PHYSICS

1. RADIO PHYSICS

Wireless communications make use of electromagnetic waves to send signals across long distances. From a user's perspective, wireless connections are not particularly different from any other network connection: your web browser, email, and other applications all work as you would expect. But radio waves have some unexpected properties compared to Ethernet cable. For example, it's very easy to see the path that an Ethernet cable takes: locate the plug sticking out of your computer, follow the cable to the other end, and you've found it! You can also be confident that running many Ethernet cables alongside each other won't cause problems, since the cables effectively keep their signals contained within the wire itself.

But how do you know where the waves emanating from your wireless device are going? What happens when these waves bounce off objects in the room or other buildings in an outdoor link? How can several wireless cards be used in the same area without interfering with each other?

In order to build stable high-speed wireless links, it is important to understand how radio waves behave in the real world.

What is a wave?

We are all familiar with vibrations or oscillations in various forms: a pendulum, a tree swaying in the wind, the string of a guitar - these are all examples of oscillations.

What they have in common is that something, some medium or object, is swinging in a periodic manner, with a certain number of cycles per unit of time. This kind of wave is sometimes called a ***mechanical*** wave, since it is defined by the motion of an object or its propagating medium.

When such oscillations travel (that is, when the swinging does not stay bound to one place) then we speak of waves propagating in space. For example, a singer singing creates periodic oscillations in his or her vocal cords. These oscillations periodically compress and decompress the air, and this periodic change of air pressure then leaves the singers mouth and travels, at the speed of sound.

A stone plunging into a lake causes a disturbance, which then travels across the lake as a ***wave***.

A wave has a certain ***speed***, ***frequency***, and ***wavelength***.
These are connected by a simple relation:

$$\text{Speed} = \text{Frequency} * \text{Wavelength}$$

The wavelength (sometimes referred to as ***lambda,* λ**) is the distance measured from a point on one wave to the equivalent part of the next (or, in a more technical way, to the next point that is in the same phase), for example from the top of one peak to the next.
The frequency is the number of whole waves that pass a fixed point in a period of time. Speed is measured in metres/second, frequency is measured in cycles per second (or Hertz, represented by the symbol ***Hz***), and wavelength is measured in metres. For example, if a wave on water travels at one metre per second, and it oscillates five times per second, then each wave will be twenty centimetres long:

$$1 \text{ metre/second} = 5 \text{ cycles/second} * W$$
$$W = 1\,/\,5 \text{ metres}$$
$$W = 0.2 \text{ metres} = 20 \text{ cm}$$

Waves also have a property called ***amplitude***. This is the distance from the centre of the wave to the extreme of one of its peaks, and can be thought of as the "height" of a water wave. Frequency, wavelength, and amplitude are shown in Figure RP 1.

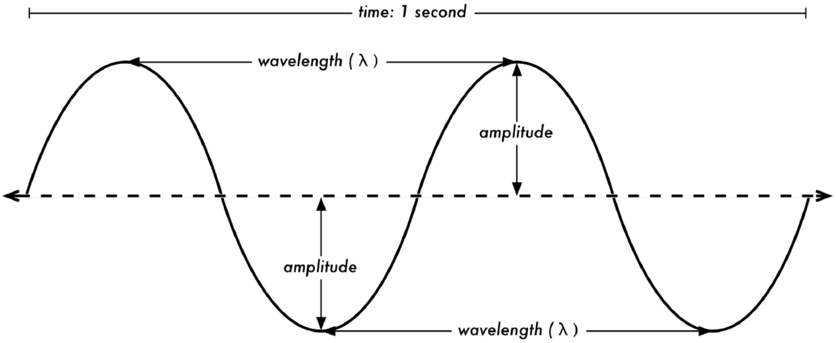

Figure RP 1: Wavelength, amplitude, and frequency. For this wave, the frequency is 2 cycles per second, or 2 Hz, while the speed is 1 m/s.

Waves in water are easy to visualize.

Simply drop a stone into the lake and you can see the waves as they move across the water over time. In the case of electromagnetic waves, the part that might be hardest to understand is: "What is it that is oscillating?"

In order to understand that, you need to understand electromagnetic forces.

Electromagnetic forces

Electromagnetic forces are the forces between electrical charges and currents. Our most direct access to those is when our hand touches a door handle after walking on synthetic carpet, or brushing up against an electrical fence.

A more powerful example of electromagnetic forces is the lightning we see during thunderstorms.

The ***electrical force*** is the force between electrical charges.

The ***magnetic force*** is the force between electrical currents.

Electrons are particles that carry a negative electrical charge. There are other charged particles too, but it is the electrons that are responsible for most of what we need to know about how radio behaves.

Let us look at what is happening in a piece of straight vertical wire, in which we push the electrons from one end to the other and back, periodically. At one moment, the top of the wire is negatively charged - all the negative electrons are gathered there. This creates an electric field from the positively charged end to the negatively charged one along the wire.

The next moment, the electrons have all been driven to the other side, and the electric field points the other way. As this happens again and again, the electric field vectors (represented by arrows from plus to minus) are leaving the wire, so to speak, and are radiated out into the space around the wire.

What we have just described is known as a dipole (because of the two differently charged poles, plus and minus, that are created in the straight vertical wire), or more commonly a ***dipole antenna***.

This is the simplest form of an omnidirectional antenna. The moving electric field is commonly referred to as an electromagnetic wave because there is also an associated magnetic field. A moving electric field, such as a wave, always comes together with a magnetic field - you will not find one with out the other. Why is this the case?

An electric field is caused by electrically charged objects.

A moving electric field is produced by moving electrically charged objects, such as we have just described above in a dipole antenna.

Wherever electrical charges are moving, they induce a magnetic field. Mathematically, this is formulated in Maxwell's equations:
https://en.wikipedia.org/wiki/Electromagnetic_field#Mathematical_description

Since the electrical and magnetic components are tied together in this way, we speak of an electromagnetic field.
In practical wireless networking, we focus in the electrical component but there be always a magnetic component as well.

Let us come back to the relation:

*Speed = Frequency * Wavelength*

In the case of electromagnetic waves, the speed is ***c***, the speed of light.

$$c = 300{,}000\ km/s = 300{,}000{,}000\ m/s = 3*10^8\ m/s$$

$$c = f * \lambda$$

Electromagnetic waves differ from mechanical waves in that they require no medium in which to propagate. Electromagnetic waves will even propagate through perfect vacuum.
The light from the stars is a good example: it reaches us through the vacuum of space.

Symbols of the international system of units

In physics, maths, and engineering, we often express numbers by powers of ten.
We will meet these terms again, and the symbols used to represent them, e.g. gigahertz (GHz), centimetres (cm), microseconds (µs), and so on.

These symbols are part of the international system of measurement **SI** (http://www.bipm.org/utils/common/pdf/si_brochure_8_en.pdf), they are not abbreviations and should not be changed.
The case is significant and should not be altered.

SI symbols

atto	10^{-18}	1/1000000000000000000	a
femto	10^{-15}	1/1000000000000000	f
pico	10^{-12}	1/1000000000000	p
nano	10^{-9}	1/1000000000	n
micro	10^{-6}	1/1000000	µ
milli	10^{-3}	1/1000	m
centi	10^{-2}	1/100	c
kilo	10^{3}	1000	k
mega	10^{6}	1000000	M
giga	10^{9}	1000000000	G
tera	10^{12}	1000000000000	T
peta	10^{15}	1000000000000000	P
exa	10^{18}	1000000000000000000	E

Knowing the speed of light, we can calculate the wavelength for a given frequency. Let us take the example of the frequency of 802.11b wireless networking, which is:

$$f = 2.4\ GHz = 2{,}400{,}000{,}000\ cycles\ /\ second$$

$$wavelength\ (\lambda) = c\ /\ f = 3*10^{8}\ /\ 2.4*10^{9} = 1.25*10^{-1}\ m = 12.5\ cm$$

Frequency and therefore wavelength determine most of an electromagnetic wave's behaviour. It governs the dimensions of the antennas that we build as well as the effect of the interactions with objects that are in the propagation path, including the biological effects in living beings.

Wireless standards of course are distinguished by more than just the frequency they are working at - for example, 802.11b, 802.11g, 802.11n and 802.16 can all work at 2.4 GHz -, yet they are very different from one another.

The chapter called ***Telecommunications Basics*** will discuss modulation techniques, media access techniques, and other relevant features of wireless communications standards. However, the basic capabilities of electromagnetic waves to penetrate objects, to go long distances, and so forth - these are determined by physics alone. The electromagnetic wave "does not know or care" what modulation or standard or technique you put on top of it. So, while different standards may implement advanced techniques to deal with NLOS (Non Line of Sight), multipath and so forth - they still cannot make a wave go through a wall, if that wall is absorbing the respective frequency. Therefore, an understanding of the basic ideas of frequency and wavelength helps a lot in practical wireless work.

Phase

Later in this chapter, we will talk about concepts like interference, multipath and Fresnel zones. In order to understand these, we will need to know about the ***phase*** of a wave, or rather, ***phase differences*** between waves. Look at the sine wave shown in Fig RP 1 - now imagine we have two such waves moving. These can be in exactly the same position: Where the one has its peak, the other one also has a peak. Then, we would say, they are in phase, or, their phase difference is zero. But one wave could also be displaced from the other, for example it could have its peak where the other wave is at zero. In this case, we have a phase difference. This phase difference can be expressed in fractions of the wavelength, e.g. λ//4, or in degrees, e.g. 90 degrees - with one full cycle of the wave being 360 degrees. A phase difference of 360 degrees is the same as that of 0 degrees: no phase difference.

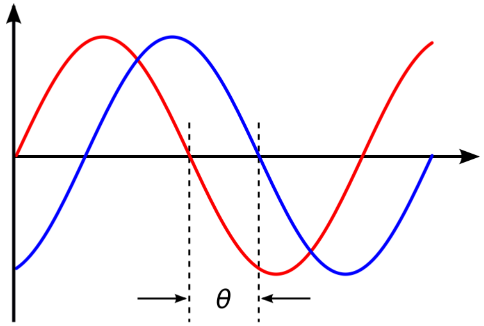

Figure RP 2: Phase Difference between Two Waves

Polarization

Another important quality of electromagnetic waves is ***polarization***. Polarization describes the direction of the electrical field vector.

If you imagine a vertically aligned dipole antenna (the straight piece of wire), electrons can only move up and down, not sideways (because there is no room to move) and thus electrical fields only ever point up or down, vertically. The field leaving the wire and travelling as a wave has a strict linear (and in this case, vertical) polarization. If we put the antenna flat on the ground, we would find horizontal linear polarization.

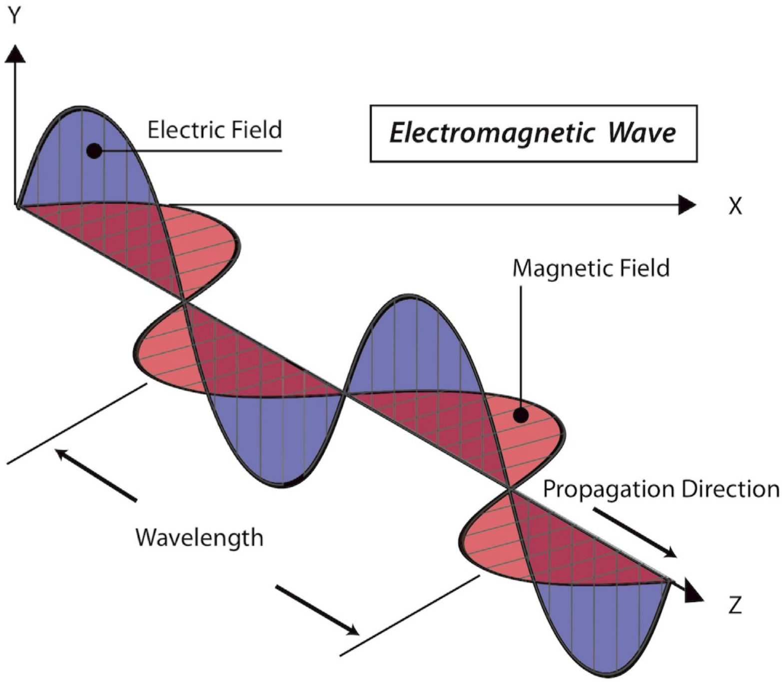

Figure RP 3: Vertically polarized electromagnetic wave

Linear polarization is just one special case, and is never quite so perfect: in general, we will always have some component of the field pointing in other directions too. If we combine two equal dipoles fed with the same signal, we can generate a circularly polarized wave, in which the electric field vector keeps rotating perpendicularly to the wave's trajectory.

The most general case is elliptical polarization, in which the electric field vector maximum value is not the same in the vertical and horizontal direction. As one can imagine, polarization becomes important when aligning antennas. If you ignore polarization, you might have very little signal even though you have the best antennas. We call this polarization mismatch.

Much in the same way, polarization may also be used in a smart way, to keep two wireless links independent and without interference, even though they might use the same end points (or even share a common reflector) and therefore the same trajectory: if one link is polarized vertically and the other horizontally, they will not "see" each other. This is a convenient way to double data rates over one link using a single frequency.

The antennas used in this kind of application must be carefully built in order to reject the "unwanted" polarization, i.e. an antenna meant for vertical polarization must not receive or transmit any horizontally polarized signal, and vice versa. We say they must have a high "cross polarization" rejection.

The electromagnetic spectrum

Electromagnetic waves span a wide range of frequencies (and, accordingly, wavelengths). This range of frequencies or wavelengths is called the ***electromagnetic spectrum***. The part of the spectrum most familiar to humans is probably light, the visible portion of the electromagnetic spectrum. Light lies roughly between the frequencies of $7.5*10^{14}$ Hz and $3.8*10^{14}$ Hz, corresponding to wavelengths from circa 400 nm (violet/blue) to 800 nm (red).

We are also regularly exposed to other regions of the electromagnetic spectrum, including Alternating Current (***AC***) or grid electricity at 50/60 Hz, AM and FM radio, Ultraviolet (at frequencies higher than those of visible light), Infrared (at frequencies lower than those of visible light),
X-Ray radiation, and many others.

Radio is the term used for the portion of the electromagnetic spectrum in which waves can be transmitted by applying alternating current to an antenna. This is true for the range from 30 kHz to 300 GHz, but in the more narrow sense of the term, the upper frequency limit would be about 1 GHz, above which we talk of microwaves and millimetric waves.

When talking about radio, many people think of FM radio, which uses a frequency around 100 MHz. In between radio and infrared we find the region of microwaves - with frequencies from about 1 GHz to 300 GHz, and wavelengths from 30 cm to 1 mm.

The most popular use of microwaves might be the microwave oven, which in fact works in exactly the same region as the wireless standards we are dealing with. These regions lie within the bands that are being kept open for general unlicensed use. This region is called the ***ISM band***, which stands for Industrial, Scientific, and Medical.

Most other parts of the electromagnetic spectrum are tightly controlled by licensing legislation, with license values being a huge economic factor. In many countries the right to use portions of the spectrum have been sold to communications companies for millions of dollars. In most countries, the ISM bands have been reserved for unlicensed use and therefore do not have to be paid for when used.

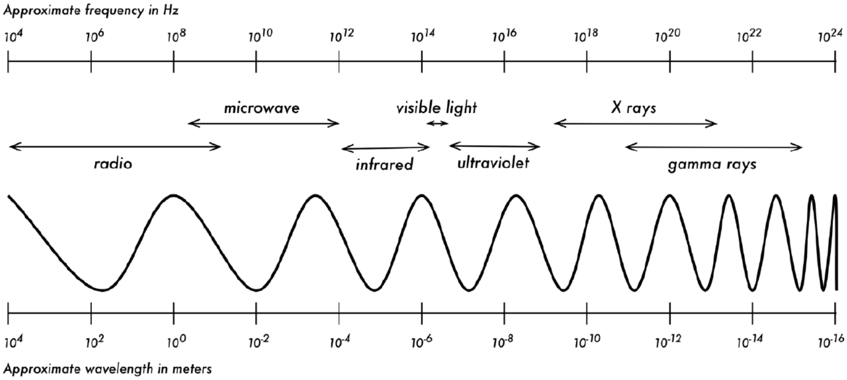

Figure RP 4: The electromagnetic spectrum.

The frequencies most interesting to us are 2.400 - 2.495 GHz, which is used by the 802.11b and 802.11g standards (corresponding to wavelengths of about 12.5 cm), and 5.150 - 5.850 GHz (corresponding to wavelengths of about 5 to 6 cm), used by 802.11a. The 802.11n standard can work in either of these bands.

See the Chapter called ***WiFi Family*** for an overview of standards and frequencies. In addition you can find out more about the Radio portion of the electromagnetic spectrum in the Chapter called ***Radio Spectrum.***

Bandwidth

A term you will meet often in radio physics is ***bandwidth***. Bandwidth is simply a measure of frequency range. If a range of 2.40 GHz to 2.48 GHz is used by a device, then the bandwidth would be 0.08 GHz (or more commonly stated as 80 MHz).

It is easy to see that the bandwidth we define here is closely related to the amount of data you can transmit within it - the more room in frequency space, the more data you can fit in at a given moment. The term bandwidth is often used for something we should rather call data rate, as in "my Internet connection has 1 Mbps of bandwidth", meaning it can transmit data at 1 megabit per second. How much exactly you can fit into a physical signal will depend on the modulation, encoding and other techniques. For example, 802.11g uses the same bandwidth as 802.11b, however it fits more data into those same frequency ranges transmitting up to 5 times more bits per second.

Another example we have mentioned: you may double your data rate by adding a second link at perpendicular polarization to an existing radio link. Here, frequency and bandwidth have not changed, however the data rate is doubled.

Frequencies and channels

Let us look a bit closer at how the 2.4 GHz band is used in 802.11b. The spectrum is divided into evenly sized pieces distributed over the band as individual channels. Note that channels are 22 MHz wide, but are only separated by 5 MHz.

This means that adjacent channels overlap, and can interfere with each other. This is represented visually in Figure RP 5.

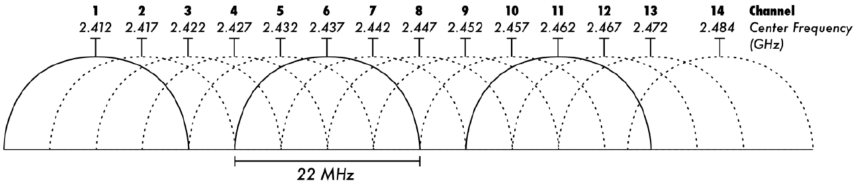

Figure RP 5: Channels and centre frequencies for 802.11b. Note that channels 1, 6, and 11 do not overlap.

Behaviour of radio waves

There are a few simple rules of thumb that can prove extremely useful when making first plans for a wireless network:

- *the longer the wavelength, the further it goes;*
- *the longer the wavelength, the better it travels through and around things;*
- *the shorter the wavelength, the more data it can transport.*

All of these rules, simplified as they may be, are rather easy to understand by example.

Longer waves travel further

Waves with longer wavelengths tend to travel further than waves with shorter wavelengths. As an example, AM radio stations have a much greater range than FM stations, which use a frequency 100 times higher. Lower frequency transmitters tend to reach much greater distances than high frequency transmitters at the same power.

Longer waves pass around obstacles

A wave on water which is 5 metres long will not be affected by a 5 mm piece of wood floating on the water. If instead the piece of wood were 50 metres big (e.g. a ship), it would modify the behavior of the wave.

The distance a wave can travel depends on the relationship between the wavelength of the wave and the size of obstacles in its path of propagation. It is harder to visualize waves moving "through" solid objects, but this is the case with electromagnetic waves. Longer wavelength (and therefore lower frequency) waves tend to penetrate objects better than shorter wavelength (and therefore higher frequency) waves.

For example, FM radio (88-108 MHz) can travel through buildings and other obstacles easily, while shorter waves (such as GSM phones operating at 900 MHz or 1800 MHz) have a harder time penetrating buildings.

This effect is partly due to the difference in power levels used for FM radio and GSM, but is also partly due to the shorter wavelength of GSM signals. At much higher frequencies, visible light does not go through a wall or even 1 mm of wood - as we all know, from practical experience.

But metal will stop any kind of electromagnetic wave.

Shorter waves can carry more data

The faster the wave swings or beats, the more information it can carry - every beat or cycle could for example be used to transport a digital bit, a '0' or a '1', a 'yes' or a 'no'.

So the data rate scales with bandwidth, and can be further enhanced by advanced modulation and media access techniques such as OFDM, and MIMO (Multiple Input, Multiple Output).

The Huygens Principle

There is another principle that can be applied to all kinds of waves, and which is extremely useful for understanding radio wave propagation.

This principle is known as the ***Huygens Principle***, named after Christiaan Huygens, Dutch mathematician, physicist and astronomer, 1629 - 1695.

Imagine you are taking a little stick and dipping it vertically into a still lake's surface, causing the water to swing and dance. Waves will leave the centre of the stick - the place where you dip in - in circles. Now, wherever water particles are swinging and dancing, they will cause their neighbor particles to do the same: from every point of disturbance, a new circular wave will start. This is, in simple form, the Huygens principle. In the words of wikipedia.org:

“The Huygens' principle is a method of analysis applied to problems of wave propagation in the far field limit. It recognizes that each point of an advancing wave front is in fact the centre of a fresh disturbance and the source of a new train of waves; and that the advancing wave as a whole may be regarded as the sum of all the secondary waves arising from points in the medium already traversed”.

This view of wave propagation helps better understand a variety of wave phenomena, such as diffraction.” This principle holds true for radio waves as well as waves on water, for sound as well as light, but for light the wavelength is far too short for human beings to actually see the effects directly.

This principle will help us to understand diffraction as well as Fresnel zones, and the fact that sometimes we seem to be able to transmit around corners, with no line of sight.

Let us now look into what happens to electromagnetic waves as they travel.

Absorption

When electromagnetic waves go through 'something' (some material), they generally get weakened or dampened.
How much they lose in power will depend on their frequency and of course the material.
Clear window glass is obviously transparent for light, while the glass used in sunglasses filters out quite a share of the light intensity and most of the ultraviolet radiation.
Often, an absorption coefficient is used to describe a material’s impact on radiation.

For microwaves, the two main absorbent materials are:

Metal. Electrons can move freely in metals, and are readily able to swing and thus absorb the energy of a passing wave.
Water. Microwaves cause water molecules to jostle around, thus taking away some of the wave’s energy.

For the purpose of practical wireless networking, we may well consider metal and water perfect absorbers: we will not be able to go through them (although thin layers of water will let some power pass). They are to microwave what a brick wall is to light.

When talking about water, we have to remember that it comes in different forms: rain, fog and mist, low clouds and so forth, all will be in the way of radio links. They have a strong influence, and in many circumstances a change in weather can bring a radio link down.

When talking about metal, keep in mind that it may be found in unexpected places: it may be hidden in walls (for example, as metal grids in concrete) or be a thin coat on modern types of glass (tinted glass, colored glass).
However thin the layer of metal, it might be enough to significantly absorb a radio wave.

There are other materials that have a more complex effect on radio absorption. For trees and wood, the amount of absorption depends on how much water they contain.

Old dead dry wood is more or less transparent, wet fresh wood will absorb a lot. Plastics and similar materials generally do not absorb a lot of radio energy, but this varies depending on the frequency and type of material.
Lastly, let us talk about ourselves: humans (as well as other animals) are largely made out of water.

As far as radio networking is concerned, we may well be described as big bags of water, with the same strong absorption.
Orienting an office access point in such a way that its signal must pass through many people is a key mistake when building office networks.
The same goes for hotspots, cafe installations, libraries, and outdoor installations.

Reflection

Just like visible light, radio waves are reflected when they come in contact with materials that are suited for that: for radio waves, the main sources of reflection are metal and water surfaces.
The rules for reflection are quite simple: the angle at which a wave hits a surface is the same angle at which it gets deflected.

Note that in the eyes of a radio wave, a dense grid of bars acts just the same as a solid surface, as long as the distance between bars is small compared to the wavelength.

At 2.4 GHz, a one cm metal grid will act much the same as a metal plate.

Although the rules of reflection are quite simple, things can become very complicated when you imagine an office interior with many many small metal objects of various complicated shapes.
The same goes for urban situations: look around you in city environment and try to spot all of the metal objects.

This explains why ***multipath effects*** (i.e. signal reaching their target along different paths, and therefore at different times) play such an important role in wireless networking.
Water surfaces, with waves and ripples changing all the time, effectively make for a very complicated reflection object which is more or less impossible to calculate and predict precisely.

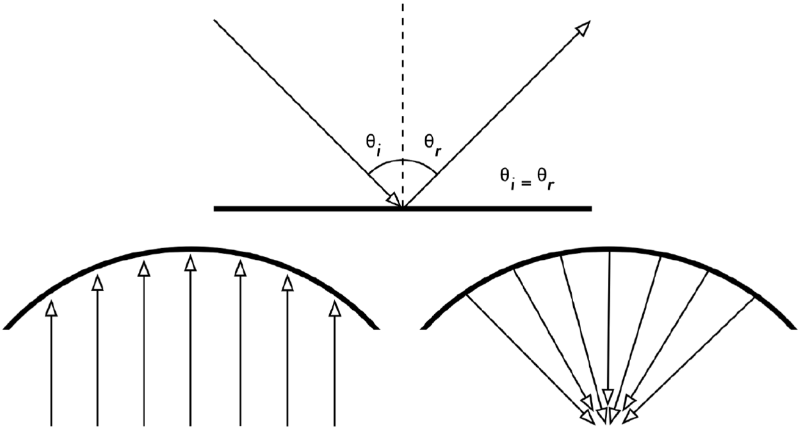

Figure RP 6: Reflection of radio waves. The angle of incidence is always equal to the angle of reflection. A metal parabolic surface uses this effect to concentrate radio waves spread out over it in a common direction.

We should also add that polarization has an impact: waves of different polarization in general will be reflected differently.

We use reflection to our advantage in antenna building: e.g. we put huge parabolas behind our radio transmitter/receiver to collect and bundle the radio signal into a single point, the focal point.

Diffraction

Diffraction is the apparent bending of waves when hitting an object.

It is the effect of "waves going around corners". Imagine a wave on water traveling in a straight wave front, just like a wave that we see rolling onto an ocean beach.

Now we put a solid barrier, say a wooden solid fence, in its way to block it. We cut a narrow slit opening into that wall, like a small door.

From this opening, a circular wave will start, and it will of course reach points that are not in a direct line behind this opening, but also on either side of it. If you look at this wavefront - and it might just as well be an electromagnetic wave - as a beam (a straight line), it would be hard to explain how it can reach points that should be hidden by a barrier.

When modelled as a wavefront, the phenomenon makes sense.

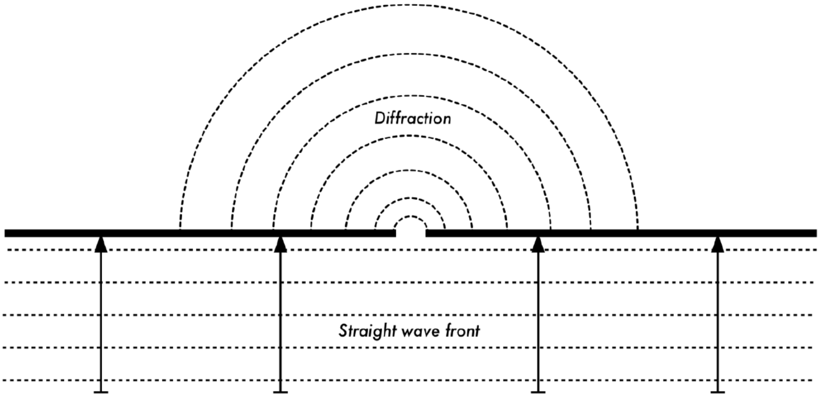

Figure RP 7: Diffraction through a narrow slit.

The Huygens Principle provides one model for understanding this behavior. Imagine that at any given instant, every point on a wavefront can be considered the starting point for a spherical "wavelet".
This idea was later extended by Fresnel, and whether it adequately describes the phenomenon is still a matter of debate. But for our purposes, the Huygens model describes the effect quite well.

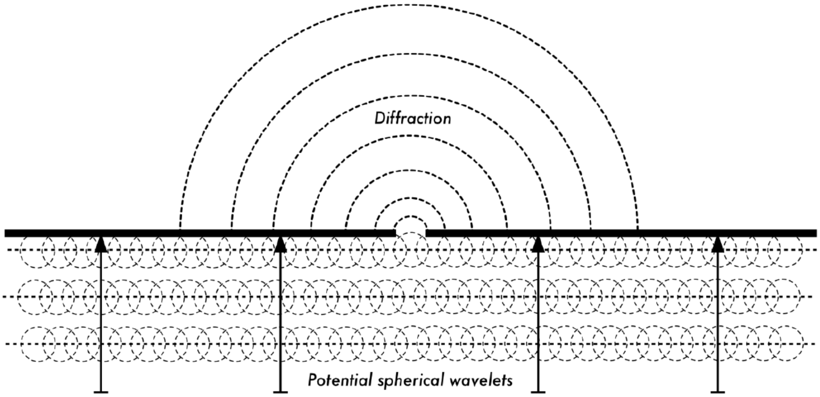

Figure RP 8: The Huygens Principle.

Through means of the effect of diffraction, waves will "bend" around corners or spread through an opening in a barrier.

The wavelengths of visible light are far too small for humans to observe this effect directly.
Microwaves, with a wavelength of several centimeters, will show the effects of diffraction when waves hit walls, mountain peaks, and other obstacles. It seems as if the obstruction causes the wave to change its direction and go around corners.

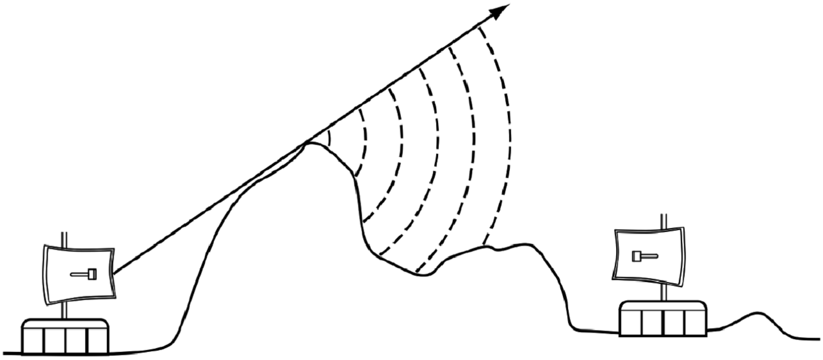

Figure RP 9: Diffraction over a mountain top.

Note that diffraction comes at the cost of power: the energy of the diffracted wave is significantly less than that of the wavefront that caused it. But in some very specific applications, you can take advantage of the diffraction effect to circumvent obstacles.

Interference

Interference is one of the most misunderstood terms and phenonema in wireless networking.
Interference often gets the blame when we are too lazy to find the real problem, or when a regulator wants to shut down someone else's network for business reasons. So, why all the misunderstandings?
It is mostly because different people mean different things though they are using the same word.
A physicist and a telecommunications engineer will use the word "Interference" in very different ways. The physicists' view will be concerned with the "behaviour of waves". The telecommunications engineer will talk about “... any noise that gets in the way”.

Both views are relevant in wireless, and it is important to be able to know them both and know the difference. Let us start with the physicists' view: When working with waves, one plus one does not necessarily equal two. It can also result in zero.

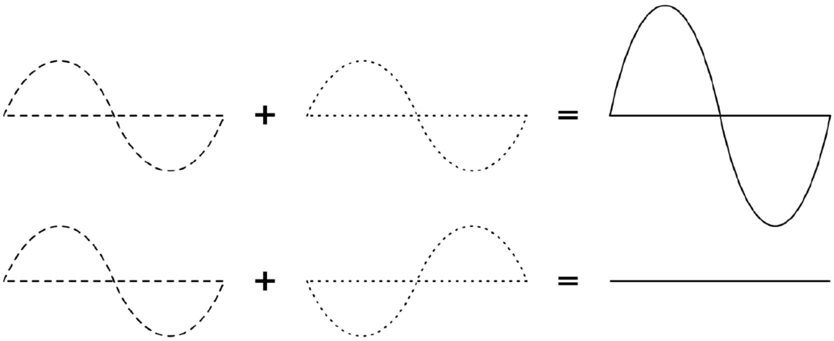

Figure RP 10: Constructive and destructive interference.

This is easy to understand when you draw two sine waves and add up the amplitudes. When the phase difference is zero, peak hits peak, and you will have maximum results (1 + 1 = 2).
This is called ***constructive interference***.
When the phase difference is 180 degrees, or λ/2, peak hits valley, and you will have complete annihilation ((1 + (-)1 = 0) - ***destructive interference***.
You can actually try this with waves on water and two little sticks to create circular waves - you will see that where two waves cross, there will be areas of higher wave peaks and others that remain almost flat and calm. In order for whole trains of waves to add up or cancel each other out perfectly, they have to have the exact same wavelength and a fixed phase relation.

You can see obvious examples of interference in action when you look at the way that antennas are arranged in what are called ***beamforming*** arrays, in order to give maximum constructive interference in the directions where you want the signal, and destructive interference (no signal) where you want no signal.
Technically, this is achieved by a combination of physical dimensioning and control of phase shifts.

Simplified, imagine that you have three antennas - and you don't want antenna 3 to pick up signal from antenna 1 and 2. You would then place antenna 3 at a position where the signals from antennas 1 and 2 cancel each other out.

Now let us have a look at the way the word interference is typically used: in a wider sense, for any disturbance through other RF sources, any noise that might get in our way, e.g. from neighboring channels or competing providers. So, when wireless networkers talk about interference they typically talk about all these kinds of disturbance by other networks, and any other sources of microwave, whether it has exactly the same frequency and a fixed phase relation or not. Interference of this kind is one of the main sources of difficulty in building wireless links, especially in urban environments or closed spaces (such as a conference space) where many networks may compete for use of the spectrum.

But, interference of this kind is also often overrated: for example, imagine you had to build a point to point link that has to cross a crowded inner city area, before reaching its target on the other side of the city. Such a highly directional beam will cross the "electric smog" of the urban centre without any problem. You may imagine this like a green and a red light beam crossing each other in a 90 degrees angle: while both beams will overlap in a certain area, the one will not have any impact on the other at all.

Generally, managing spectrum and coexistence has become a main issue especially in dense indoor environments and urban areas.

Line of sight

The term ***line of sight***, often abbreviated as ***LOS***, is quite easy to understand when talking about visible light: if we can see a point B from point A where we are, we have line of sight. Simply draw a line from A to B, and if nothing is in the way, we have line of sight.

Things get a bit more complicated when we are dealing with microwaves. Remember that most propagation characteristics of electromagnetic waves scale with their wavelength.

This is also the case for the widening of waves as they travel.

Light has a wavelength of about 0.5 micrometres, microwaves as used in wireless networking have a wavelength of a few centimetres.

Consequently, their beams are a lot wider - they need more space, so to speak.

Note that visible light beams widen just the same, and if you let them travel long enough, you can see the results despite their short wavelength. When pointing a well focussed laser at the moon, its beam will widen to well over 100 metres in radius by the time it reaches the surface. You can see this effect for yourself using an inexpensive laser pointer and a pair of binoculars on a clear night. Rather than pointing at the moon, point at a distant mountain or unoccupied structure (such as a water tower). The radius of your beam will increase as the distance increases. This is due to the diffraction.

The line of sight that we need in order to have an optimal wireless connection from A to B is more than just a thin line - its shape is more like that of a cigar, an ellipsoid. Its width can be described by the concept of Fresnel zones - see next section for an explanation. You will also find the abbreviation ***NLOS***, for "non line of sight", which is mostly used to describe and advertise technologies that allow for dealing with waves that reach the receiver through multiple trajectories (multipath) or diffraction. It does not indicate that the single electromagnetic beam goes "around corners" (other than through diffraction) or "through obstacles" any better than that of other technologies. For example, you might call White Space technology NLOS, as its lower frequencies (longer wavelengths) allow it to permeate objects and utilize diffraction much better than comparable 2.4 GHz or 5 GHz transmissions.

Understanding the Fresnel zone

The exact theory of Fresnel (pronounced “Fray-nell”) zones is quite complicated. However, the concept is quite easy to understand: we know from the Huygens principle that at each point of a wavefront new circular waves start, we know that microwave beams widen as they leave the antenna, we know that waves of one frequency can interfere with each other. Fresnel zone theory simply looks at a line from A to B, and then at the space around that line that contributes to what is arriving at point B. Some waves travel directly from A to B, while others travel on paths off axis and reach the receiver by reflection.

Consequently, their path is longer, introducing a phase shift between the direct and indirect beam.

Whenever the phase shift is one half wavelength, you get destructive interference: the signals cancel.

Taking this approach you find that when the reflected path is less than half a wavelength longer than the direct path, the reflections will add to the received signal. Conversely, when the reflected path length exceeds the direct path by more than one half wavelength, its contribution will decrease the received power.

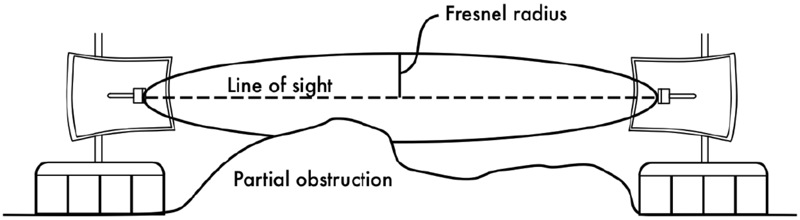

Figure RP 11: The Fresnel zone is partially blocked on this link, although the visual line of sight appears clear.

Note that there are many possible Fresnel zones, but we are chiefly concerned with the first zone, because the contributions from the second zone are negative. The contributions from the third zone are positive again, but there is no practical way to take advantage of those without the penalty incurred in going through the second Fresnel Zone.

If the first Fresnel zone is partially blocked by an obstruction, e.g. a tree or a building, the signal arriving at the far end would be diminished. When building wireless links, we therefore need to be sure that the first zone is kept free of obstructions. In practice, it is not strictly necessary that the whole of this zone is clear, in wireless networking we aim to clear about 60 percent of the radius of the first Fresnel zone.

Here is one formula for calculating the radius of the first Fresnel zone:

$$r=17.31\sqrt{\left(\frac{(d_1*d_2)}{(f*d)}\right)}$$

...where r is the radius of the zone in metres, d_1 and d_2 are distances from the obstacle to the link end points in metres, d is the total link distance in metres, and f is the frequency in MHz.

The first Fresnel zone radius can also be calculated directly from the wavelength as:

$$r = \sqrt{\left(\frac{\lambda * d_1 * d_2}{d}\right)}$$

with all the variables in metres

It is apparent that the maximum value of the first Fresnel zone happens exactly in the middle of the trajectory and its value can be found setting $d_1=d_2=d/2$ in the preceding formulas.Note that the formulae give you the radius of the zone, not the height above ground.

To calculate the height above ground, you need to subtract the result from a line drawn directly between the tops of the two towers.

For example, let's calculate the size of the first Fresnel zone in the middle of a 2 km link, transmitting at 2.437 GHz (802.11b channel 6):

$$r = 17.31\sqrt{\left[\frac{(1000 * 1000)}{(2437 * 2000)}\right]}$$

$$r = 17.31\sqrt{\left(\frac{1000000}{4874000}\right)}$$

r = 7.84 metres

Assuming both of our towers were ten metres tall, the first Fresnel zone would pass just 2.16 metres above ground level in the middle of the link.

But how tall could a structure at that point be to block no more than 60% of the first zone?

*r = 0.6 * 7.84 metres*
r = 4.70 metres

Subtracting the result from 10 metres, we can see that a structure 5.3 metres tall at the centre of the link would block up to 40% of the first Fresnel zone.

This is normally acceptable, but to improve the situation we would need to position our antennas higher up, or change the direction of the link to avoid the obstacle.

Power

Any electromagnetic wave carries energy - we can feel that when we enjoy (or suffer from) the warmth of the sun.
The amount of energy divided by the time during which we measure it is called power. The power ***P*** is measured in W (watts) and is of key importance for a wireless links to work: you need a certain minimum power in order for a receiver to make sense of the signal.

We will come back to details of transmission power, losses, gains and radio sensitivity in the chapter called *Antennas/Transmission Lines.*

Here we will briefly discuss how the power P is defined and measured.
The electric field is measured in V/m (potential difference per metre), the power contained within it is proportional to the square of the electric field:

$$P \sim E^2$$

Practically, we measure the power in watts by means of some form of receiver, e.g. an antenna and a voltmetre, power metre, oscilloscope, spectrum analyser or even a radio card and laptop.
Looking at the signal's power directly means looking at the square of the signal in volts and dividing by the electrical resistance.

Calculating with dB

By far the most important technique when calculating power is calculating with decibels (dB). There is no new physics hidden in this - it is just a convenient method which makes calculations a lot simpler.

The decibel is a dimensionless unit, that is, it defines a relationship between two measurements of power. It is defined by:

$$dB = 10 * Log (P_1 / P_0)$$

where P_1 and P_0 can be whatever two values you want to compare. Typically, in our case, this will be some amount of power.
Why are decibels so handy to use? Many phenomena in nature happen to behave in a way we call exponential.

For example, the human ear senses a sound to be twice as loud as another one if it has ten times the physical signal power.

Another example, quite close to our field of interest, is absorption. Suppose a wall is in the path of our wireless link, and each metre of wall takes away half of the available signal. The result would be:

0 metres = 1 (full signal)
1 metre = 1/2
2 metres = 1/4
3 metres = 1/8
4 metres = 1/16
n metres = $1/2^n = 2^{-n}$

This is exponential behaviour.

But once we have used the trick of applying the logarithm (log), things become a lot easier: instead of taking a value to the n-th power, we just multiply by n. Instead of multiplying values, we just add.

Here are some commonly used values that are important to remember:

+3 dB = double power
-3 dB = half the power
+10 dB = order of magnitude (10 times power)
-10 dB = one tenth power

In addition to dimensionless dB, there are a number of definitions that are based on a certain base value P_0. The most relevant ones for us are:

dBm relative to $P_0 = 1\ mW$
dBi relative to an ideal isotropic antenna

An isotropic antenna is a hypothetical antenna that evenly distributes power in all directions.

It is approximated by a dipole, but a perfect isotropic antenna cannot be built in reality. The isotropic model is useful for describing the relative power gain of a real world antenna.

Another common (although less convenient) convention for expressing power is in milliwatts. Here are equivalent power levels expressed in milliwatts and dBm:

1 mW = 0 dBm
2 mW = 3 dBm
100 mW = 20 dBm
1 W = 30 dBm

For more details on dB refer to the dB math lecture of the Wireless Training kit:
http://wtkit.org/sandbox/groups/wtkit/wiki/820cb/attachments/ebdac/02-dB_Math-v1.12_with-notes.pdf

Physics in the real world

Don't worry if the concepts in this chapter seem challenging. Understanding how radio waves propagate and interact with the environment is a complex field of study in itself.

Most people find it difficult to understand phenomenon that they can't even see with their own eyes.

By now you should understand that radio waves don't travel only in a straight, predictable path.

To make reliable communication networks, you will need to be able to calculate how much power is needed to cross a given distance, and predict how the waves will travel along the way.