Basic Radio Physics

Network Startup Resource Center
www.nsrc.org

Last edit: Sebastian Büttrich, Sept 2015

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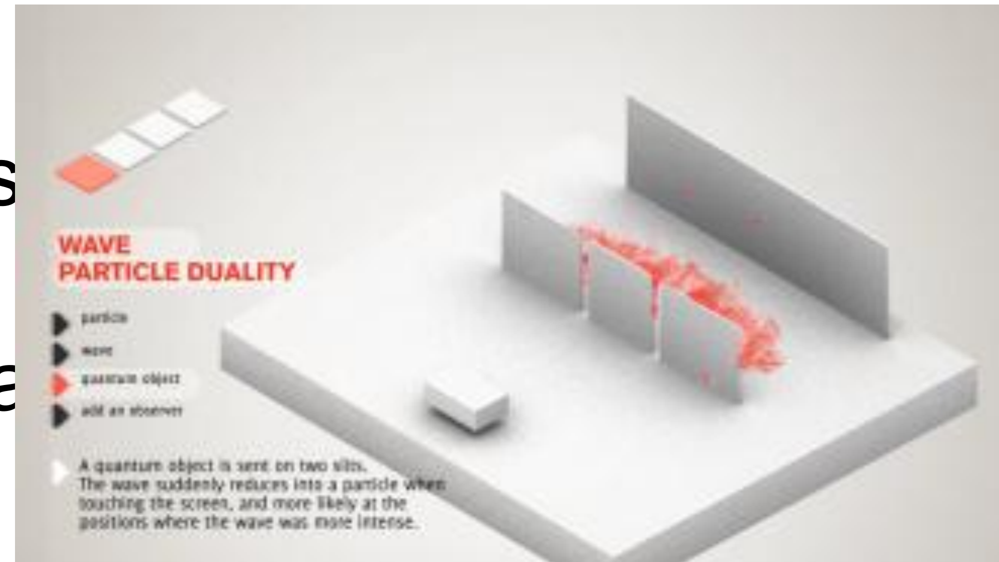
What are Radio Waves?

Radio Waves are Electromagnetic Waves -
Just like light, x-ray, radar.
In many ways, they behave like light -
But their frequency and wavelengths are very different.

What is light – wave, beam or particle?

Light is strange – or,
our description of light is



Light can be described a

A wave

A beam – like a straight line

A particle (a photon)

A quantum object

All these descriptions are "*correct*" – it just depends on what aspect you are looking at.

Interested? Read more here:

For our purposes, we best think of

waves

"2006-01-14 Surface waves" by Roger McLassus. Licensed under CC BY-SA 3.0 via Wikimedia Commons
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Waves

Mechanical waves are most familiar to us

- Sound, waves in water, ...

Electromagnetic Waves are different: they need no medium to travel in!

They transport energy through nothing

How we describe electromagnetic waves

$c = \lambda * \nu$

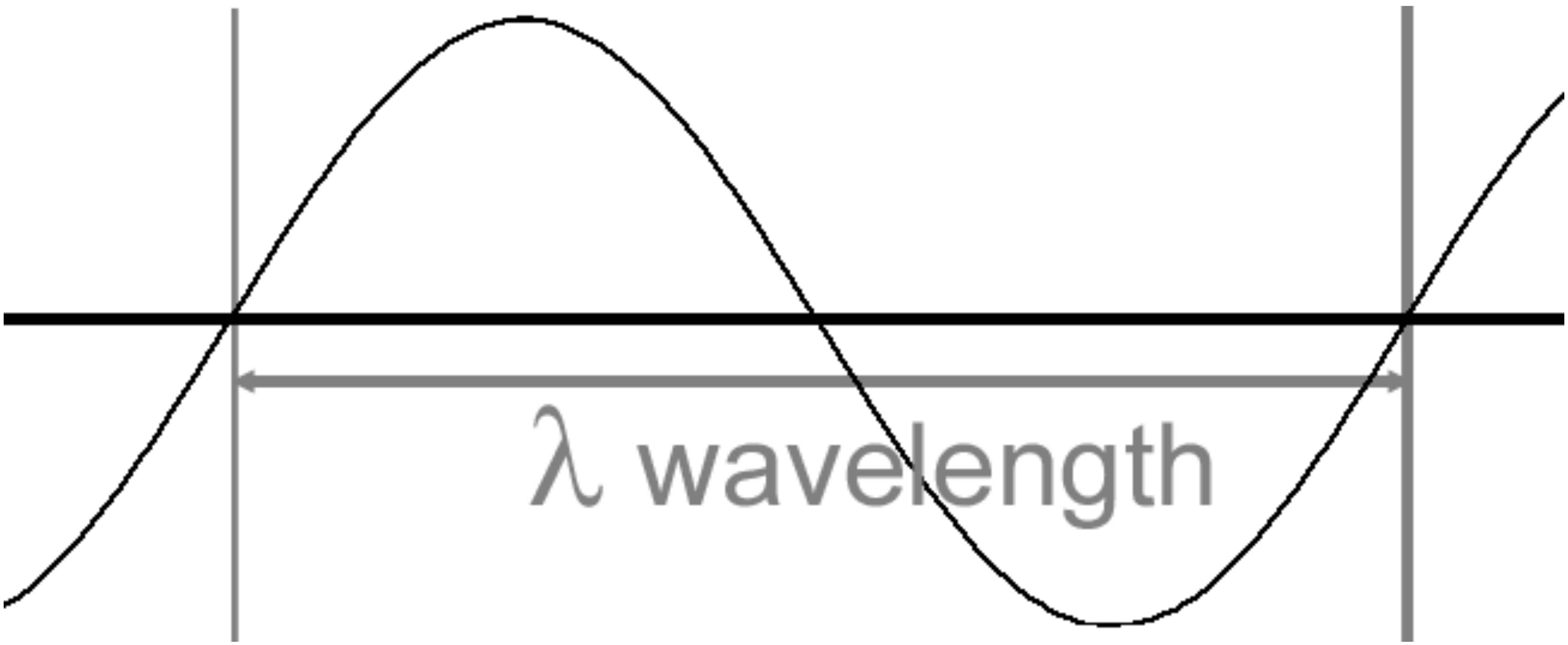
c is the speed of light (3×10^8 m/s = 300,000 m/s)

λ Lambda is the wavelength [m]

ν Nu is the frequency [1/s = Hz]

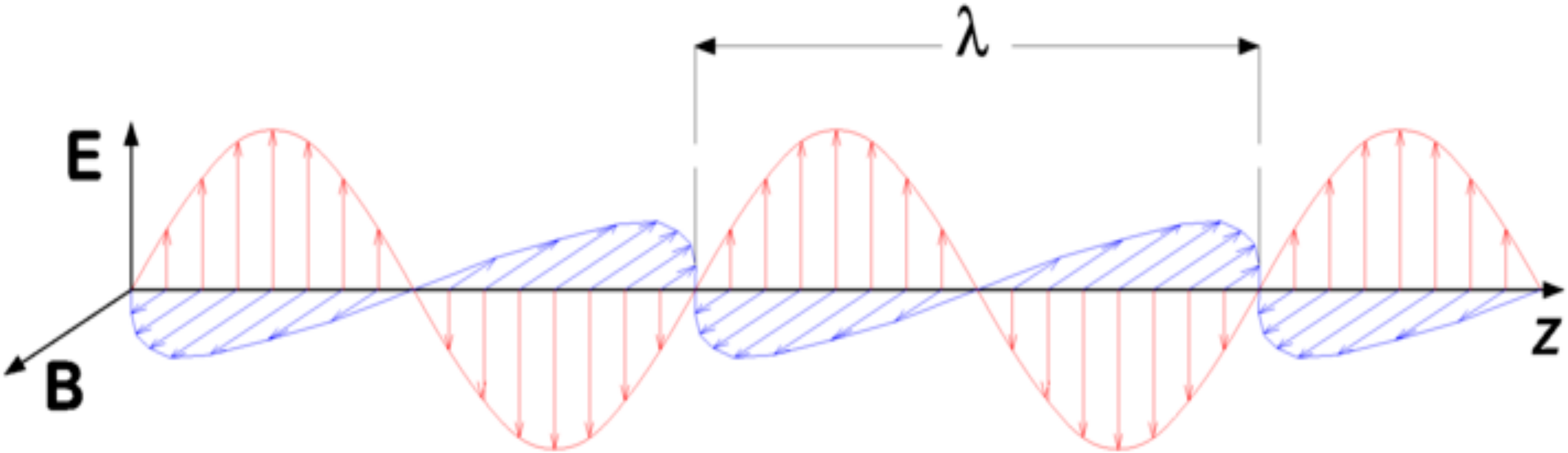
Light needs 1.3 seconds from the moon to earth, and 8 minutes from the sun - and how long for 100 km? Hint: time = distance / speed

A Wave



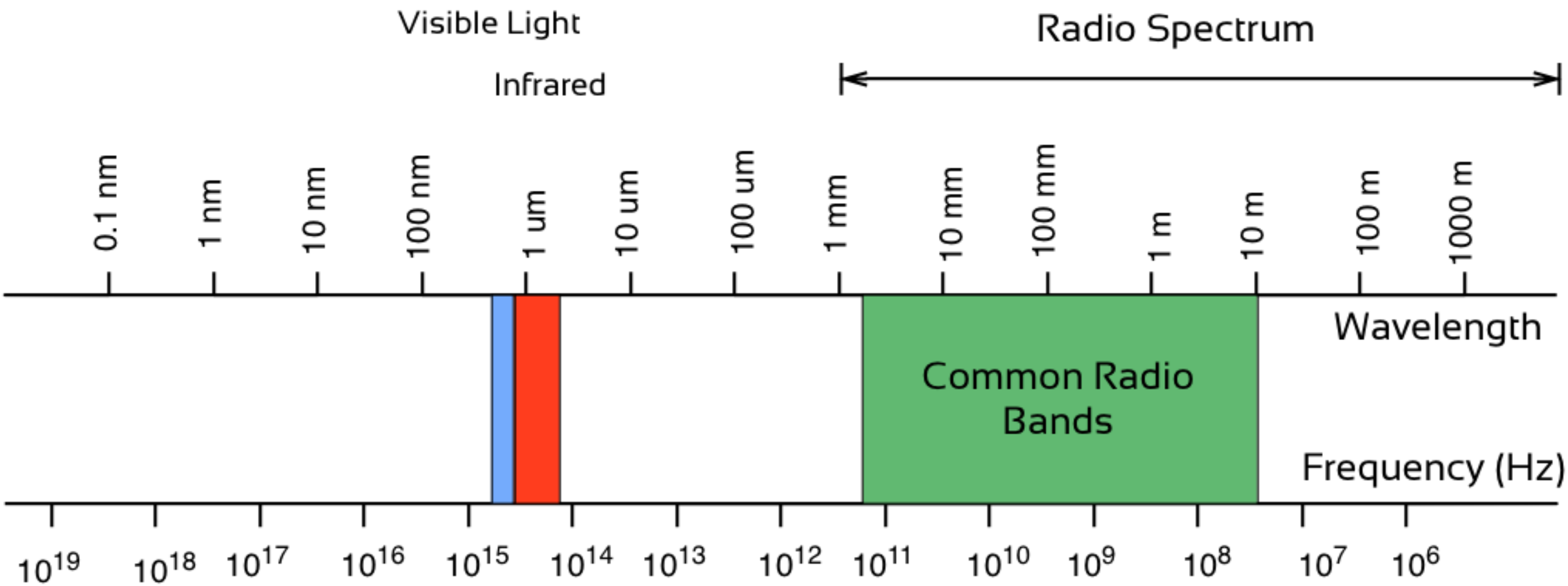
Wave Polarization

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



"Electromagnetic wave" by P.wormer Licensed under CC BY-SA 3.0 via Wikimedia Commons http://commons.wikimedia.org/wiki/File:Electromagnetic_wave.png#/media/File:Electromagnetic_wave.png

Electromagnetic spectrum



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?

Wireless Networking Frequencies

- ISM (license exempt) bands at
  - 2.4 GHz – 802.11b/g – 12 cm
  - 5.x GHz – 802.11a – 5...6 cm
- Other bands interesting to us
  - 470 – 790 MHz
  - 915 MHz
  - 3.5 GHz
  - 24 GHz
  - 60-80 GHz

What can happen to Radio Waves

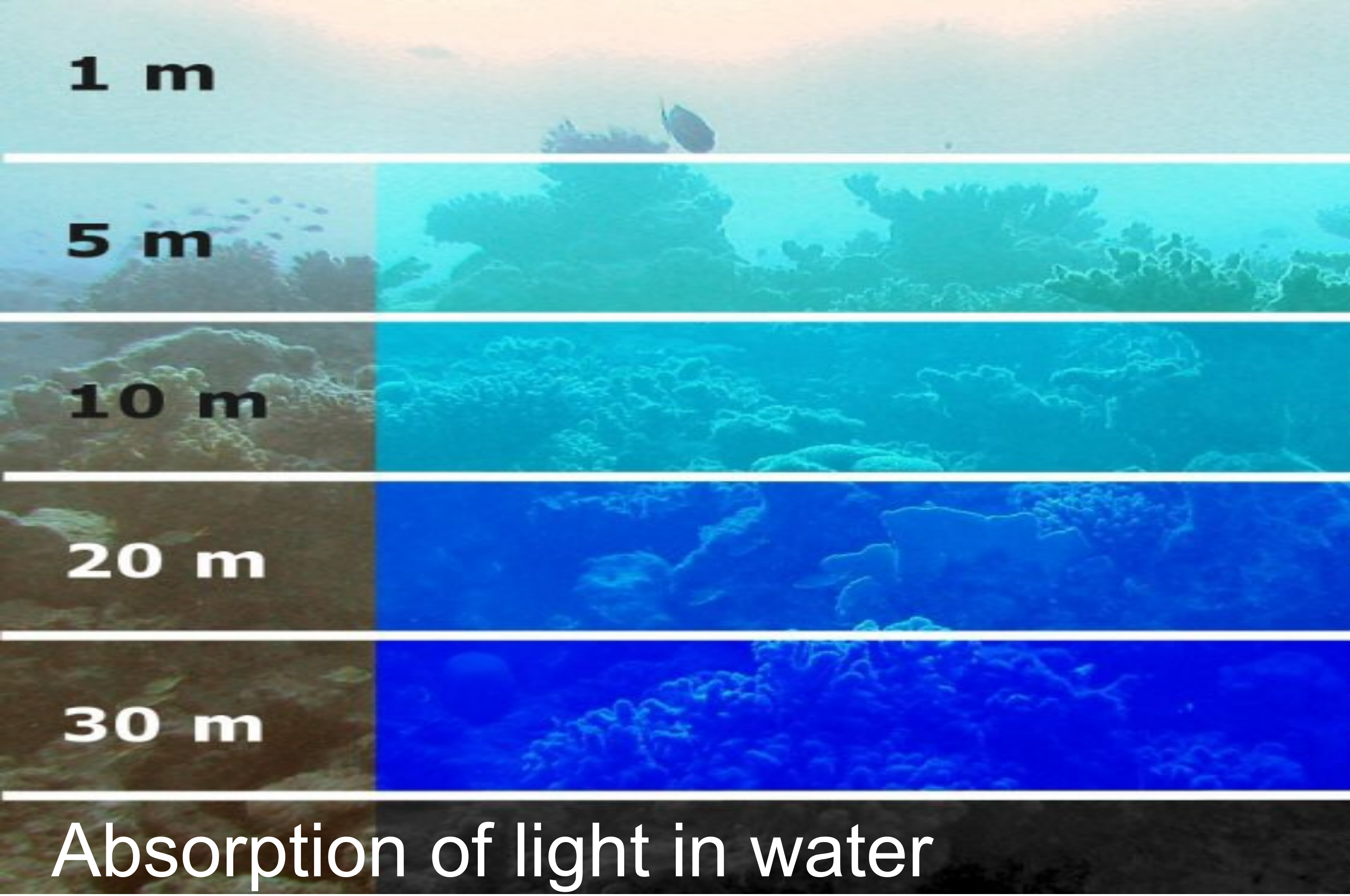
Absorption
Reflection
Diffraction
Interference

(The first two are quite easy to understand - for the latter two, we need to look at waves)

Absorption

- Converts energy into heat
- Decreases power exponentially
  - this is a linear decrease in dB
- For radio waves, water and metal are the strongest absorbers
- Also consider: stones, bricks, concrete, wood, trees, ...

Absorption of light in water



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Absorption

Depends strongly on material
Depends on frequency

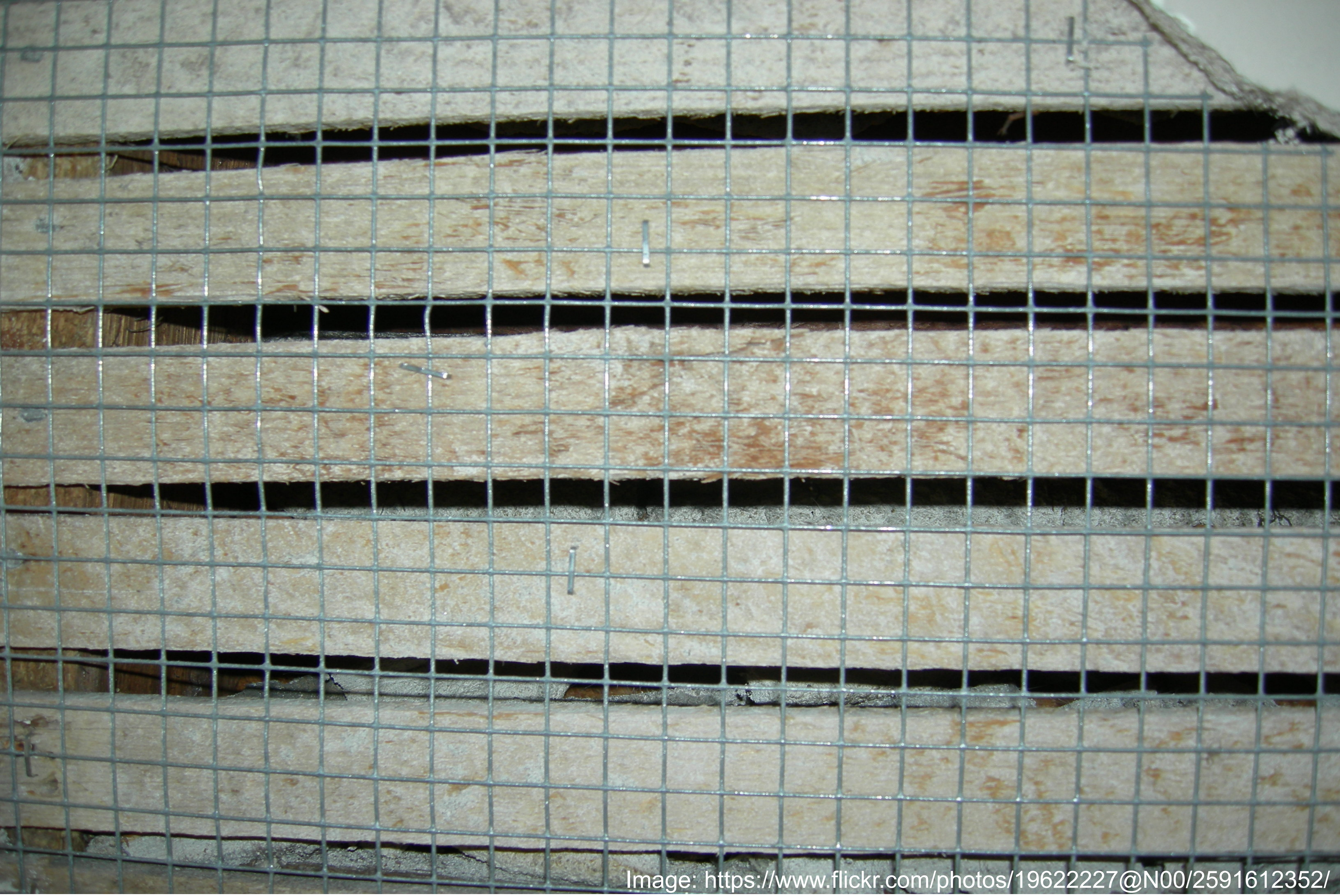
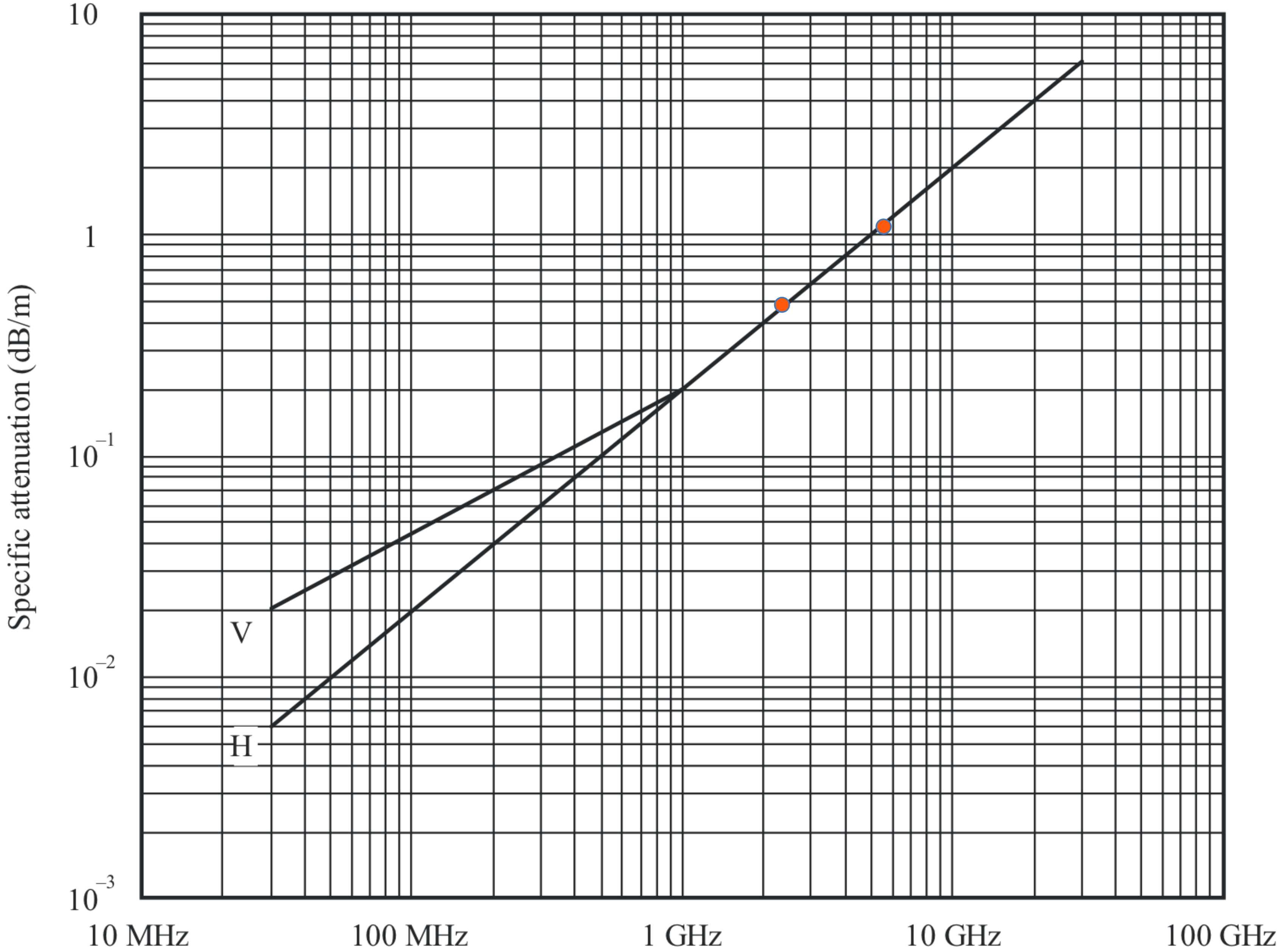


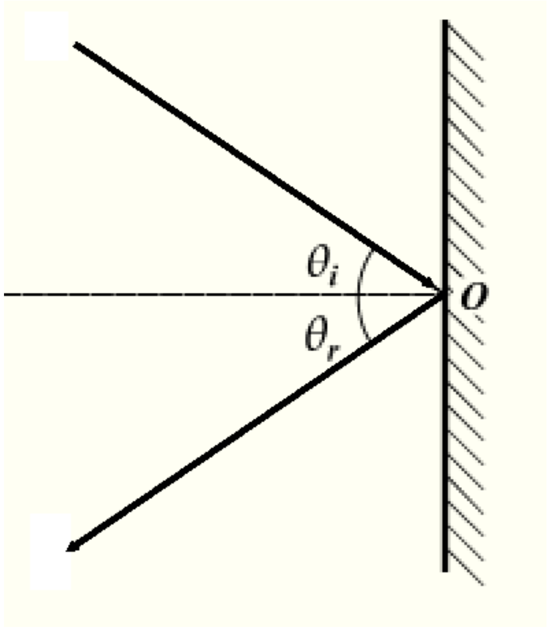
Image: https://www.flickr.com/photos/19622227@N00/2591612352/

Specific attenuation due to woodland

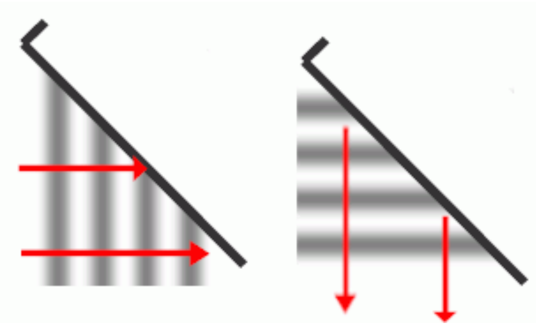


Reflection

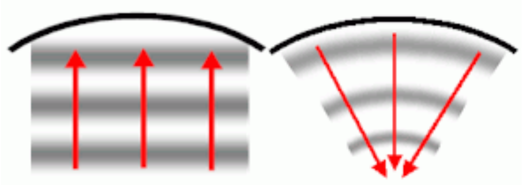
e.g. on metal – we will see this in antennas
angle in = angle out



plane



parabole

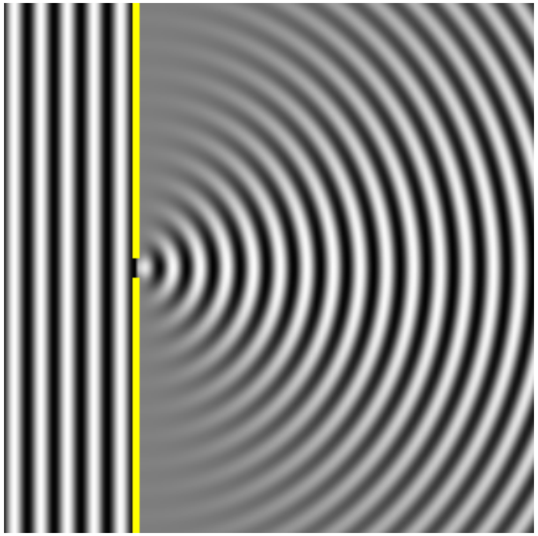


Diffraction

Diffraction is the phenomenon of waves "going around corners" -
It is easiest to understand by looking at the **Huygens Principle:**
"Every point of a wavefront is the source of a new wave."

(This happens even to light – the effects are just too small to see for us!)

Huygens principle



Animated images thanks to Fu-Kwun Hwang and author of Easy Java Simulation = Francisco Esquembre
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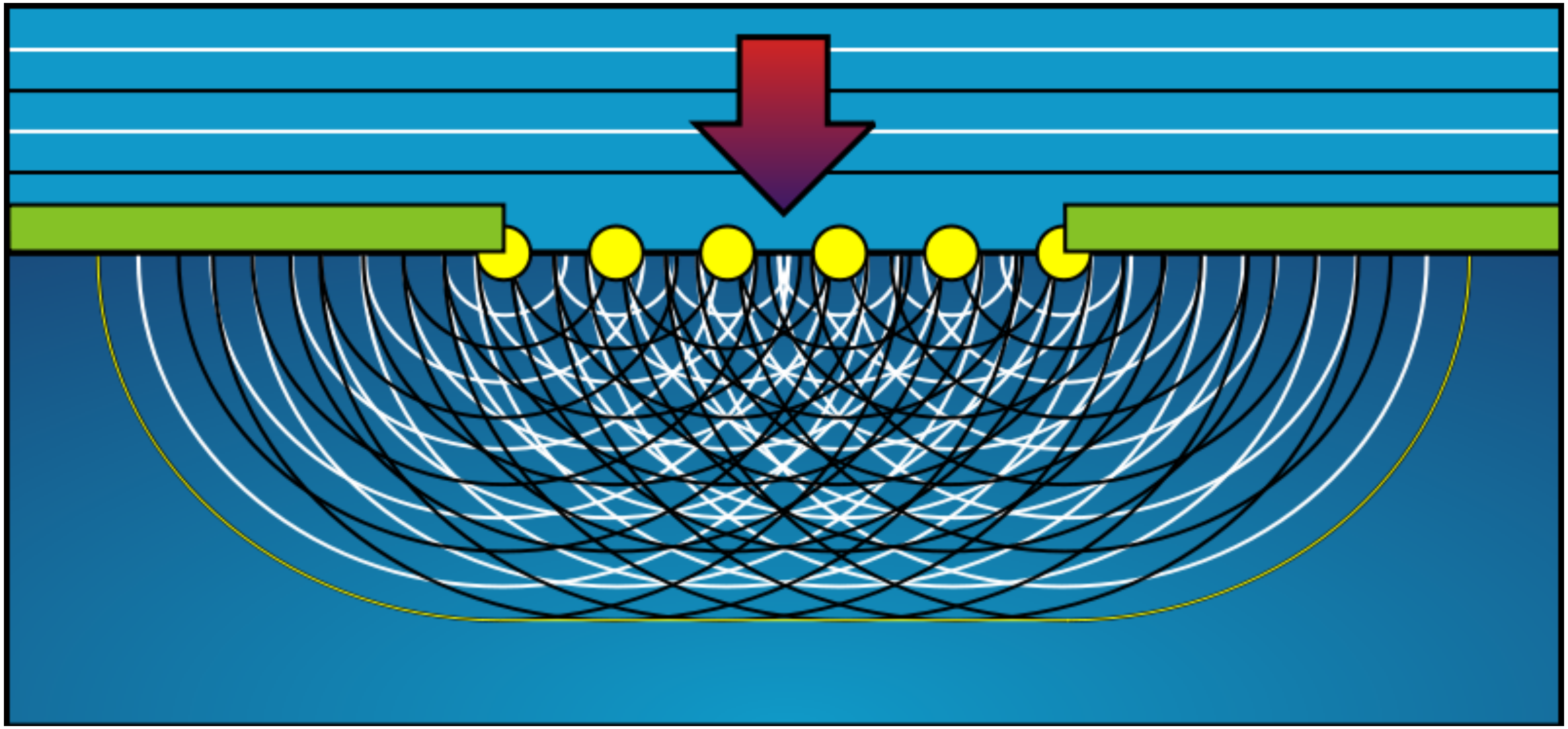
http://commons.wikimedia.org/wiki/File:Wavelength%3Dslitwidth.gif#/media/File:Wavelength%3Dslitwidth.gif

Huygens principle



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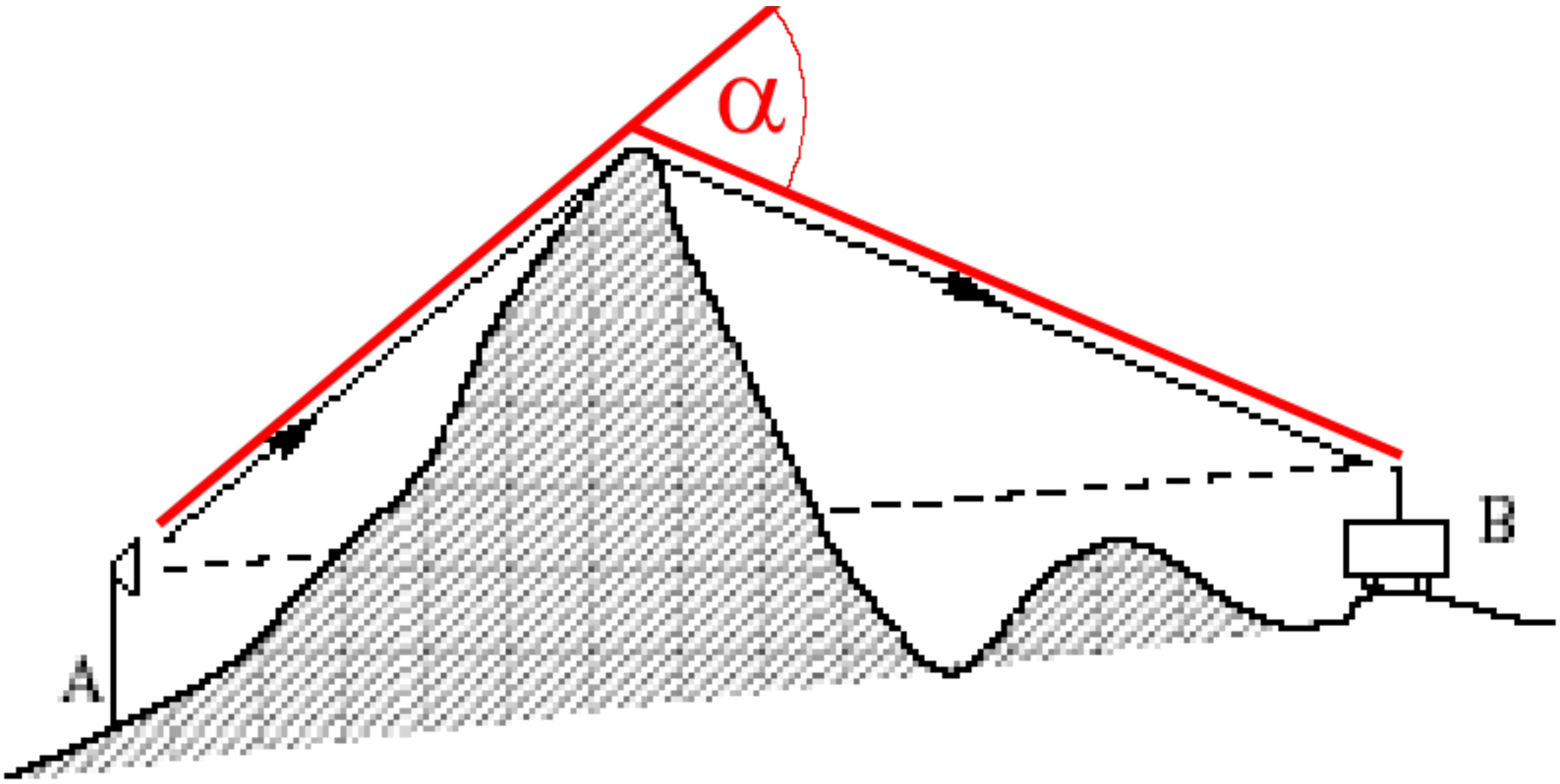
Diffraction in action



Interference: different meanings

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

Interference

We often hear "Interference" when it is really something else

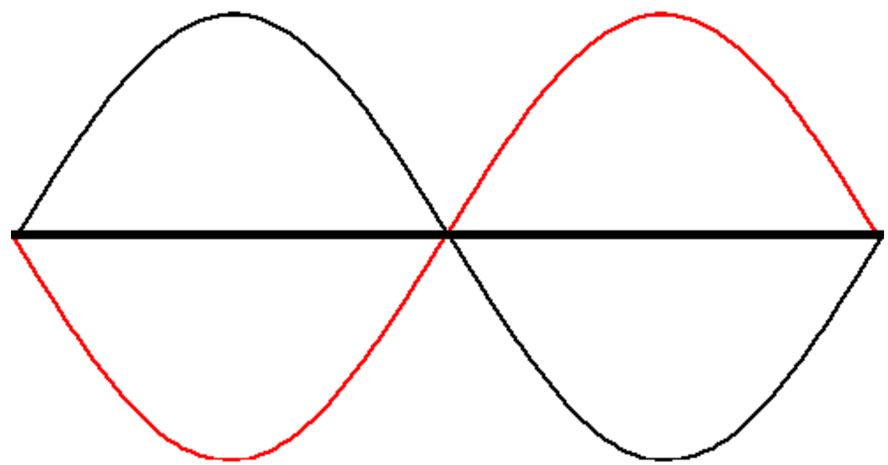
Think twice, when you here it!

Is it really interference? or are we too lazy to find the real problem?

Interference: Physicist's View

Waves can annihilate each other:

1 + 1 = 0



but only when they have fixed **frequency and phase relation**

Waves can also enhance each other

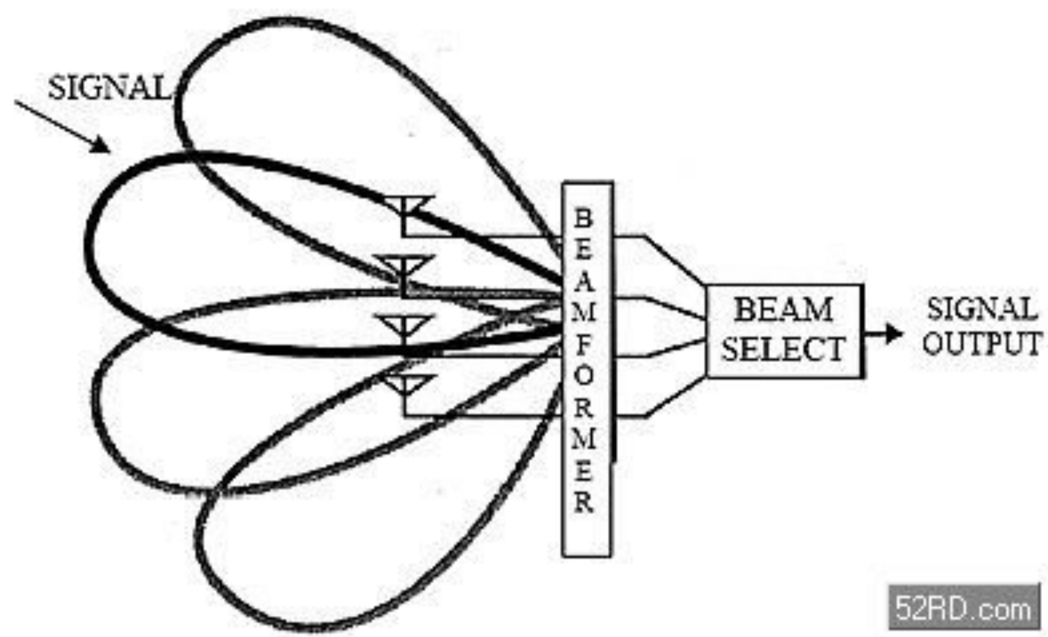
Interference: thought experiment

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

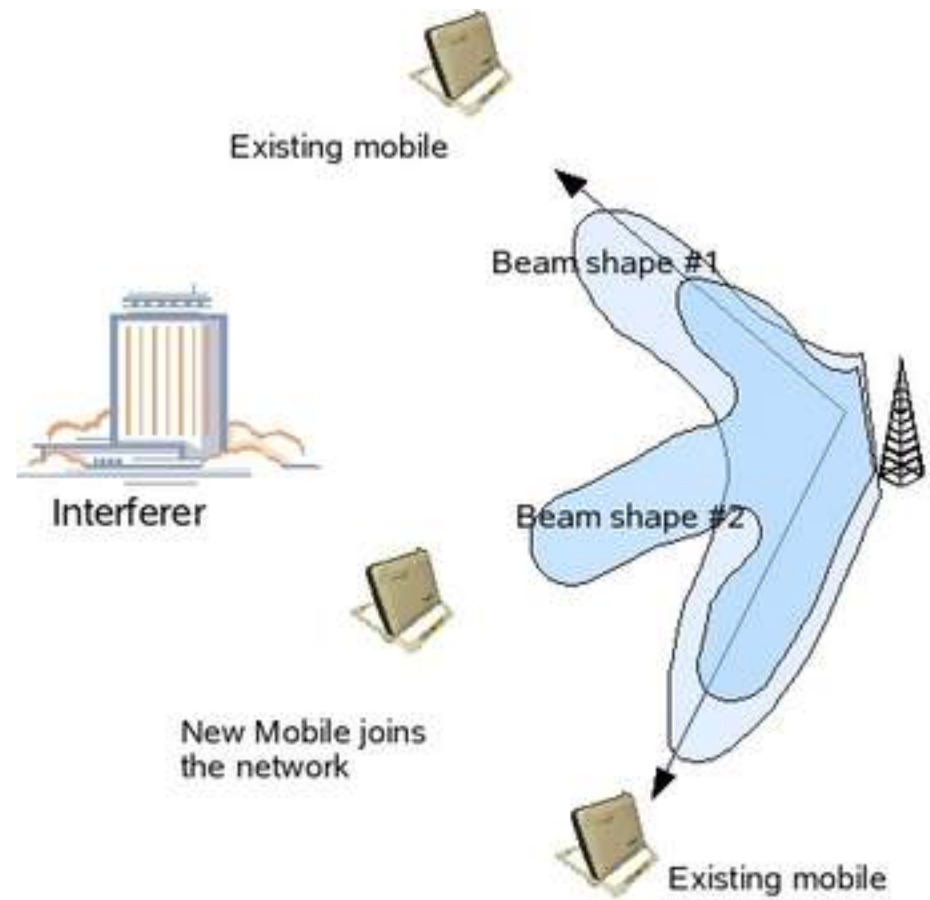
- Interference is used for good in:
  beam-shaping, smart antennas, MIMO

  MIMO techniques use interference to optimize antennas, direct signals at users, 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

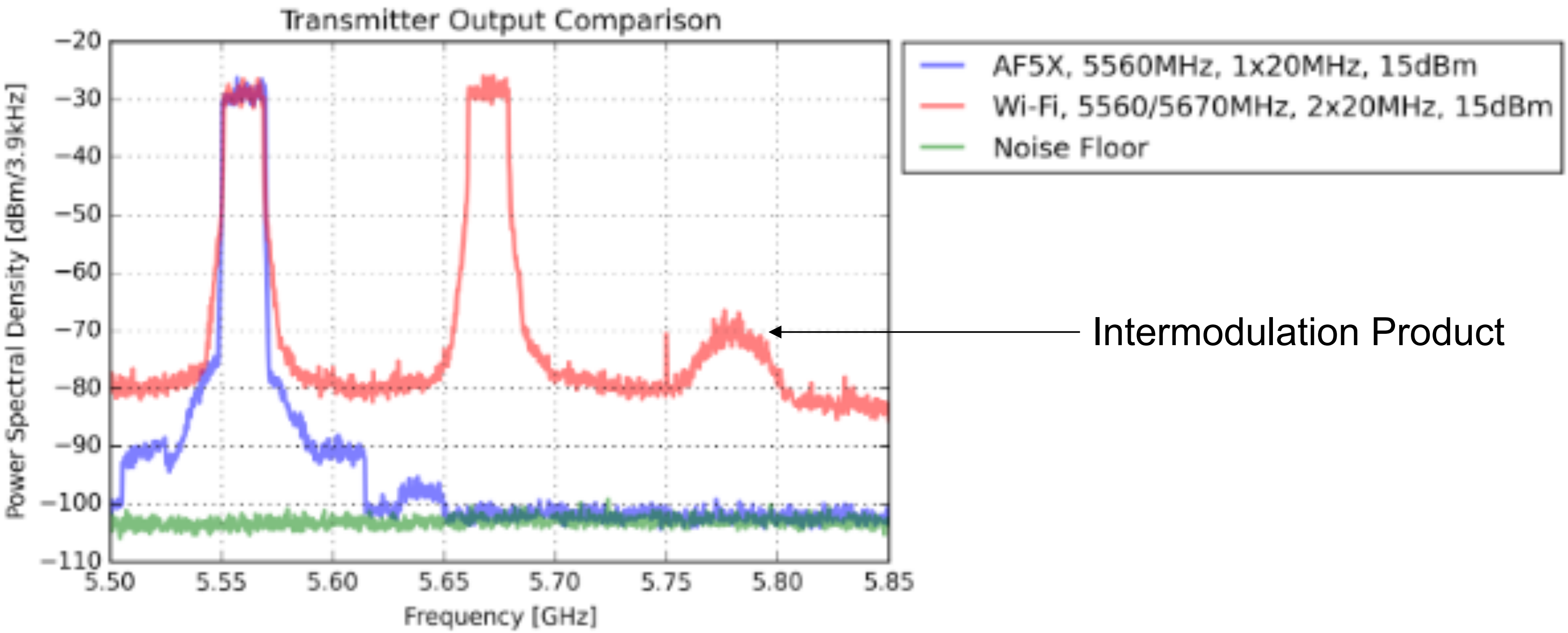
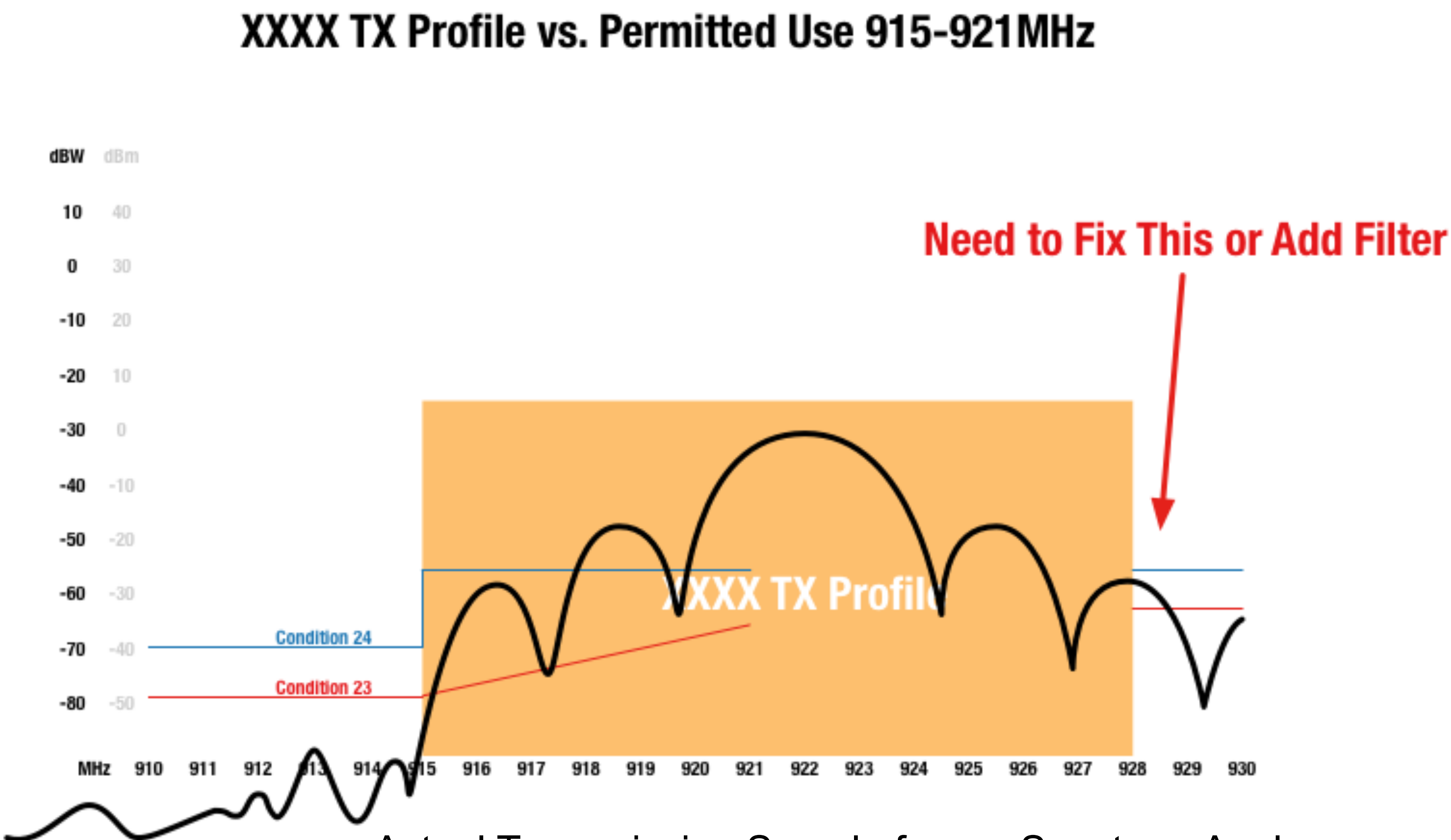


Image: http://community.ubnt.com/t5/airFiber-Stories/AF5X-Why-you-owe-it-to-yourself-to-use-these-radios-for-backhaul/cns-p/1239600

Some Transmitters Interfere



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

Frequency dependent behavior

- Longer wavelengths / lower frequencies
  - Go further
  - Travel better through obstacles
  - Bend better around obstacles
  - Need bigger antennas
- Shorter wavelengths / higher frequencies
  - Can transport more data
  - Need smaller antennas

Frequency dependent behavior

5GHz: 802.11a Wi-Fi
2.4GHz: 802.11b/g Wi-Fi
2.1GHz: 3G
1.8GHz: 2G & LTE
900MHz: 3G
700MHz: LTE
470-790MHz: TV White Spaces
100MHz: Radio

Capacity →

Antenna Size ↓

Better Propagation ↓

Radio propagation in free space

Free space loss
Fresnel zones
Line of Sight

Free space loss

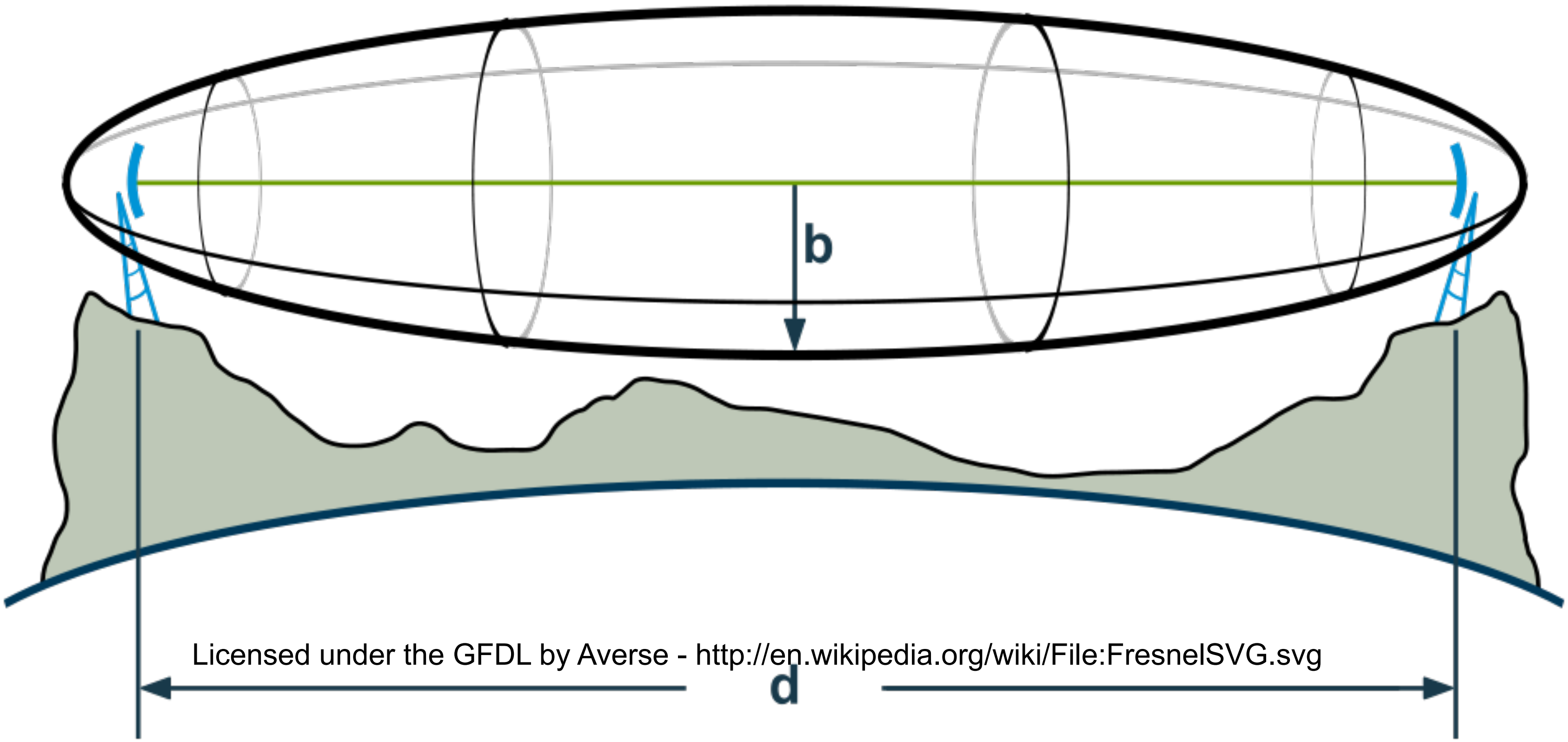
Proportional to square of the distance
Proportional to square of the radio frequency
FSL *(dB) = 20 x log[4π x distance/wavelength]*

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!

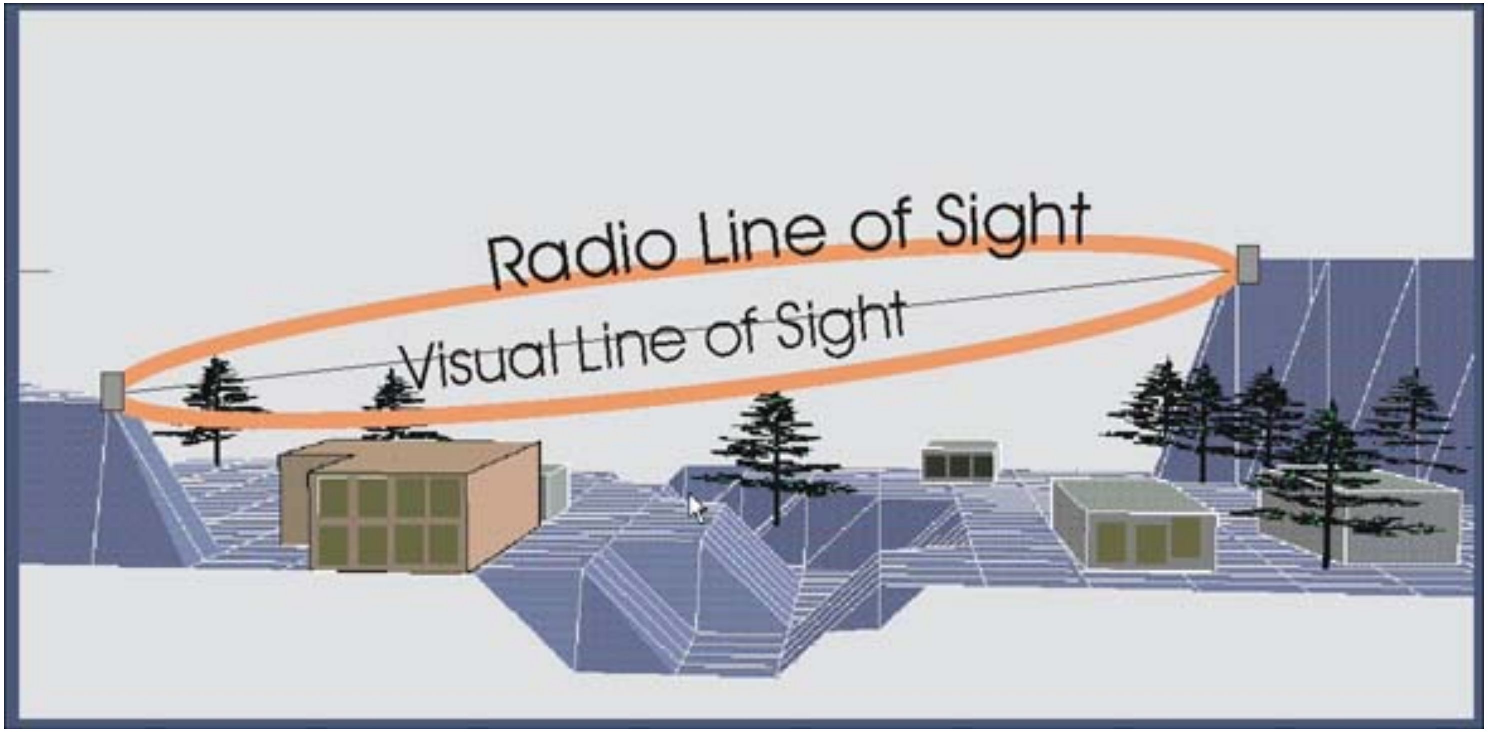
Fresnel zones

Fresnel zones are an effect due to the wave nature of radio
Fresnel zones are best kept clear of obstacles
Absorption in the fresnel zones weakens the arriving signal
Reflection in the fresnel zones leads to (good/bad) interference



Line of sight

Required for higher frequencies (> 1GHz)
Less absorption / reflection = better links



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 spring, dry to humid ..
when it is rush hour in the city
with long distance links (speed of light!)

Examples: indoor network

Indoor networks typically have massive multi-path conditions caused by reflections
Reflections: metal infrastructure (computers, radiators, desks, windows)
Absorption: from people, plants, books, ...
Choice of locations and antennas essential!

Changing seasons: absorption

Vegetation, humidity, rain all change with the seasons
Dry trees might be radio transparent – but wet green trees are not

Rush Hour: reflection/diffraction

Urban conditions change with the day and the hour:

- People, vans, cars,
- Electromagnetic Interference (Noise Floor)

Always test on a monday what you measure on a sunday ...

The speed of light

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

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

Appendix: The dB

The dB

- Definition: $10 \times \log_{10}(P_1 / P_0)$
- 3 dB = double power
- -3dB = half the power
- 10 dB = one order of magnitude up = x 10
- -10 dB = one order of magnitude down = /10
- Calculating in dBs is easier :)
- 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 in Transmit Power

Example from a 802.11a/b radio:

Output Power:

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

dB in Receive Sensitivity

Example from a 802.11b card

Receive Sensitivity:

1 Mbps: -95 dBm;

2 Mbps: -93 dBm;

5.5 Mbps: -91 dBm

11 Mbps: -89 dBm

The dB: datasheet examples

UniFi® Datasheet

Networking Interface	(2) 10/100/1000 Ethernet Ports
Buttons	Reset
Antennas 2.4 GHz 5 GHz	 Integrated 5 dBi Omni (Supports 3x3 MIMO with Spatial Diversity) Integrated 5 dBi Omni (Supports 3x3 MIMO with Spatial Diversity)
Wi-Fi Standards	802.11 a/b/g/n/ac
Power Method	Passive Power over Ethernet (48V), 802.3at Supported (Supported Voltage Range: 39 to 57VDC)
Power Supply	48V, 0.5A PoE Gigabit Adapter Included
Maximum Power Consumption	22 W
Maximum TX Power 2.4 GHz 5 GHz	 28 dBm 28 dBm