

# ITRAINONLINE MMTK BASIC RADIO PHYSICS HANDOUT

Developed by: Sebastian Buettrich, wire.less.dk  
Edited by: Alberto Escudero Pascual, IT +46

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## 1. About this document

These materials are part of the ItrainOnline Multimedia Training Kit (MMTK). The MMTK provides an integrated set of multimedia training materials and resources to support community media, community multimedia centres, telecentres, and other initiatives using information and communications technologies (ICTs) to empower communities and support development work.

## 1.1 Copyright information

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## 1.2 Degree of Difficulty

The degree of difficulty of this unit is "Basic" with some additional "Advanced" parts. All "Advanced" sections are marked with a red frame to make the reader aware of a higher degree of difficulty.

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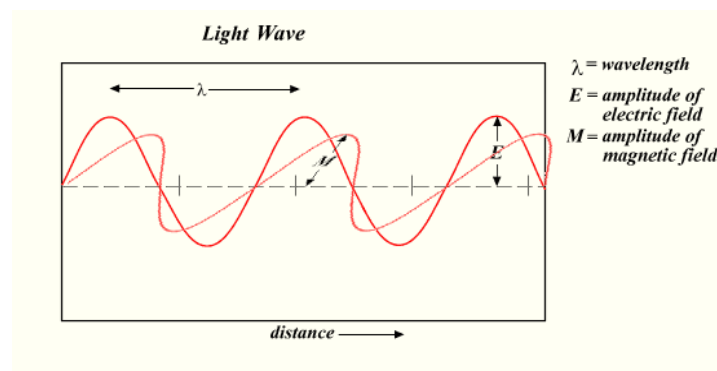
## 2. Introduction

This unit aims to give the reader a basic overview of radio physics as a necessary knowledge base for further study in the topic of wireless communications. In specific, it addresses the basic physical principles of waves in wireless data communications.

The unit introduces that essence of electromagnetic fields and their characteristics. Electromagnetic concepts, such as absorption, reflection, diffraction, refraction and interference, are briefly presented. The issue of free space propagation of electromagnetic waves are thoroughly discussed together with concepts as Free Space Loss, Fresnel zones, Line of Sight and Multipath. Finally, a set of practical examples are presented to the reader together with general good advices to overcome problems that can arise.

## 3. Electromagnetic fields and waves

Electromagnetic radiation, also known as Electromagnetic wave, is a propagating wave in space with electrical and magnetic components. The electrical and the magnetic components oscillate **perpendicular to each other and to the direction of the propagation**.



Source: Wikipedia.org

Image 1: An illustration of the electrical and magnetic field oscillating around its on axis, perpendicular to each other and the direction of the propagation.

### 3.1 Characteristics of Electromagnetic waves

Some of the characteristics of electromagnetic waves are described below.

#### 3.1.1 E and H Fields

Electromagnetic forces act between electric charges and electric currents. For every point in space, an electromagnetic field (the force felt by a charge or current at that very point) can be defined and measured.

The electric field **E** describes the force between charges.

The magnetic field **H** describes the forces between currents.

#### 3.1.2 Carrier Medium

One very important quality of electromagnetic waves is that they do not need any carrier medium. There is no air or ether needed to propagate them electromagnetic waves, unlike sound, air pressure waves that propagate, that needs a carrier. Examples of electromagnetic waves are light, X-rays, microwaves and other radio waves.

#### 3.1.3 Wavelength and Frequency

An electromagnetic wave, like any wave, has by its basic shape of a sinus, troughs and crests. The wavelength is the distance between two crests (or 2 troughs) and is measured in meter. The wavelength is represented by the Greek letter  $\lambda$  (lambda).

The frequency of a wave is its rate of oscillation and is measured in hertz (Hz). The SI unit of frequency is the 1 oscillation per second (1/s)

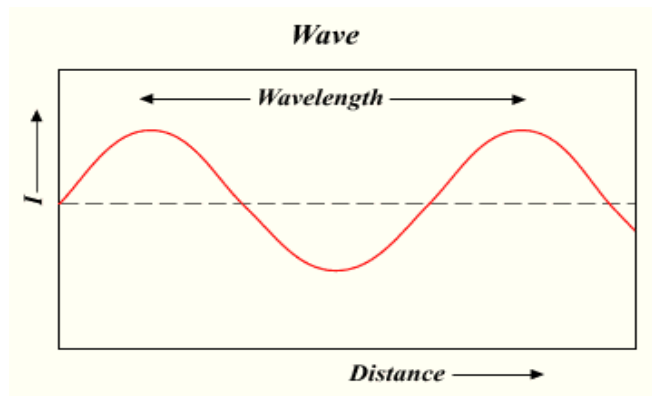


Image 2: Characteristics of an electromagnetic wave.

The frequency and the wavelength of a wave has the following relation:

$$c = \lambda * f$$

whereas:

$c$  = the speed of light [m/s] ( $3 \times 10^8$  m/s = 300,000 km/s)

$\lambda$  = wavelength [m]

$f$  = frequency\* [1/s]

(\*) the frequency is also called  $\nu$  (Nu)

In this way, an electromagnetic wave with a frequency of 2.4GHz has a wavelength of 12,5 cm.

Light (or a radio signal) that travels with the speed of the light needs 1.3 seconds from the Moon to Earth, 8 minutes from the Sun, and 300 microseconds (0.3 milliseconds) for 100 km.

Below follows a reminder of the denotation of the “powers of ten”, which are used for all kinds of units, e.g micrometer, kilohertz or Megabytes.

<b>Prefix</b>	<b>Quantity</b>		<b>Symbol</b>
Nano	$10^{-9}$	1/ 1,000,000,000	n
Micro	$10^{-6}$	1/1,000,000	$\mu$
Milli	$10^{-3}$	1/1,000	m
Centi	$10^{-2}$	1/100	c
Kilo	$10^3$	1,000	k
Mega	$10^6$	1,000,000	M
Giga	$10^9$	1,000,000,000	G

Table 1: Prefix and symbols for “powers of ten”.

## 4. Polarization

Polarization is the direction of the electric field vector in a propagating wave. Polarization can be

- Linear
- Elliptic
- Circular

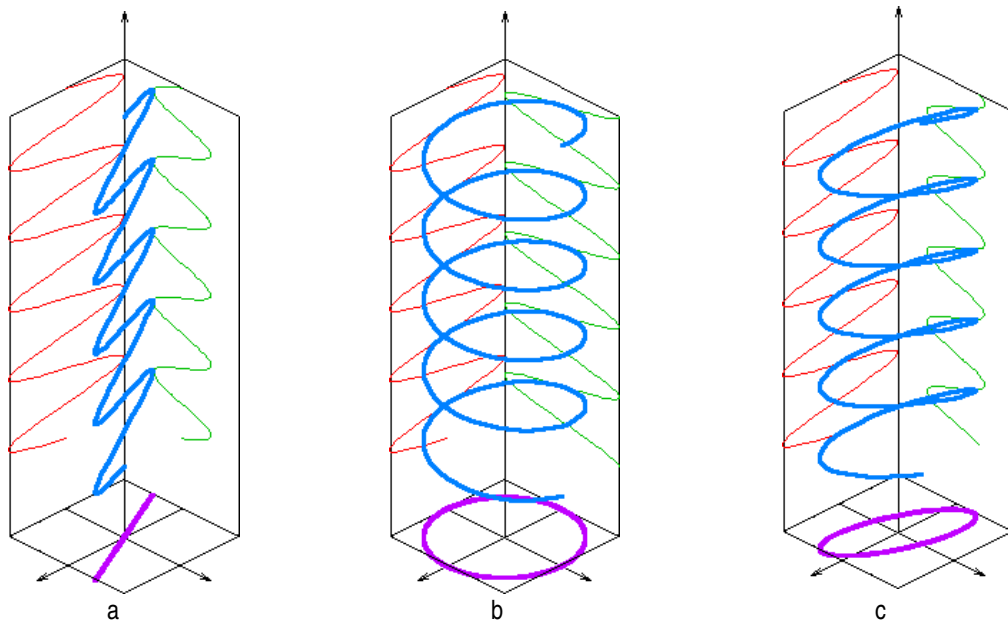


Image 3: Polarization of waves a) Linear b) Circular c) Elliptical

## 5. Dipole radiation

Dipole radiation is the electromagnetic field leaving the system of electrons swinging in a linear conductor, e.g. a straight piece of wire.

This is one of the most simple forms of an antenna; the dipole antenna.

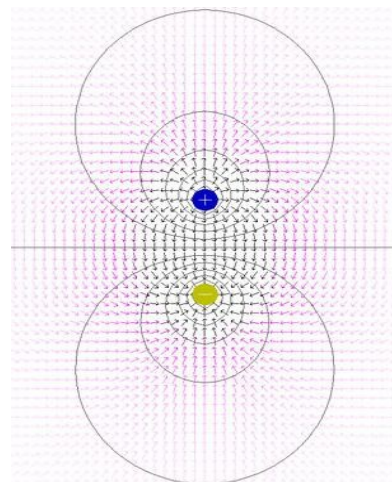
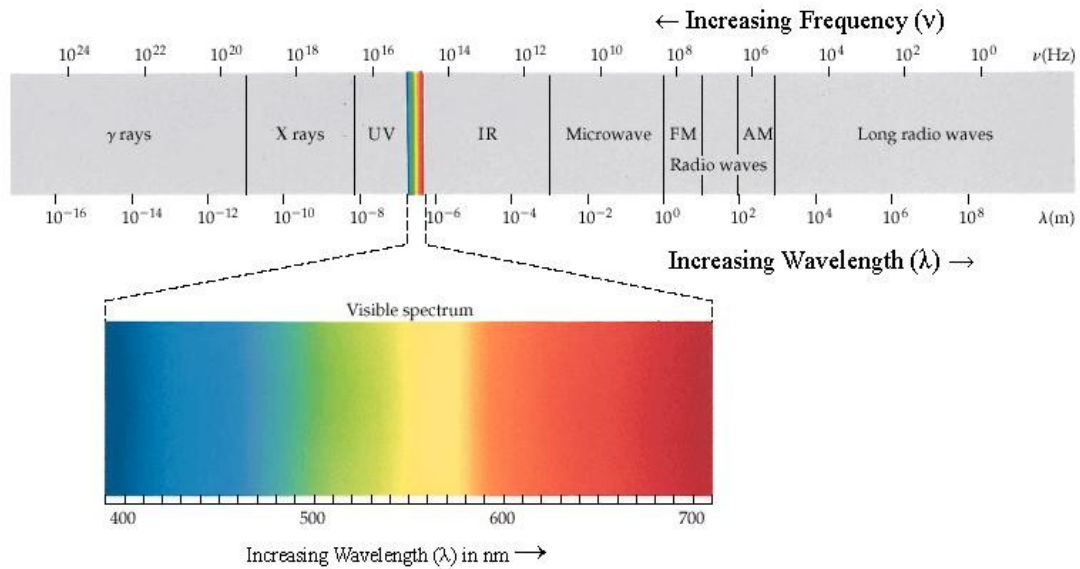


Image 4: Dipole radiation

## 6. The electromagnetic spectrum



Source: Wikipedia.org

Image 5: The electromagnetic spectrum

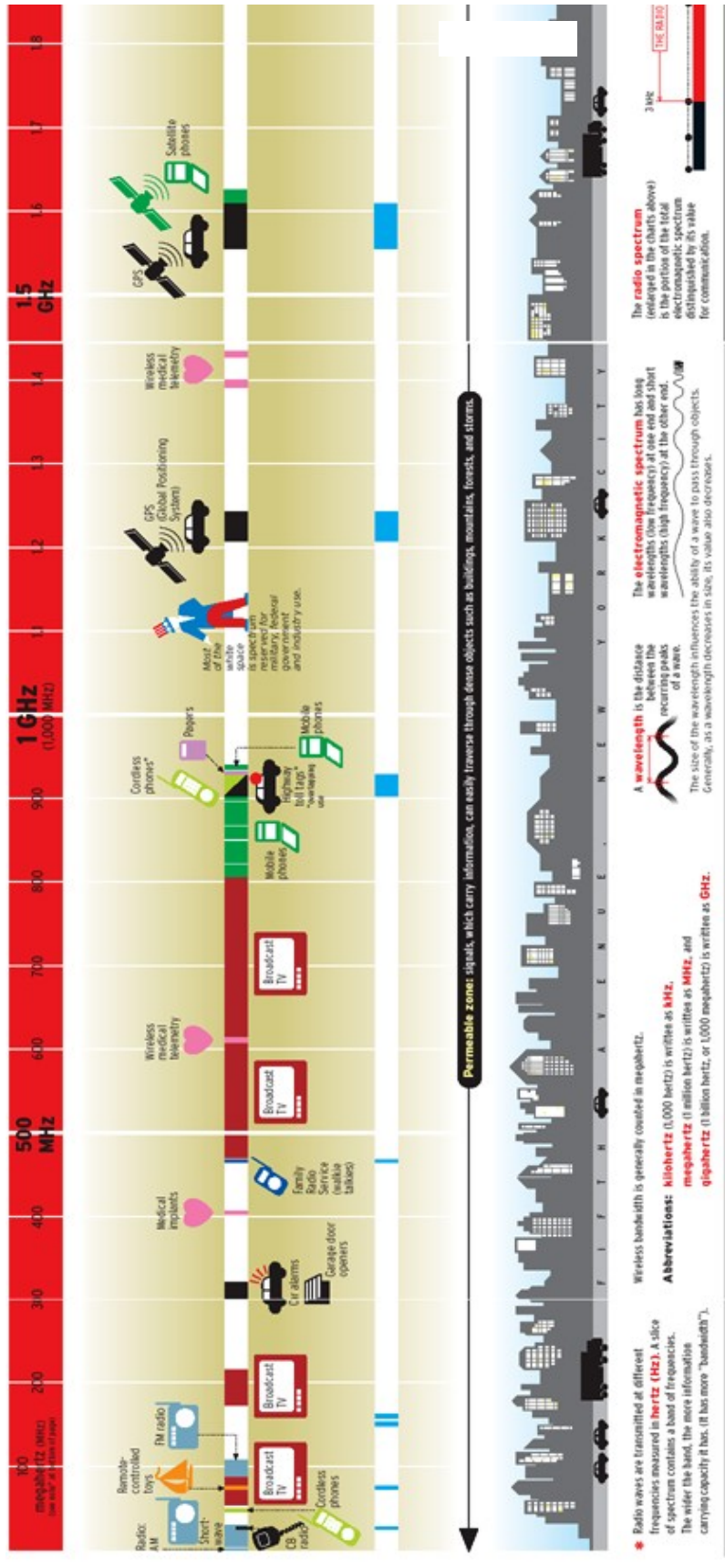
### 6.1 Frequencies in wireless networking

In the context of wireless networking, we predominantly focus on the ISM (industrial, scientific, and medical - license exempt) bands at

<b>Frequency</b>	<b>Standard</b>	<b>Wavelength</b>
2.4 GHz	802.11 b/g	12,5 cm
5.x GHz	802.11a	5-6 cm

Table 2: Frequencies and wavelengths in wireless networking

The following two pictures (Image 6 and Image 7) give an overview of the electromagnetic spectrum, its usage in different wavelength values.



Source: The Citizens Guide to the Airwaves, New America Foundation.  
<http://newamerica.net>

Image 6: The usage of the electromagnetic field from 500 Mhz to 1.5 GHz

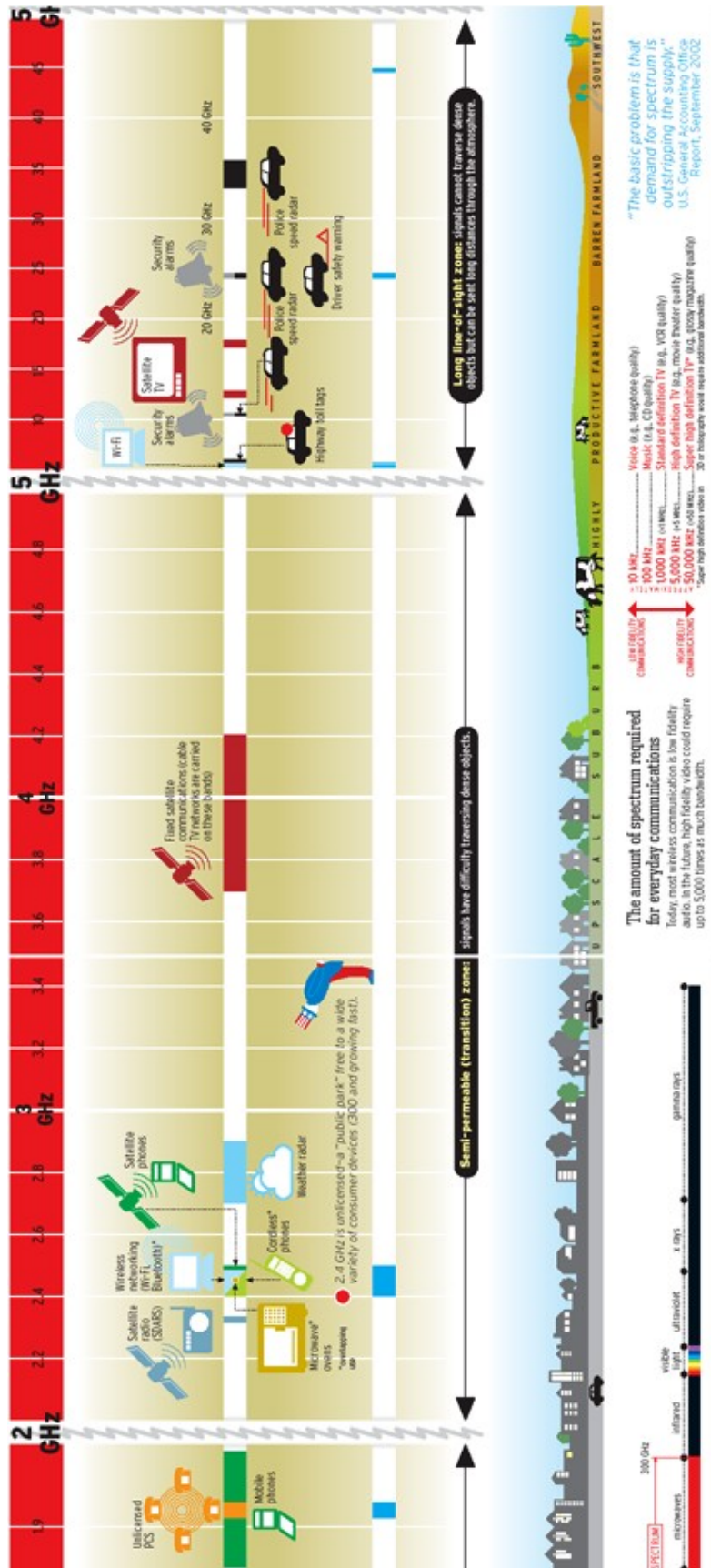


Image 7: The usage of the electromagnetic field from 2 GHz to 5 GHz

## 7. Propagation of electromagnetic waves

A very important principle when trying to understand the propagation of electromagnetic, and thus radio waves, is the *Huygens principle*, which in simplified form can be formulated as:

“At any point of a wave, new spherical waves start”

Adding up all these spherical waves along a so called wave front, lets you understand why an undisturbed wave front continues to travel as one.

The Huygens principle also explains why light (or radio waves, or any electromagnetic wave) not always travels in straight line.

Electromagnetic waves are subject to a number of key effects:

1. Absorption
2. Reflection
3. Diffraction
4. Refraction
5. Interference

### 7.1 Absorption

Radio waves of whatever kind get dampened or weakened, by transferring energy to the medium they are travelling through.

The power of the wave decreases exponentially in the medium, corresponding to a linear decrease in dB (see Link Budget Calculations for calculations with dB).

Often, an absorption coefficient (in dB/m) is used to quantitatively describe the impact of the medium on radiation.

In general, we find strong absorption in conducting materials, most of all in metal. The other strong absorber for radio waves in the frequency range relevant in wireless networking (microwave range of frequencies) is water in all its forms (such as rain, fog, water pipes, and humans).

We find intermediate absorption in stones, bricks and concrete, depending on the exact parameters of the materials. The same goes for wood, trees and other material, their behaviour is to a large extent determined by their water concentration.

In the context of radio absorption, human beings and most animals can be seen as containers of water, thus strong absorbers.

## 7.2 Reflection

We are all familiar with the reflection of visible light in mirrors or on water surfaces. For radio frequencies, reflection mainly occur on metal, but again also on water surfaces and other suitable materials.

The basic principle of reflection is that the wave is reflected back in the same angle it hits a surface.

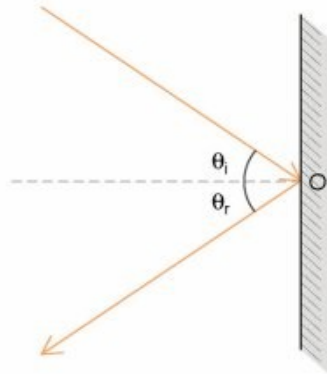


Image 8: Reflection of a wave, same outgoing angle and the incoming angle.

Two important cases of reflection are reflection on a plane surface and reflection of a parabolic surface.

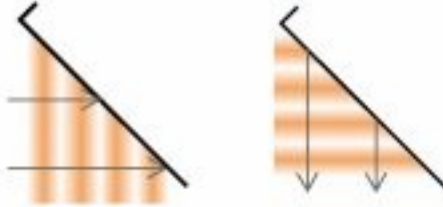


Image 9: Reflection on a plane



Image 10: Reflection on a parabola

### 7.3 Diffraction

Diffraction is a phenomena that is based on the fact that waves do not propagate in a single direction. It occurs when waves are propagating through a medium and diverge into wider beams. Diffraction implies that waves can be “bent” around corners, just like the image below tries to illustrate.

Diffraction is a direct consequence of the Huygens principle, and it scales roughly with the wavelength. This means that you can expect waves to bend more easily the bigger is the wavelength. That is the reason why an AM Radio station operating at 100 kHz can be heard easily (the wavelength is of 3 kms) while in wireless communication line of sight between sender and receiver is required (the wavelength is 12 cms)

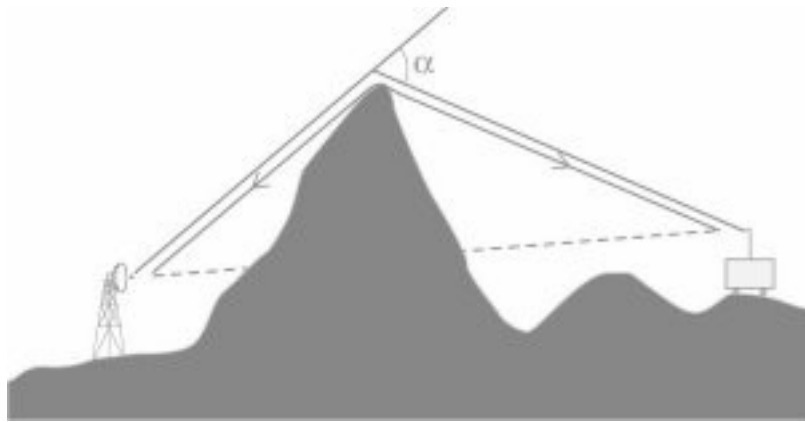


Image 11: Diffraction of a electromagnetic wave

## 7.4 Refraction

Refraction is the apparent “bending” of waves when they meet an obstacle with a different density.

When a wave moves from one medium to another of a different density, it change speed and direction when entering the new medium (Image 12) .

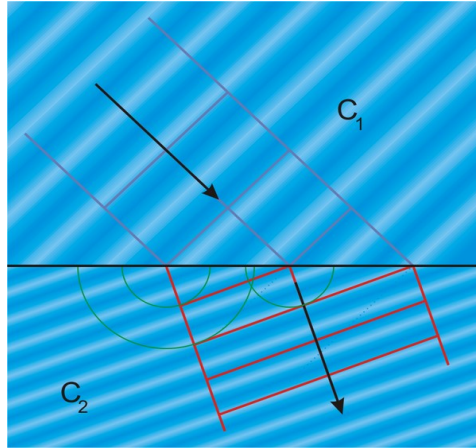


Image 12: Wave refraction

The blue lines represent the incoming waves while the red lines represents the by refraction “bended” waves.  $C_1$  is a medium with less density than  $C_2$ . The angle that the waves break into depends on the density of the material of the obstacle ( $C_2$ )

## 7.5 Interference

Waves of the same frequency and a fixed phase relation (relative position of waves) can annihilate each other, so that one wave plus another wave equals zero.

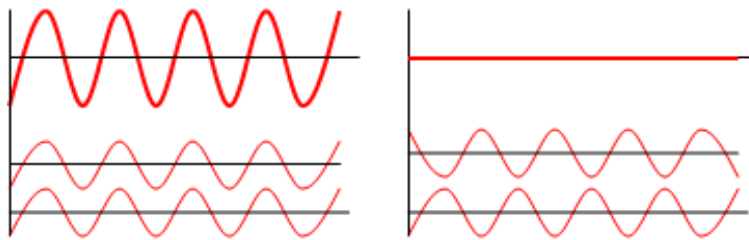


Image 13:

a) Maximum amplification

b) Complete annihilation

For this to occur in its purest form (complete annihilation or maximum amplification), waves would have to have the exact same wavelength and energy and a fixed phase relation.

In wireless technology, the word *interference* is typically used in a wider sense, for disturbance through other RF sources, e.g. neighbouring channels.

## 8. Effects dependence of frequency

These effects are more or less present depending on the frequency of the wave. Formulas to measure these effects are complex in nature (for example when looking at resonance absorption), however, a few very simple rules of thumb prove to be very handy in understanding and planning radio propagation.

- The lower frequency, the further it goes
- The lower frequency, the better it goes through and around things
- The higher frequency, the more data it can transport

## 9. Radio propagation in free space

In the following section we will take a closer look at four relevant effects and concepts in radio propagation.

1. Free Space Loss (FSL): the fact that a radio wave loses power even along a straight line through a vacuum
2. Fresnel Zones: the fact that radio waves travel through a wide cigar shaped zone rather than just on a straight line
3. Line of Sight: how it may be defined for radio waves
4. Multipath Effects – the fact that one initial signal might find different ways to reach a given receiver

Note at this point that, to a large extent, all of these concepts can be understood by applying the Huygens principle.

### 9.1 Free space loss (FSL)

The majority of the power of a radio signal will be lost in the air. The Free Space Loss measures the power losses in a free space without any kind of obstacles. The radio signal weakens while expanding into a spherical surface.

The power loss of electromagnetic waves in free space is proportional to the square of the distance and also proportional to the square of the radio frequency. In the relative unit decibel (dB), that results in:

$$FSL(\text{dB}) = 20\log_{10}(d) + 20\log_{10}(f) + K$$

d = distance

f = frequency

K = constant that depends on the units used for d and f

If d is measured in meters, f in Hz and the link uses isotropic antennas, the formula is:

$$FSL(\text{dB}) = 20\log_{10}(d) + 20\log_{10}(f) - 147.5$$

As a rule of the thumb in a 2.4 GHz wireless network, 100 dB are loss in the first kilometre and it reduces 6 dB every time that the distance doubles. A 2 kms link has a loss of 106 dB. while a 4 kms link has a loss of 112 dB.

## 9.2 Fresnel zones

Remembering the Huygens principle, it is easy to see that also the points that are not in the direct axis between A and B radiate some power towards the receiving point B.

A detailed analysis is taking into account interference between all the different waves. While this analysis is beyond the scope of this unit, it leads to this formula for the first Fresnel zone, that should be kept free in order to transmit a great part of the power from A to B.

If there are obstacles inside of the Fresnel zone, the reflections of the waves in those obstacles can provoke higher attenuations of the signal in the receiving point B.

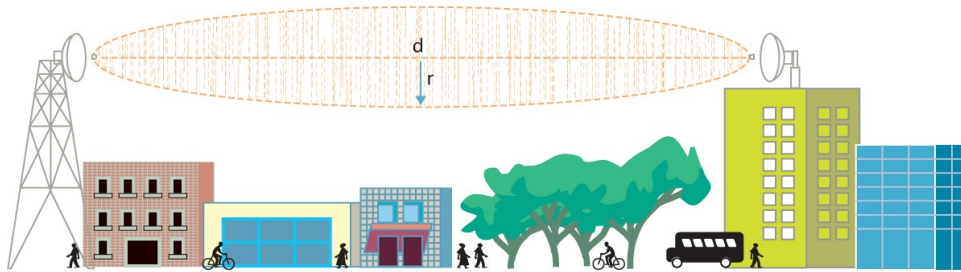


Image 14: Fresnel Zone

The formula for the first Fresnel zone is:

$$r = 17,32 * \sqrt{(d/4f)}$$

d = distance [km]

f= frequency [Ghz]

r= radius [m]

A radio link of 9,6 kms will require that there are no obstacles in r=17,32 meters under the direct line of sight.

### 9.3 Line of sight

For visible light, the line of sight is easy to understand and verify. However, things are a bit more complicated for radio links as they are not visible for our eyes. In general, you need to have a free (optical) line of sight (LOS) for a radio link. Additionally, you need “a bit of space around it”, as defined by the Fresnel Zones.

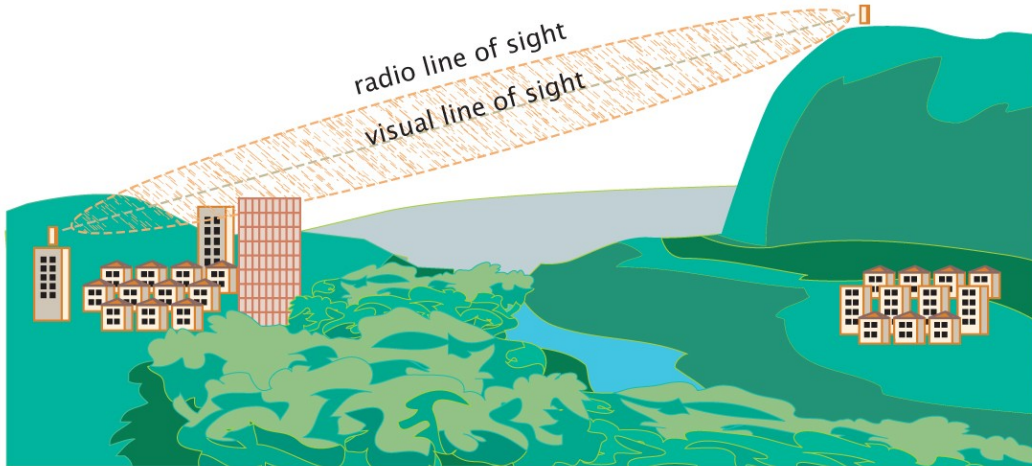


Image 15: Line of sight (LOS) vs visual line of sight.

### 9.4 Multipath

A radio wave can reach the receiving side via many different paths by reflection. Delays, interference and partial modification of signals can cause problems when receiving the signal.

However, the effects of multipath are not all bad and you can sometimes take advantage of multipath effects in order to overcome the limits of line of sight. A non-line-of-sight (NLOS) link can become possible with wireless technologies that are robust enough against multipath effects to let them contribute to the transmission of signals. (See Wireless Standards: MIMO IEEE 802.11n)

## 10. Where physics really matters

Concluding from sections before, we will take a look at some practical cases of wireless networking where understanding physics really matters.

#### When an access point is placed under a desk

- Offices typically have massive multipath conditions and many problematic objects such as people and metal infrastructure (computers, radiators, desks).
- Thus, the choice of location and antennas is essential.

#### When winter turns to spring

- Regardless of your climate zone, factors like vegetation, humidity, rain change with the seasons.
- Dry trees might be transparent but green trees are not.

### **During rush hour in the city**

- People consists 60% of water, absorption is a problem
- Conditions change with the hour (people, vans, cars, electromagnetic interference)
- You need to verify on a Monday what you measure on a Sunday

### **When you are doing very long distance links**

- For long distance links, the travel time of the signal might lead to timeout and performance losses.
- Depending on hardware, this may become relevant already at 1-2 kilometres. For 100 kms you will for sure have to consider it.
- Typical indicator of time out problems is e.g. high packet loss in spite of a good radio signal.

### **When you need to differentiate marketing talk from the truth**

- One antenna or radio device never has a *reach* or *distance*
- The gain of an antenna or the TX power of a radio card are the reliable values
- Even with WIMAX promising NLOS (None line of sight), microwaves still do not go through absorbing materials.
- Modulation techniques make some protocols more robust for multipath and high reflection environments (e.g. urban areas) and thus let you “go round corners”
- For the actual physical waves though, nothing has changed. A blocking wall is still a blocking wall.

## **11. Conclusions**

We have learnt that to be familiar with some basic radio physics concepts can come very handy when working with wireless networks. This knowledge does not only help us to understand how our radio equipment is working, but also makes us aware of the implications of physics in our own environment that can affect the performance of the network.

The five main issues to remember for this unit can be summarized as follows:

1. The carrier in wireless networking are electromagnetic waves in the GHz range
2. Electromagnetic waves are affected by
  - Wave propagation
  - Absorption
  - Reflection
  - Diffraction
  - Refraction
  - Interference
3. You will benefit from understanding the implications of those effects when building wireless implementations.
4. The propagation of radio waves in free space affects the signal in different ways:
  - Free space loss
  - Fresnel zones
  - Line of Sight
  - Multipath effects
5. The conditions of your surrounding environment are constantly changing. The changes might be invisible to the human eye but not to radio waves.