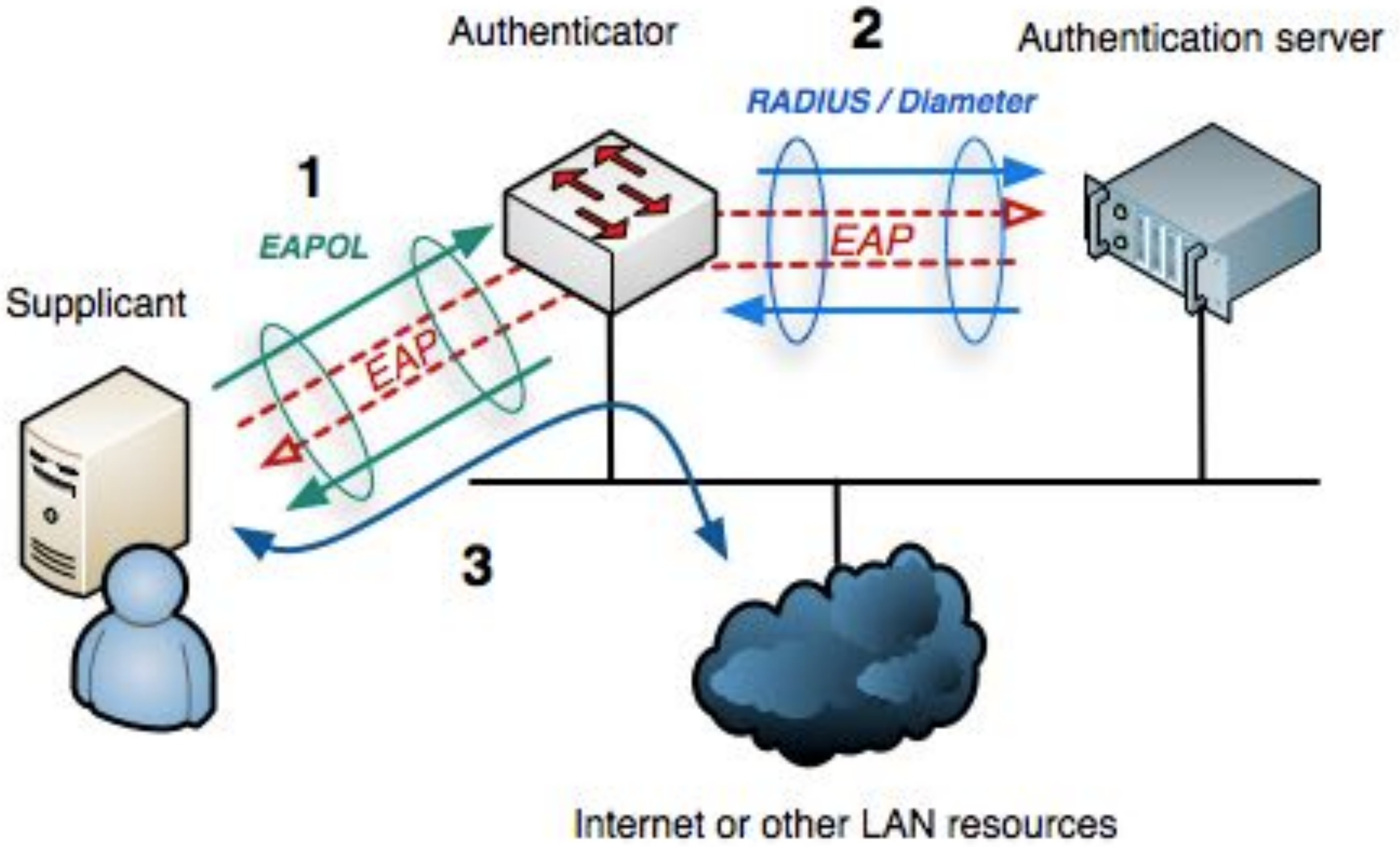
Captive Portals: Vendors

- Many vendors and open source projects
  - CoovaChilli, CoovaAP
  - WiFidog
  - M0n0wall, pfSense
  - zeroshell
- Many networking vendors offer captive portals
  - Aptilo, Aruba, Cisco, HP, Mikrotik, Ubiquiti

802.1x/EAP (WPA2 Enterprise)

- Originally designed for wired networks (EAPoL)
- Modified for wireless networks (RFC5216)
- Layer 2 protocol with 4 states:
  1. Initialization (all traffic including DHCP)
  2. Initiation (authenticator sends EAP-Requests, and client responds with EAP-Response-Identity)
  3. Negotiation of a method of authentication
  4. Authentication if negotiation succeeds
- Traffic is allowed through

802.1x/EAP – How does it work



Source: Wikipedia

802.1x/EAP

- Positive
  - Transparent for Applications
  - In-line: does not require interaction with upper layers like DHCP, IP, HTTP to function
  - Standardized for both wired and wireless LANs
- Negative
  - More challenging in deployment
  - Requires external authentication server (RADIUS)

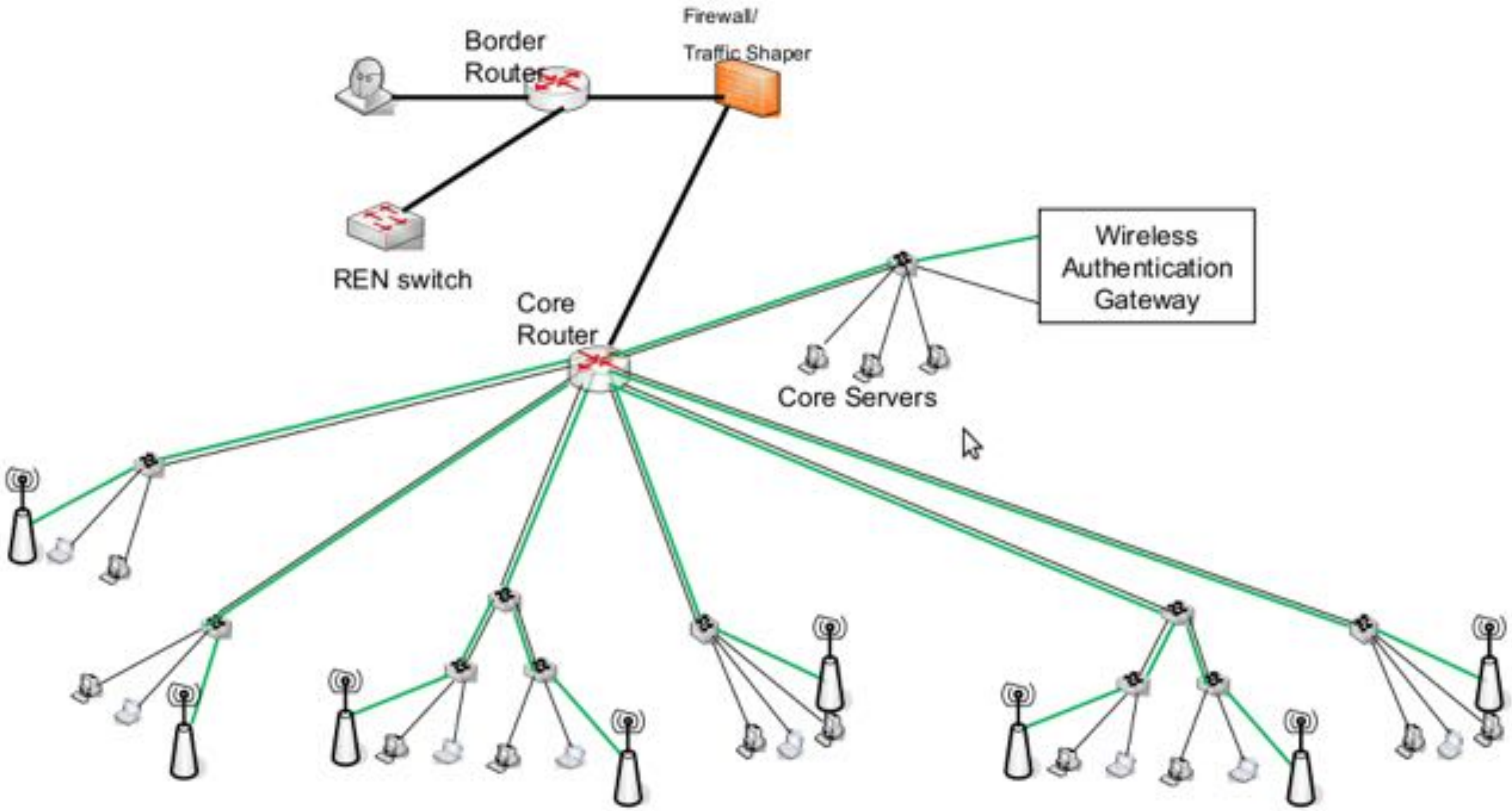
802.1x & EAP vs Captive Portals

- **Captive Portals**
  - Intuitive & easy for first time users and guests
  - Can guide guests, provide information & help
- **802.1x**
  - Is streamlined & standardized for regular access
    - Making it preferable for known users
  - But there’s overhead for first-time users
- **Combining both may be useful**
  - 802.1x can be used on all LAN/WLAN
  - Captive portals can be used on guest Wi-Fi SSIDs

802.1x & EAP vs Captive Portals

- 802.1x operates at Layer 2
- Captive Portals operate at Layers 3-7
- Both need authentication back-ends:
  - SQL or LDAP/Active Directory
  - Can be local flat text file
    - (only for small organizations, or as start/test)
- Back-ends can be shared between technologies
  - (captive portal + 802.1x)
- **RADIUS** can use any of the above solutions

Authentication in the Core Network



802.1x Security Problems

- 802.1x or WPA2/EAP is the recommended authentication option, but has security problems
- Outer tunnels rely on TTLS/SSL certificates
  - These are vulnerable to man-in-the-middle attacks – if the client device does not properly check the certificate, then it will give its credentials to ANY AP, e.g. rogue APs
- Inner tunnel authentication is MSCHAP2
  - MSCHAP2 is known to be compromised

802.1x Security Problems

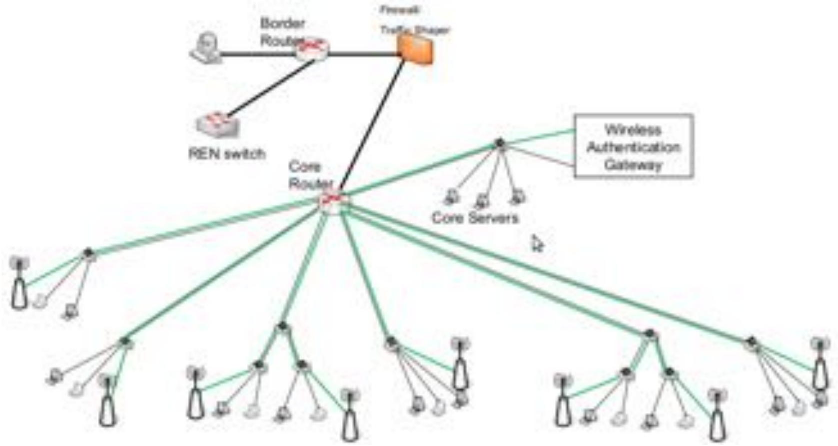
- Client devices that do not check certificates…
  - Will give their credentials to any AP, even a rogue one!
  - Are vulnerable to man-in-the-middle attacks.
- Nothing can protect clients that don't check…
  - CN (Common Name) or CA (Certificate Authority)
- However we can protect our networks
  - We can enforce the best possible client configuration, for example using the eduroam CAT tool. https://cat.eduroam.org
  - See also security recommendations on https://wiki.geant.org/

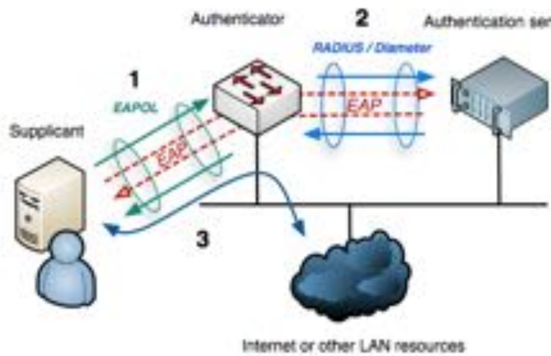
802.1x MITM Attack

- Get user to associate to rogue AP and start handshake & Authentication process
- Packet dump everything
- Analyze the traffic, isolate the handshake
- The outer tunnel is easy – as the attacker owns certificate and keys
- The inner tunnel (typically MSCHAP2) can be cracked (via offline or online services)

NSRC Recommends

- User store in LDAP/AD, e.g. OpenLDAP
- RADIUS, e.g. FreeRADIUS
- Despite the security problems…
- **802.1x remains the best option**
- Captive Portal is a valid second option





eduroam

A recommended addition to your campus networks authentication is eduroam:

An international roaming service for users in research, higher education and further education.

Learn more at:
eduroam.org

Building wireless core networks & point-to-point links

Network Startup Resource Center
www.nsrc.org

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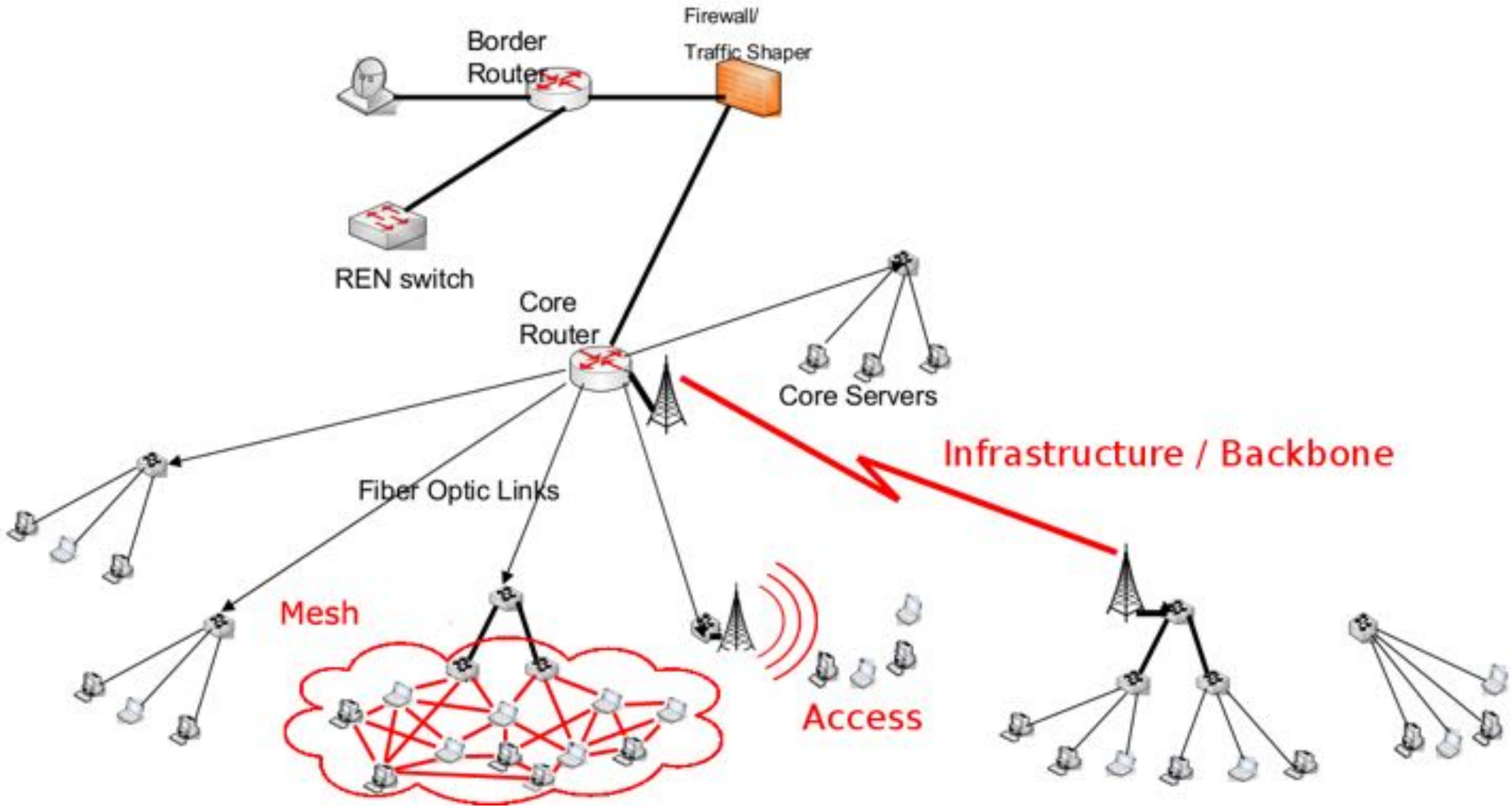
Roles of Wireless

- In integrated (campus) networks
  - Infrastructure / Backbone
  - Access / end user / hotspot
  - Mixed roles in Mesh Networks

Roles of Wireless



How Far Can We Go?

- When building infrastructure, key question:
    - How far can we go and still have sufficient bandwidth and stability?

How Far Can We Go?

- A standard AP (e.g. Ubiquiti Unifi) to a laptop:
  - a few hundred meters
- P-P Links with DIY Antennas (e.g. Cantenna):
  - 10 kilometers or more
- P-P Links with parabolic antennas:
  - 100 kilometers or more

World record: 382 km

Ermanno Pietrosemoli and his team,

Venezuela 2007, 2.4 GHz

Link Budgets

- Not all links need to be world records
- But all links need planning
- The key to planning is a Link Budget
- Budget = Sum of all gains – sum of all loss

The Language of Link Budgets

- Some terms come from basic radio physics
  - Free space loss, Fresnel zones, dB
- Some from antenna theory
  - Gain, radiation patterns, EIRP
- Others are specific to radio linking
  - Link Margin, RSSI, Transmit Power

EIRP: Effective Isotropic Radiated Power

- Hold your hand one meter from a candle
  - You feel some warmth
- Put a reflector behind the candle
  - You feel twice as much warmth!
- EIRP is a measure of radiated power relative to an isotropic antenna.
- It’s the sum of TX power and antenna gain

Transmit (TX) Power

- Output from Radio
- Higher powers = lower modulation (less data)
- TX Power is always in data/spec sheets
- For wireless typically 20-30dBm

Cable Loss

- As per Antennas & Waveguide Unit
  - Longer cables = more loss
  - Higher frequencies = more loss
  - Thinner cable = more loss
- Add at least .25 dB loss per connector
- Add 1 dB loss per lightning arrestor
- Keep your cables as short as possible

Antenna Gain

- Depends on Frequency
- Smaller Waves = More gain from same area
  - 300 mm antenna at 2.4 GHz = ~ 16 dBi
  - 300 mm antenna at 5.7 GHz = ~ 23 dBi
  - 250 mm antenna at 60 GHz = ~ 40 dBi
- Antenna gain directs power, does not amplify!
- Equal contribution to TX power and RX gain

RSSI: Received Signal Strength Indicator

- Commonly seen as “RSSI”
- A measurement of the received power
- Expressed in dBm (decibel milliwatts)
- Typically a negative number. Higher is better
- You might see:
  - -8dBm on a 40 gbps fibre optic link
  - -66dBm on 1.5 gbps radio link at 24 GHz

Link Margin

- How much signal is left after all loss & gain
- Most links require a margin of 20dB
  - Higher signal to noise = better performance
- Links that will fade (rain, thermal) need more

Free Space Loss

- Proportional to square of distance and square of frequency

- ***FSL*** *(dB) = 20 x log[4π x distance/wavelength]*

  – *where distance and wavelength are in the same units*

- Free space loss is pure geometry – it has nothing to do with absorption, air, fog, rain or any obstacles!

Free Space Loss

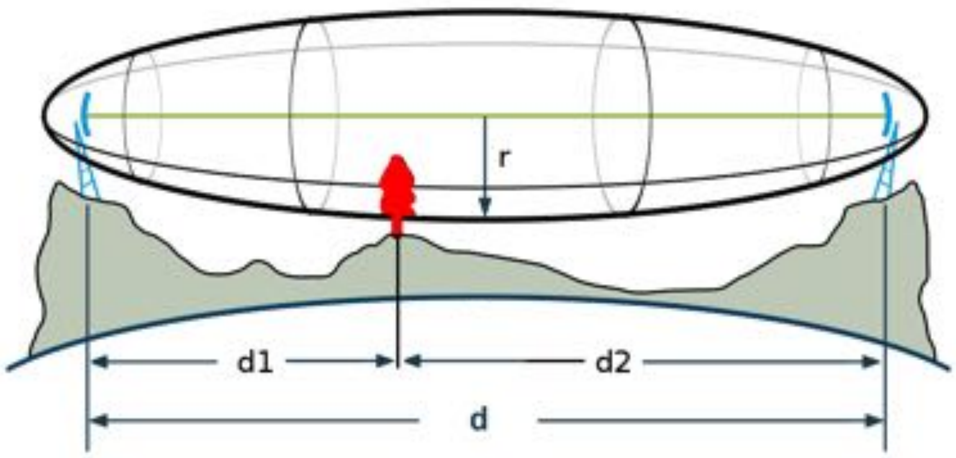
- 20 x log[4π x distance/wavelength]
- where distance and wavelength are in the same units
- Free space loss is pure geometry – it has nothing to do with absorption, air, fog, rain or any obstacles!

Absorption & Reflection

- Trees, bushes, buildings, cars, people
  - We can't always avoid them
- Try to keep the Line of Sight free
- Obstructed paths will work, however
  - Lower frequencies will work better
  - Lower modulations & speeds necessary

Fresnel Zone

- Obstacles within the Fresnel Zone might reflect waves towards the receiver.
  - This can both decrease & increase radio signal
- Even earth curvature can obstruct the Fresnel Zones



Licensed under the GFDL by Averse - http://en.wikipedia.org/wiki/File:FresnelSVG.svg

Fresnel Zone Calculation

For d = link distance, d_1, d_2 = distances to obstacle in meters, f = frequency in MHz, r = radius of zone in meters

$$r = 17.31 * \sqrt{\frac{d1 * d2}{f * d}} \quad \text{or} \quad r = \sqrt{\left(\frac{\lambda * d_1 * d_2}{d}\right)}$$

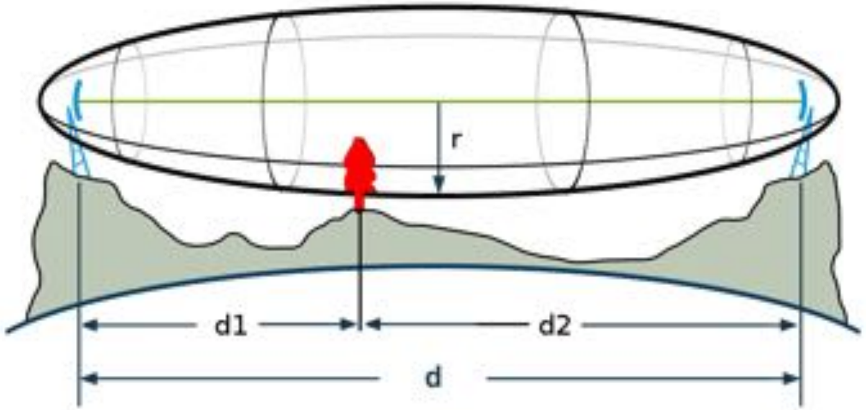
(wavelength and distances in same unit!)

for obstacle in middle d_1=d_2 = d/2

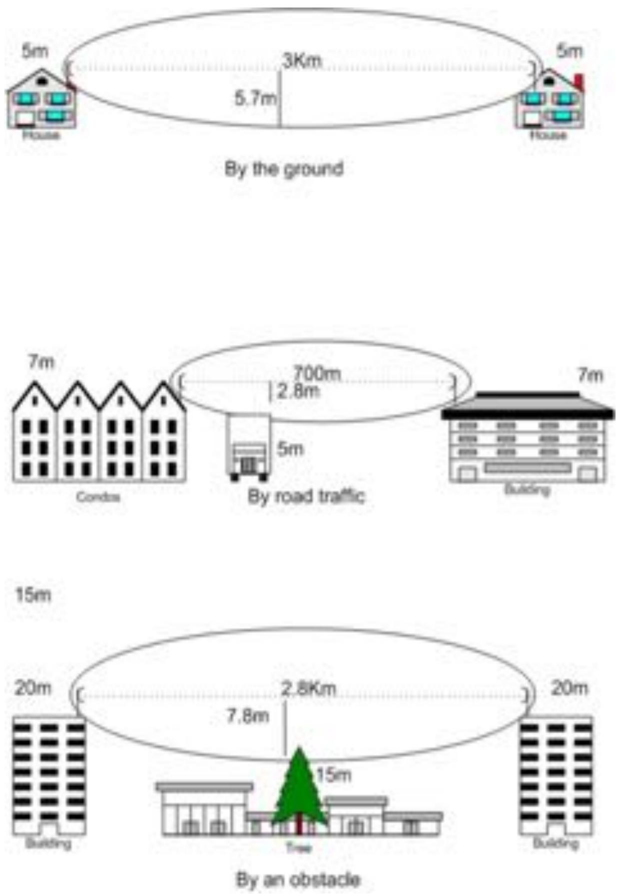
$$r = 17.31\sqrt{\frac{d}{4 * f}}$$

60% zone:

$$r = 10.4\sqrt{\frac{d}{4 * f}} = 5.2\sqrt{\frac{d}{f}}$$



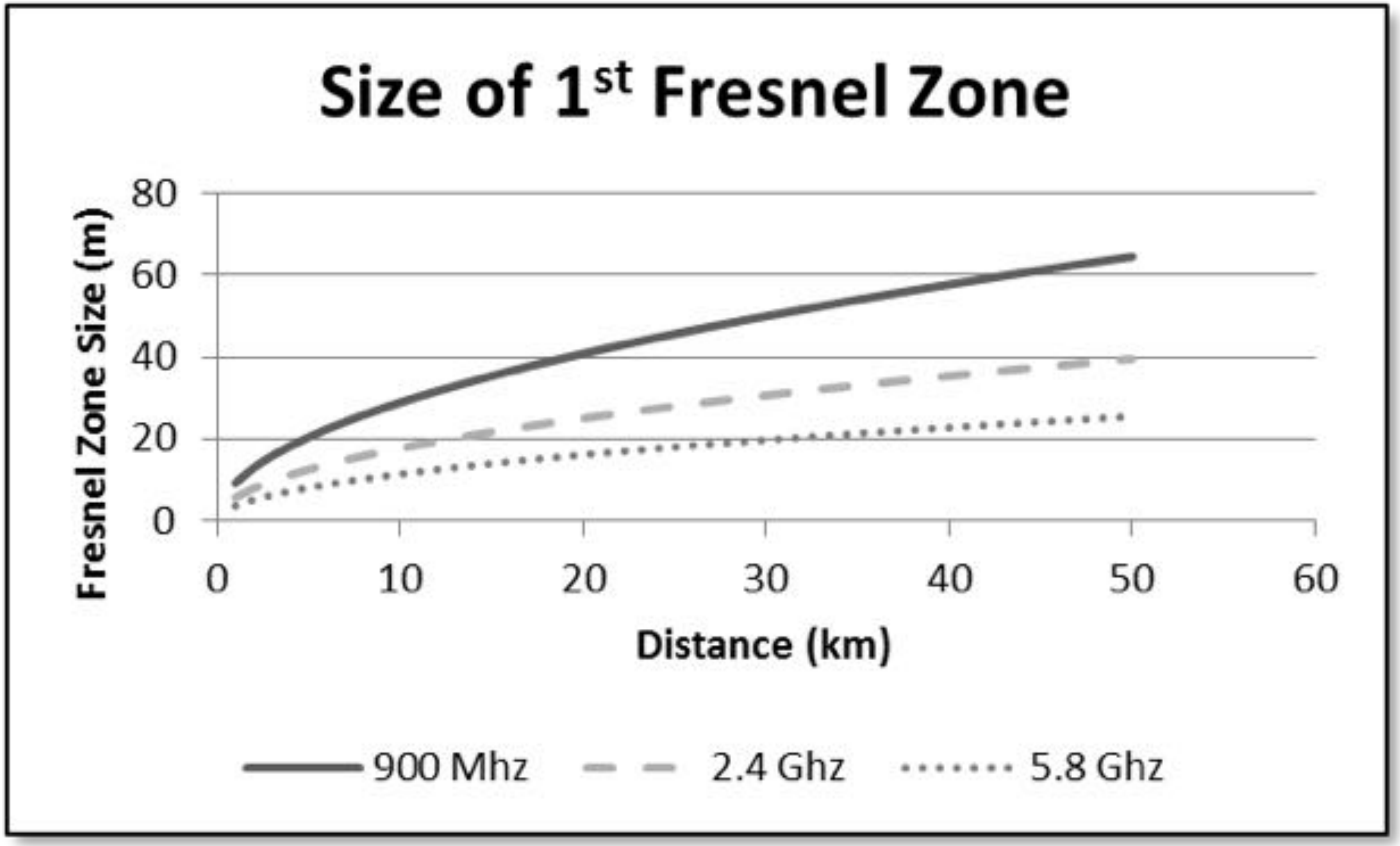
Fresnel Zone Interruptions



https://commons.wikimedia.org/

wiki/File:Fresnel_zone_disrupted.png

Fresnel Zones



source: www.wisptools.net

Antenna gain - RX

Antenna gains on the receiving side have the same impact as on the TX side

Cable losses - RX

Cable losses on the receiving side have the same impact as on the transmitting side

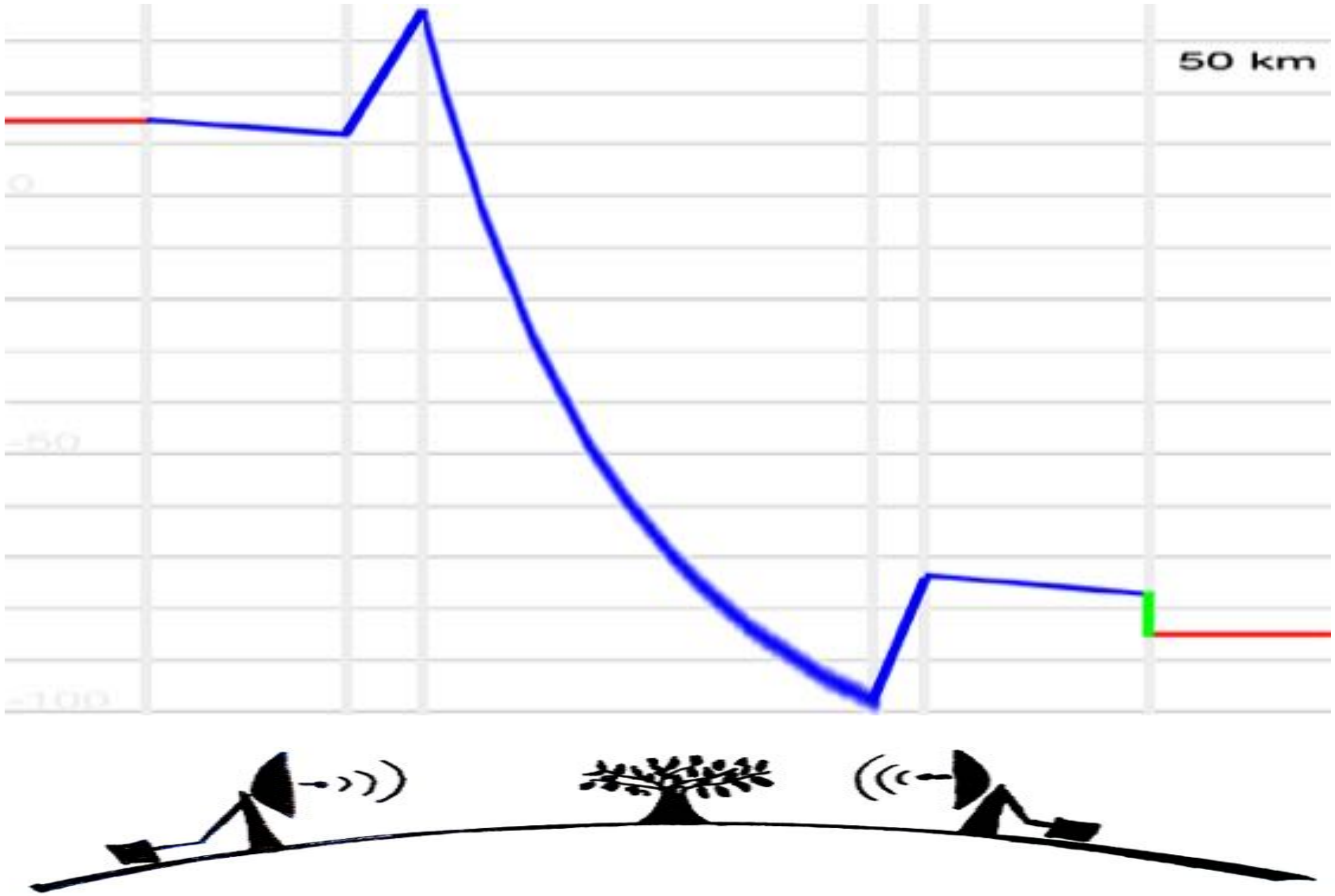
Receive Sensitivity

- Receivers need a minimum RSSI to operate
- This is the receive sensitivity
- Higher RSSI can allow higher modulations
- Device datasheets specify receive sensitivity
- Some Examples at 24 GHz (Ubiquiti Airfiber):
  - -66 dBm for 1.5 gbps
  - -72 dBm for 1.0 gbps
  - -80 dBm for 250 mbps
  - -88 = no link at all!

Link Budget Example 1

Transmit output	+ 015 dBm
Cable + Connectors	- 003 dB
Antenna TX	+ 024 dBi
FSL (50 km at 2.4 Ghz)	
	- 134 dB
Antenna RX	+ 024 dBi
Cable + Connectors	- 003 dB
Receive Sensitivity	- 085 dBm (subtract!)
TOTAL	**+ 008 dB Link Margin**

Link Budget Example 1

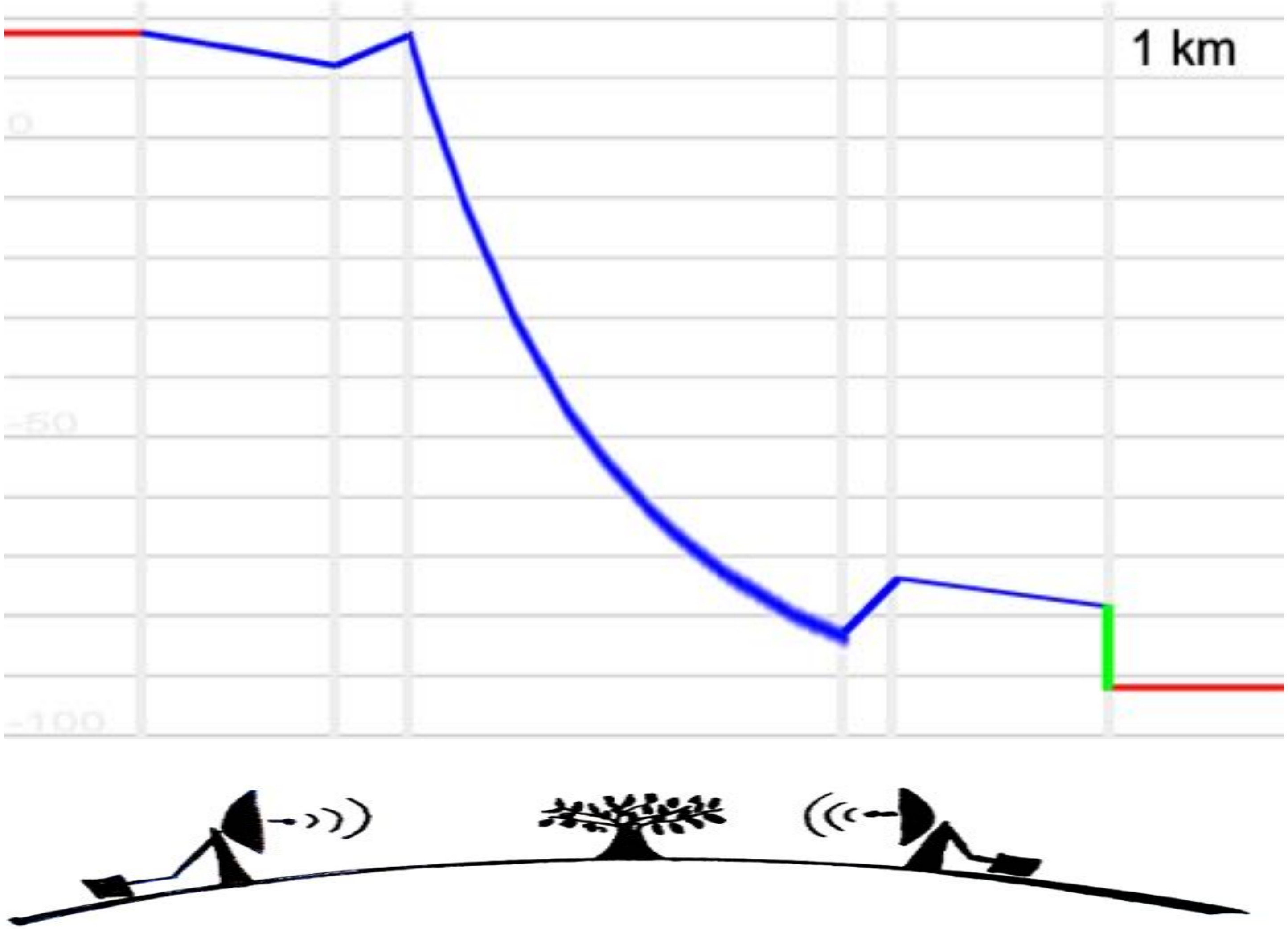


Link Budget Example 2

Transmit output	+ 018 dBm
Cable + Connectors	- 005 dB (low quality cabling)
Antenna TX	+ 005 dBi (an omni)
FSL (1 km at 2.4 Ghz)	
	- 100 dB
Antenna RX	+ 008 dBi (patch antenna
Cable + Connectors	- 005 dB (bad again :)
Receive Sensitivity	- 092 dBm (subtract!)

TOTAL **+ 13 dB margin**

Link Budget Example 2



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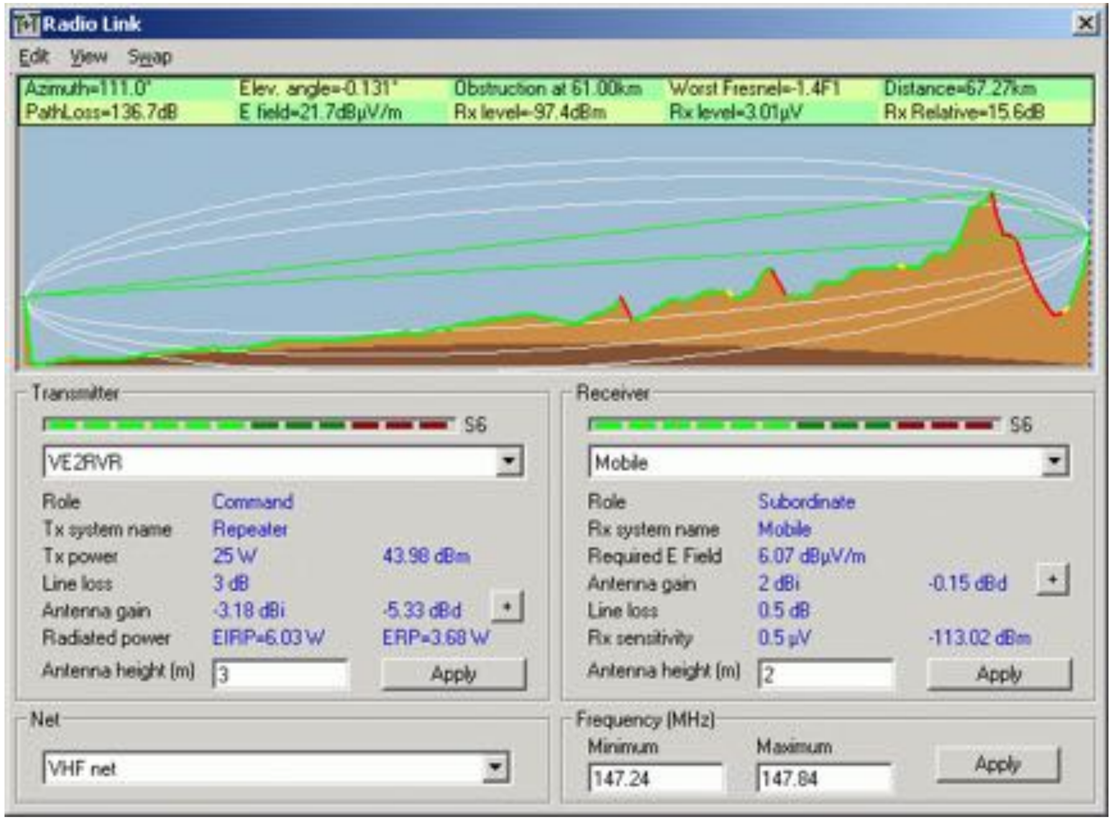
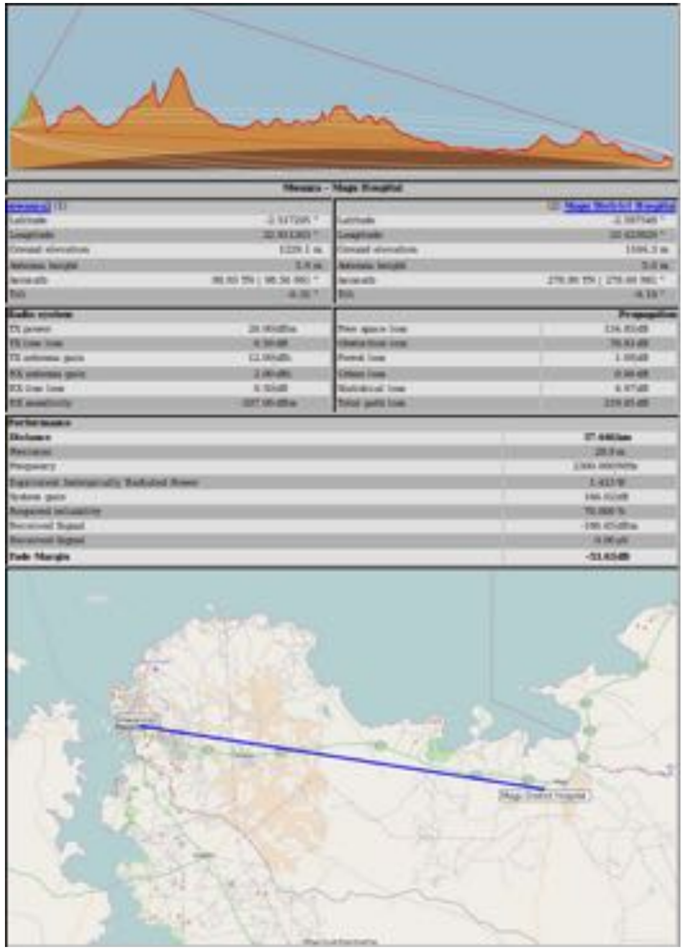
Link Simulation Software

- There are a number of very useful software tools for link and network simulation:
- RadioMobile: offline program and online http://www.cplus.org/rmw/rmonline.html
- CloudRF: https://cloudrf.com/
- Ubiquiti Airlink: https://airlink.ubnt.com/
- Vendor tools from Cambium, Mimosa, and more!

Radio Mobile

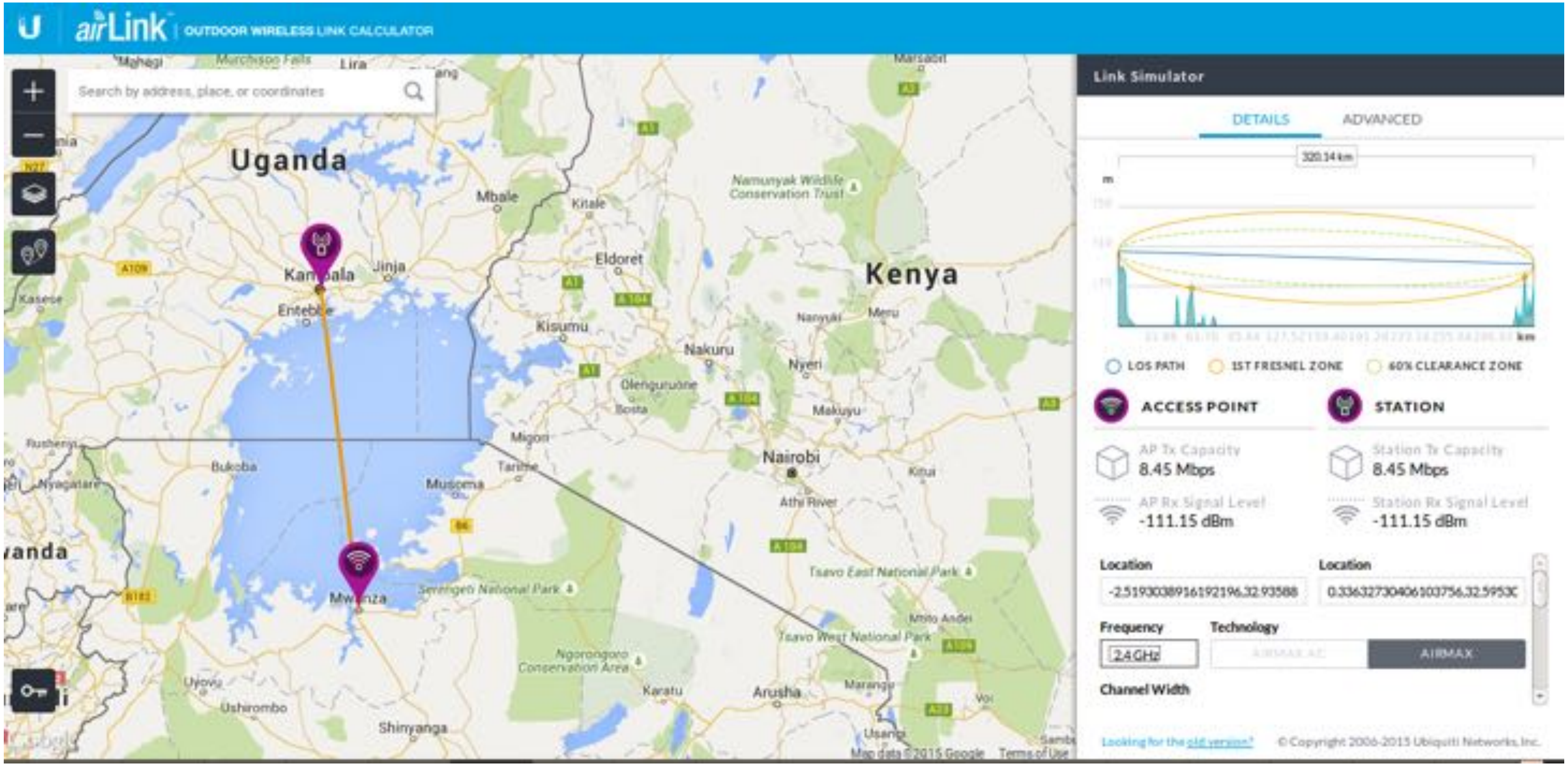


source: RadioMobile – www.cplus.org



source: wire.less.dk

Airlink



source: Airlink / https://airlink.ubnt.com

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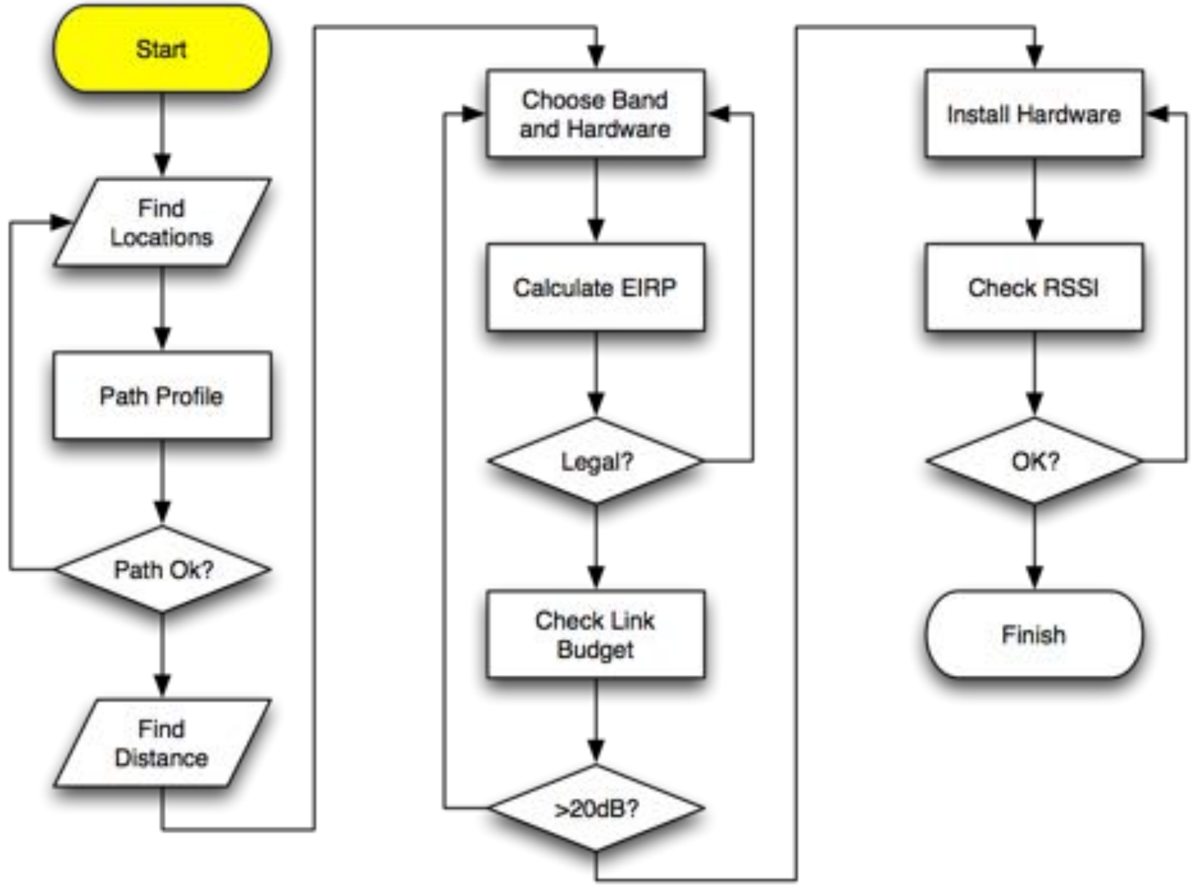
Limits of software link simulation

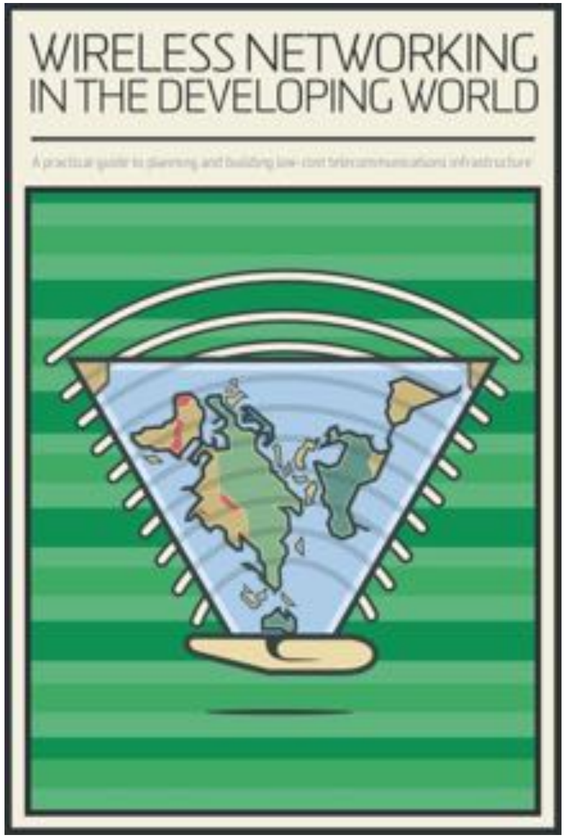
- These tools, made for long range link simulation, can also be useful for metro / campus links.
- Free tools do not model clutter (buildings, obstacles, vegetation), or small changes in terrain.
- Paid tools (WinProp, EDX, etc.) can model everything.
- When planning a link, nothing can replace a site survey and the human eye.

A useful planning diagram



source: Telco2 / http://telco2.co.nz/

You can read more here:



http://wndw.net