Training & Support

OPEN KNOWLEDGE

A Hitchhiker’s Guide

to the

UBNT Wireless Networking Galaxy

PART 1 >

RF Primer

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Introduction

Before you even start to think about engaging yourself in the wireless industry, you ought to better know some fundamental facts about the technology that will enable your business.

It is probably true that any advanced RF engineering works do include either some sort of voodoo, esoteric incantations or perhaps just black magic to make it all work - even if the engineers deny it... But:

DON'T PANIC!

Radio Frequency (RF) technology has become ubiquitous in today's world. Satellites, TV, Radio, cell phones, GPS navigation, Police radio, Train control and signaling systems – all of these telecommunication systems heavily depend on RF technology.

Not too long ago, none of it meant all that much to most *IT folks*. With the advent of the Wireless LAN or sometimes Radio LAN (WLAN/RLAN) at the end of the last century, RF technology slowly worked its way into the ever increasing number of computers, mobile devices and networks out there. This has created the need for a deeper understanding of the underlying technology and principles - for admins, programmers, CEOs, CIOs, consultants, engineers, resellers, supporters and users alike.

Don't worry. This primer will try to show you just some very basic concepts and essential principles, and will try to explain things as intuitively as possible. I won't go into difficult mathematics and I shall use a lot of pictures and figures to illustrate everything.

You might still find the reading well worth, because you don't necessarily need to become a diploma RF engineer to work with WLAN gear: Knowing a few basic facts and understanding some of the key concepts behind the technology will greatly aid you on your quest to get the most out of your UBNT gear.

Chris Burri
Burri IT Systems

1. Radio Frequency?

Technically, the term “Radio Frequency” refers to an oscillating electromagnetic field, or radiation. So, how does it work and what’s the benefit?

Let’s start our quest for enlightenment by asking Wikipedia what it has to say about it all:

> ***Wikipedia says…***
>
> *Electric currents that oscillate at radio frequencies have special properties not shared by direct current or alternating current of lower frequencies. The energy in an RF current can radiate off a conductor into space as electromagnetic waves (radio waves); this is the basis of radio technology.*
>
> *RF current does not penetrate deeply into electrical conductors but flows along their surfaces; this is known as the skin effect. For this reason,* ***when the human body comes in contact with high power RF currents it can cause superficial but serious burns called RF burns****.*
>
> *RF current can easily ionize air, creating a conductive path through it. This property is exploited by "high frequency" units used in electric arc welding, which use currents at higher frequencies than power distribution uses.*
>
> *Another property is the ability to appear to flow through paths that contain insulating material, like the dielectric insulator of a capacitor.*
>
> *When conducted by an ordinary electric cable, RF current has a tendency to reflect from discontinuities in the cable such as connectors and travel back down the cable toward the source, causing a condition called standing waves, so RF current must be carried by specialized types of cable called transmission line.*

RF energy, also known as Radio Wave is electromagnetic energy (which can become dangerous at higher power levels, note the warning above) that emits from a source and travels through free space.

WLAN leverages RF technology to transmit digital information across a distance. This is done by modulating the frequency (carrier) with the data payload. Many different modulation schemes exist. You might have heard of AM and FM modulation – this is what was used for analogue Radio broadcasting. The modulation changes pieces of information into a signal that can be put on the airwaves. The receiver attempts to demodulate the signal to obtain the original information.

The benefit is mobility and, potentially, ease of operation due to non-existent wiring having NOT to be set up.

2. The inverse-square law

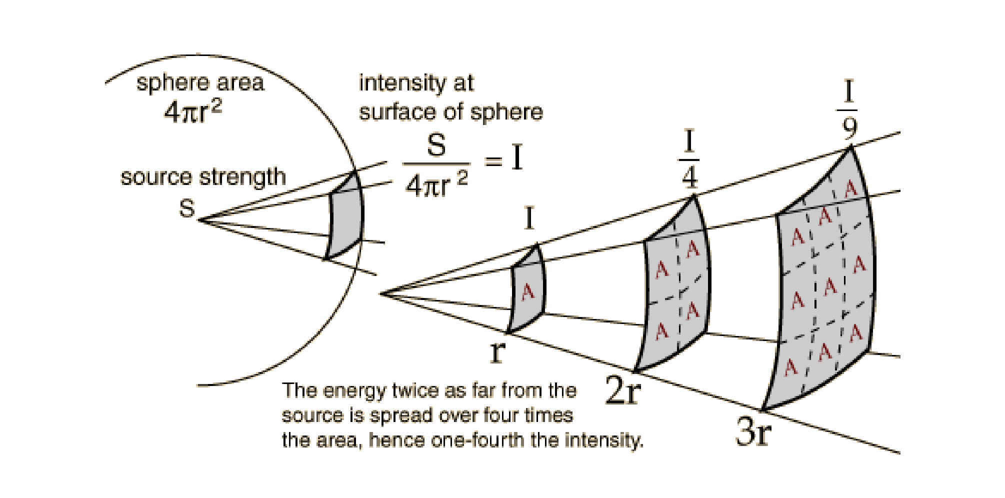
First of all, the signal doesn't travel on forever. After a distance long enough, it will have gotten so faint that a receiver cannot successfully decode it (or even detect its presence) anymore: The signal gets attenuated as it expands through space. Just how much can be roughly predicted by inverse-square law, which states that the power density of an electromagnetic wave is proportional to the inverse of the square of the distance from a point source. Engineers express this as:

$$\rho_P \propto \frac{1}{r^2}.$$

The signal dilutes and spreads all over the volume of space that it travels through. Just like the bright spot a flashlight produces on a perpendicular surface expands in diameter and loses its brilliance as you direct the beam towards a surface located further away.

Doubling the distance reduces the power density of the radiated wave to one-quarter of the original value, because the irradiated area is then 4 times the original size:

The inverse-square law:



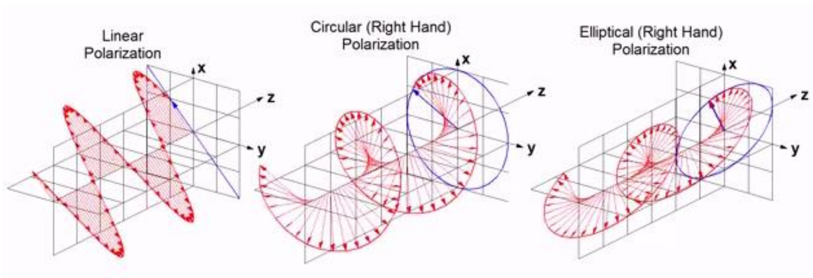
This means that any RF signal is going to be useful only within a given distance from the transmitter. Naturally, more TX power means greater range, but that doesn't always hold up in practice. Plus with WLAN networking, there's a special twist to it: The ACK timeout. We'll get to that later.

Just keep in mind for now that there are several possibilities to increase a WLAN's range. A higher transmit power is the most obvious but that's not always efficient, and sometimes it might not help at all or prove counter-effective.

3. Polarization

Because the electromagnetic wave is, well…a wave, it does have polarization. There are other polarization types but linear polarization can be thought of as the movement of water, as ripples move along its surface. These figures will illustrate the principle quite effectively:

Understanding Polarization:



Animation: http://www.youtube.com/watch?v=Q0qrU4nprB0

Linear	**Circular**	**Eliptical**
Horizontal	Right Hand	Right Hand
Vertical	Left Hand	Left Hand

Polarization is not limited to RF waves. It rather is a property of any wave. As such, it’s important to many aspects of our modern day lives, even if we don’t usually notice it. It’s the basic principle behind the famous Polaroid sunglasses, and also works at the core of each and every LCD display there is, just to name two prominent examples. A signal’s polarization depends on the aerial and the way it is mounted; we’ll cover that a bit later on.

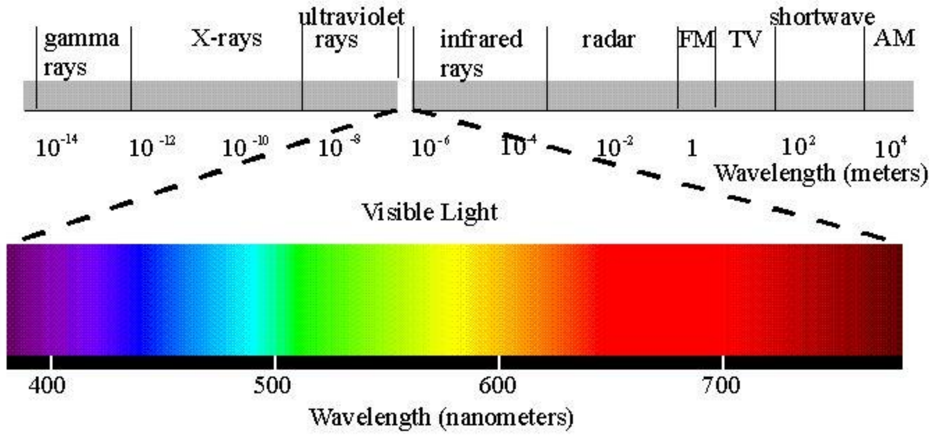
4. Frequency

The rate at which the wave oscillates per second, or at which the photons move back and forth along the wave’s polarization, is designated the Frequency. Frequencies are commonly measured in Hertz (Hz) or a multiple thereof. Those orders of magnitude are commonly used: 1000Hz = 1kHz, 1000kHz = 1MHz, 1000MHz = 1GHz, 1000GHz = 1THz.

The audible spectrum begins down at around 20Hz and reaches up to 20kHz, for young people. Common WLAN gear operates at frequencies around 2.4GHz (802.11b/g/n) and 5.5GHz (802.11a/n), whereas GSM networks operate at lower (900MHz, 1800MHz, 2100MHz) and DVB-S TV broadcasting at much higher frequencies (12GHz) in the electromagnetic spectrum. High speed microwave backhauls operate between 60GHz and 80GHz. Visible light can be found in a much, much higher band at 405THz to 790THz.

Currently, the use of so called TV White Space for wireless subscriber connections is a hot topic in the US. This large, unused spectrum between 50MHz and 700MHz results from abandonment of analog TV broadcasting systems. For most of the world outside the US, this technology is only marginal, as the whitespace is being reallocated for DAB, DAB+ and DMB digital audio broadcasting standards everywhere else.

An overview of the electromagnetic frequency spectrum:



Visible light occupies a relatively small band between ultraviolet (shorter waves) and infrared (longer waves) at an insanely high frequency. The high frequency of light is also the reason why fiber optics can (but don't have to per se) provide very much higher data transfer rates than any copper based system ever will be able to offer.

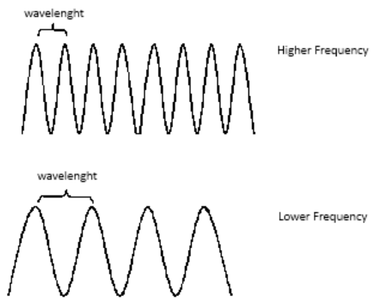
TV whitespace is such a hot topic because these relatively low frequencies allow for a better penetration of obstacles, such as the walls of a building. Life would be so much easier for WISPs and their customers if the CPE could be sent by mail and simply placed indoors by the customer themselves – just as it is common practice with cable and DSL based CPEs.

5. Wavelength

A signal's wavelength is the distance that a full up/down wave cycle covers. This is of course directly related to the signal's frequency: A higher rate of oscillation will result in smaller wave cycles, thereby reducing the wavelength and a lower frequency will result in longer wave cycles, thereby increasing the wavelength.

The wavelength is commonly expressed as Lambda $\lambda = V/f$, where V is the phase speed (which is the speed of light for electromagnetic radiation in free space) and f is the signal's frequency. The following diagram illustrates the relation between frequency and wavelength:

The relation of Frequency and Wavelenght:



6. RF transparency

An important factor is RF transparency. It was mentioned earlier, not everything that is transparent to visible light is also transparent to RF waves and vice versa. Take cardboard for example; cardboard lets RF through while it blocks light. This changes however dramatically when the cardboard gets wet: RF can't pass through anymore.

Why is that? Because water molecules are being excited by the RF energy, and in the process, absorb that energy. The water molecules start to oscillate and this p roduces heat. Trees for example, contain a lot of water (in the leaves) and hence absorb a lot of signal. And while it's highly unlikely that you'll cook or even set fire to a tree by pointing your WLAN antenna at it, the signal will be attenuated - possibly to the point where it can't get past the obstacle. So you should try to avoid trees or place your aerials well above them wherever possible.

Interestingly enough, ice by itself is "transparent" to radio waves in such sense that virtually no RF energy is absorbed and thus no heating occurs. This may seem strange at first because ice is really just frozen water and you can easily boil water in a microwave. So how could ice possibly be transparent to microwaves? Because the water molecules in the ice are held rigidly in place and can't rotate in response to the RF field hence no absorption takes place and the RF energy passes through. Naturally, this only applies to *dry* ice or snow. Also note that ice on any aerial is still not a good thing due to impedance mismatch. With power levels above a few Watts, impedance mismatch can easily kill a transmitter!

Conducting materials such as metal may completely block RF, even if the material does not have a rigid body structure – such as a bug screen. Any space completely enclosed by such materials will behave similar to a Faraday cage. That's why reinforced concrete walls can pose massive problems to indoor wireless installs.

Faraday Cage:

A **Faraday cage** or **Faraday shield** is an enclosure formed by conducting material or by a mesh of such material. Such an enclosure blocks out external static and non-static electric fields. Faraday cages are named after the English scientist Michael Faraday, who invented them in 1836.

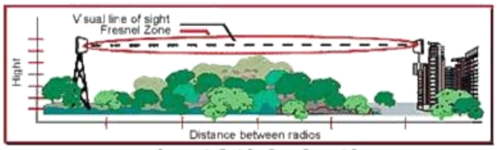
Note that -just like your UBNT gear- a Faraday Cage needs proper grounding for safe operation.

Metal shielding can thus be employed to prevent unwanted RF from entering your antenna or AP. There are several specialized shielding kits for UBNT gear, available from RFarmor.

7. Line of Sight

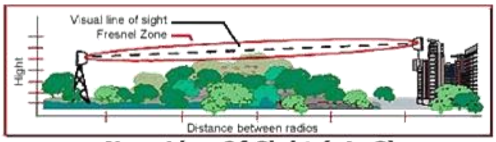
There are various modes of propagation for a wireless signal. Most important to WLAN was (and probably will be for some time to come) Line of Sight, or LoS mode. Here –as the name implies- exists a direct, unobstructed path between sender and receiver. Note that this “Line of Sight” applies from a RF point of view: While visible (to the human eye) light is unable to penetrate an opaque piece of cardboard, an RF wave will encounter no difficulties in doing so. Light, on the other hand, easily passes through a metal bug screen while RF waves won’t.

Line of Sight definition:



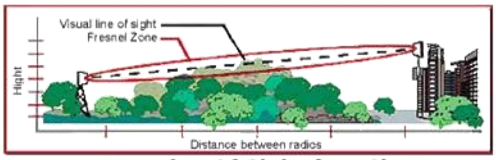
Line Of Sight (LoS)

LoS
There is a direct Line of Sight between the RX and TX aerials. The Fresnel zone is clean.



Near Line Of Sight (nLoS)

nLoS
There is a direct Line of Sight between the RX and TX aerials. The Fresnel zone is partly shadowed by obstructions.



Non Line Of Sight (NLoS)

NLoS
There is no direct Line of Sight between the RX and TX aerials. The Fresnel zone is partly or completely obstructed.

With Line of Sight mode, only “Free Space Loss” is of relevance. Free space loss is due to the distance between the sites and may also be referred to as “line of sight loss”. Calculate Free Space Loss as follows:

FSL (dB) = 36.57 + 20*log10 (Distance in miles) + 20*log10 (Frequency in MHz)

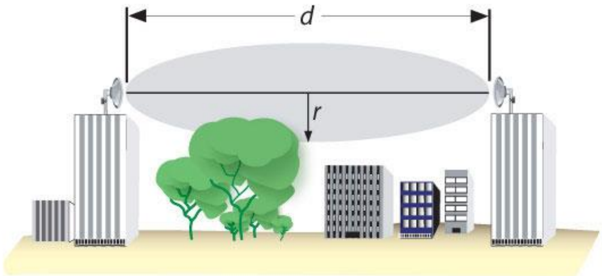
The other modes involve diffraction. Diffraction is what occurs when a wave hits an edge and gets bent around that edge and diffraction loss is the result of the radio wave hitting hills, buildings, trees and whatnot along its path.

8. Fresnel Zone

A very important aspect of any wireless link is the Fresnel zone. This is an area around the signal that has the shape of a cigar and extends between sender and receiver. This encompasses the volume in space that the signal is likely to "occupy" while travelling between transmitter (TX) and receiver (RX). If an object (such as the Earth itself) touches the zone's boundaries or penetrates into it, signal reflections will occur.

The size of the Fresnel zone can be calculated from the signal's frequency and the distance:

Calculating the Fresnel zone:



$$r_{(\text{in mts})} = 17.32 \times \sqrt{\frac{d_{(\text{in Km})}}{4f_{(\text{in GHz})}}} \qquad r_{(\text{in ft})} = 72.05 \times \sqrt{\frac{d_{(\text{in miles})}}{4f_{(\text{in GHz})}}}$$

Obstructions to the Fresnel zone result in signal attenuation through deflection – even if receiver and sender do still have Line of Sight. If 50% of the Fresnel zone is obstructed, then you can expect an extra 6dB loss on that particular link. Also, for longer links, the Earth's surface curvature itself becomes relevant and you'll need to take it into account when planning your setup.

In fact, there's more than one Fresnel zone, even an infinite number of them. However, only the first 3 of them matter in practice. The difference between them is the degree of phase shift that occurs between the reflected and the original signal.

Now, the radius of F1 is calculated in such way that the phase shift due to path length difference is 180°. The 180° shifting due to signal reflection adds up with the 180° shifting caused by that path length difference, resulting in a 360° overall phase shift. 360° means a full circle, and so both signals are in phase again.

F2 radius has a path length difference of 360°, resulting in a 540° shift, which is equal to a 180° shift. These two signals are cancelling each other out at the receiver, hence why F2 is of special interest. F3 has 540° path length difference shift, resulting in 720° total, the signals are in phase.

To make your wireless life a little bit easier, UBNT has got AirLink for you at www.ubnt.com/airlink. It's a link calculator based on Google maps and it takes the local terrain into account. Rather simplistic to use, and certainly far from perfect - but it helps you to get a basic overview of your particular link situation, quick.

X. Signal Propagation Modes

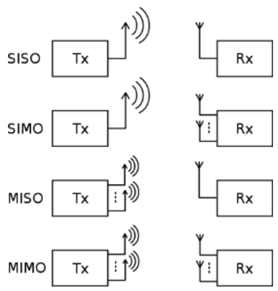
9. MIMO Systems and Non-LoS

A different mode of propagation for RF waves which becomes increasingly important in the WLAN world is the non-LoS mode. Advancements in RF engineering have brought us a set of techniques and algorithms that can be grouped together under the term “MIMO”.

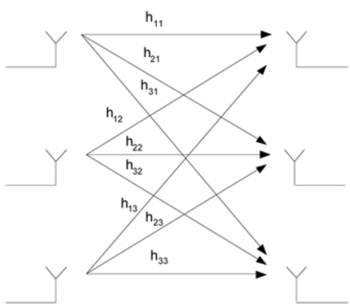
MIMO stands for multiple-input and multiple-output. At their very core, all MIMO systems share one common principle: The use of multiple transmission paths between both the transmitter and receiver to improve communication performance.

The various paths between the TX location and the RX location, through the transmission medium, form what is called the channel matrix in a MIMO system. MIMO systems differ by the size of their channel matrix and the number of available paths though that matrix:

MIMO variants:



Possible MIMO configurations



The channel matrix

Note that the inputs and outputs described refer to the channel matrix, and not to the involved devices. Hence, a transmitter with multiple TX paths produces multiple inputs to, whereas a receiver with multiple RX paths taps multiple outputs from the channel matrix.

MIMO systems provide certain benefits when compared to traditional radio systems. These are: increased range, increased throughput or increased resilience against interference or a combination of these three. Implementations however vary by vendor and even model, and may be incompatible with others.

9.1. SIMO Systems

A rather simple variant, known as SIMO (Single Input Multiple Output) dates way back, and has been extensively used in the entertainment industry for ages: Wireless microphone systems featuring antenna diversity on the receiving end.

Diversity basically means: having more than one option available. With these wireless microphones, a second RX antenna on the base station presents a spatially different path the system can use, should the path between the sender (microphone) and the primary RX antenna (base station) experience degradation.

Sennheiser cordless microphone with antenna diversity:

These first-generation systems continue to meet application requirements to this day.

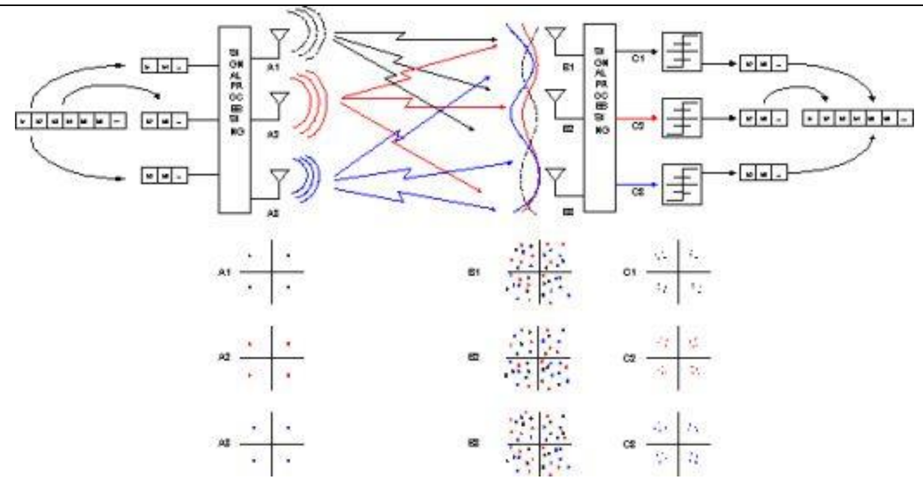
9.2. True MIMO Systems

True forms of MIMO leverage multiplexing for improved link bandwidth. Relatively simple forms of multiplexing are polarization and channel multiplexing. Channel multiplexing (bonding) is employed by 802.11n capable WLAN gear. By bonding two distinct non-interfering channels together, the bandwidth available for data transfer can be nearly doubled.

There is also polarization multiplexing. This works because if a signal arrives at an aerial which doesn't match the polarization of the TX antenna or if the polarization was shifted during transit, the signal is attenuated quite strongly. If the polarizations mismatch by 45°, attenuation will be 3dB. If polarizations mismatch by 90°, a loss of 20dB or even more will be incurred. Thus, signals with different polarization can be easily discerned in a receiver, which makes it possible to transmit simultaneously at the same frequency, using two (or more) distinct polarizations.

The most recent developments in advanced RF engineering and theoretical mathematics gave rise to the marvelous, highly sophisticated algorithms of spatial multiplexing. Spatial multiplexing capitalizes on the fact that two signals, sent simultaneously on the same spectrum but from distinct locations can –by the ways of some black-arts RF engineering and unearthly math genius wizardry- be sufficiently discerned in a receiver, so that they may both be individually and completely restored.

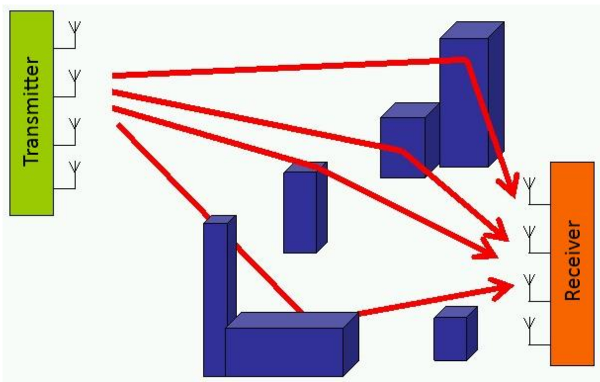
Spatial multiplexing:



In a multipath environment, each path will have its own spatial signature. Based on this spatial signature sub-streams of data across different paths will be demultiplexed and decoded in order to get back the original data stream.

This enables multipath propagation – key in attaining Non-LoS WLAN communications. Signals received are combined in such way, that normally destructive multipath fading and interference caused by reflections and different attenuations across different spatial paths of the signal can be leveraged to actually enhance the transmission quality. This particular feature is also what enables non-LoS links in the higher frequency bands:

Multipath propagation in MIMO systems:

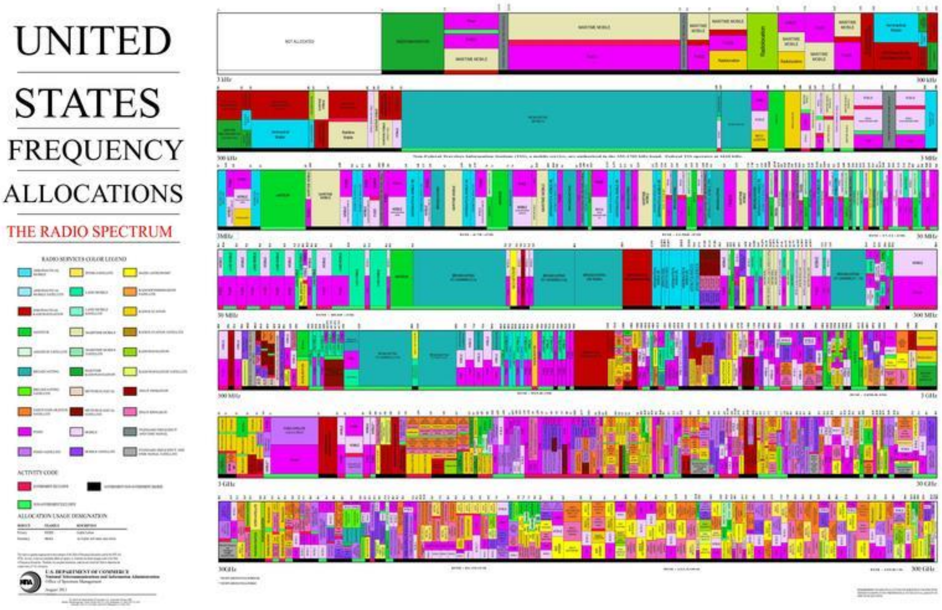


Buildings and other flat surfaces deflect the wireless signal. A MIMO system may attempt to make sense of these reflections and recombines them into a usable signal before decoding. This particular MIMO principle serves remarkably well to increase transmission performance, especially in non-Line-of-Sight applications.

10. Spectrum regulations and allocation plans

Spectrum is a public good, accessible to everyone with the proper equipment. Thus governments around the world share a strong desire to regulate access to this medium. If you consider the spectrum allocation plan of the US for the Year 2011 an example, you'll understand why:

RF spectrum allocations in the USA:



The RF Spectrum of the United States in 2011 is almost completely allocated, from 9kHz up to 270GHz.

You see, there's quite something up in the air! Now if everybody could just go on and blast kilowatts of RF power out into the Ether as they see fit, things would get ugly quick and break down for everybody soon. To prevent such a scenario, various international and national regulating bodies and authorities have been set into existence.

If you're going to operate gear within RF spectrum, then it's probably a good idea to check with your local authorities: Depending on the frequency you're going to use and your location, a proper license might be required. Some places might not allow for as much TX power as others do. And while usually everybody just copycats the FCC, sometimes there are national exceptions. A prominent example being the 2.4GHz channel 14, available in Japan only. So, here's an (incomprehensive) list of authorities and their respective jurisdiction for you:

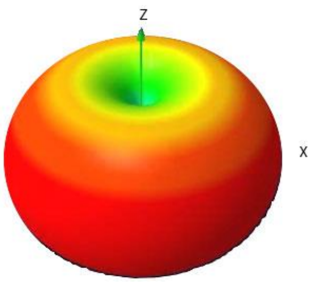
Country	Authority	Contact
USA	Federal Communications Commission (FCC)	www.fcc.gov
CH	Bundesamt für Kommunikation (BAKOM)	www.bakom.admin.ch
DE	Bundesnetzagentur	www.bundesnetzagentur.de
AT	Bundesministerium für Verkehr, Innovation und Technologie (bmvit)	www.bmvit.gv.at
FR	Agence Nationale des Fréquences (ANFR)	www.anfr.fr
AU	Australian Communications and Media Authority (ACMA)	www.acma.gov.au
EU	Electronic Communications Committee (ECC/CEPT)	www.ero.dk
CA	Industry Canada	www.ic.gc.ca

11. Aerials and how to use them

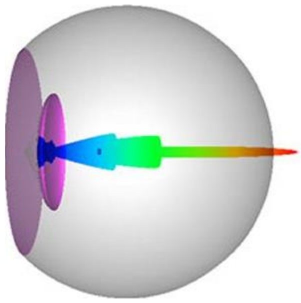
There are many different types of aerials. They are used to couple the RF signal from the transmitter off into the air, or off the air into the receiver. As each type has its characteristics and special properties, it pays off to get to know some of the most common types and their respective fields of application.

One can discern two fundamental classes of antennae: An omnidirectional antenna emits radiation in all directions, while a directional antenna focuses the radiation into a directed beam. While the ideal omnidirectional antenna would be an *isotropic radiator* that emits the same intensity of radio waves in all directions equally, this does not exist in practice. This purely theoretical isotropic radiator is still of direct relevance to us, due to the so called EIRP limits. We'll cover that in the next section.

Omnidirectional vs. Directional:



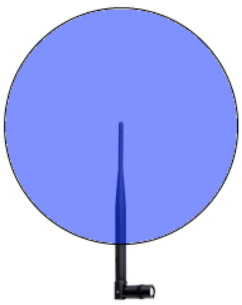
An omnidirectional antenna radiates in all directions on the horizontal plane.



A directional antenna focuses radiation into a directed beam.

An important parameter of any antenna is the antenna gain. Antenna gain does not result from some weird kind of amplification but solely from focusing the signal to a certain area, or rather volume in space. This is obvious for directional antennas, yet it also applies to omnidirectional radiators.

How can an omnidirectional antenna have gain?

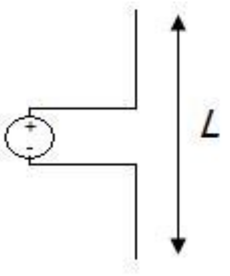
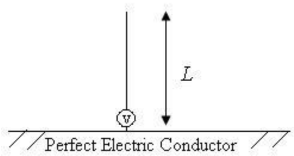


Zero gain omnidirectional radiation pattern.

A high gain omnidirectional antenna "squeezes" the RF field along the Y axis. The tighter the "squeezing", the higher the resulting antenna gain.

Antenna gain in wireless applications is often represented in dBi, which means "relative to an isotropic radiator". As the antenna gain only achieved by focusing the signal and thereby concentrating energy along a plane, consequently the theorized isotropic radiator shows zero gain, as no focusing takes place there. A high gain omnidirectional antenna on the other hand, will need to exhibit a narrow vertical aperture to retain its omnidirectional radiation pattern in the horizontal plane while delivering the extra gain.

11.1. Omnidirectional Antennas

Common types of omnidirectional antennas:	
	The *short dipole antenna* is the simplest of all antennas, being nothing more than an open-circuited wire, fed at its center. The term “short” implies “relative to wavelength”. Typically a dipole is designated short if its length is less than a tenth of a wavelength. This is an omnidirectional low gain antenna with linear polarization directly corresponding to the antenna orientation, offering an antenna gain of 2.15dBi.
 (a)	The *monopole antenna* is a dipole cut in a half and mounted perpendicular to some sort of ground plate. This is an omnidirectional antenna with a linear polarization just like the dipole. However, the monopole does not radiate below the ground plate. The smaller the ground plate, the more the radiation pattern is skewed upwards from that ground plate. Antenna gain is about twice as that of a corresponding dipole.

Omnidirectional antennas are often used in mobile applications where directional antennas simply can’t be aligned properly, as PtMP (Point to MultiPoint) base station antennas, in Mesh networks or as an additional RX diversity antenna in MIMO systems.

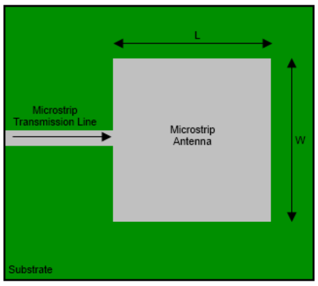
In fixed Point to Point scenarios, you’ll usually want to use a highly directional antenna with a narrow beam width because it will pick up more signal from where it points to and less interference from anywhere else.

Another factor for you to choose will be the polarization(s) you’re going to use. Vertical polarization is often used for mobile and semi-mobile applications (such as WLAN), whereas circular polarization is often beneficial in difficult environments. Satellite communications usually employ circular polarization for downlinks, due to the low power, long range nature of these channels.

11.2. Directional Antennas

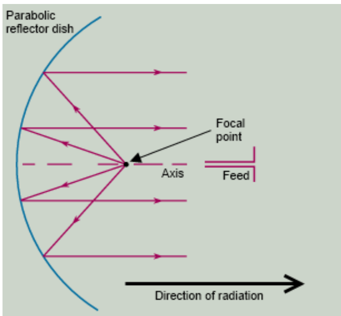
Directional antennas primarily offer a higher gain than their omnidirectional counterparts. This results in a somewhat limited coverage area but also in better noise immunity and better range. They further enable us to split coverage area into multiple sectors, allowing for more capacity per base station and finer control over signal coverage.

Common types of directional antennas:



The *microstrip or patch antenna* is printed directly onto a circuit board (substrate). They are low cost, low profile and are easily fabricated. They are often used in sector antennas.

Patch antennas are directional antennas. The polarization is linear and depends on the orientation of the feed. The patch depicted here has a horizontal polarization. The gain of a simple patch antenna is usually around 6 to 7 dBi.



In a *parabolic reflector or dish antenna*, a feed (usually a dipole or a horn antenna) is mounted at the focal point of a parabolic reflector made from conducting material. The feed emits into the reflector, which reflects the radiation as a collimated beam off into space. Polarization depends on the feed used.

Dish antennas offer very high gain (20 to 30 dBi), very strong directionality, excellent front-to-back ratio, high cross polarization isolation and a good immunity to interference due to a narrow beam.

The Y*agi antenna* is simple to construct and has a high gain and a good front-to-back ratio. Its appearance is well known, as it was commonly used during the past for analog TV reception.

Polarization is equal to the orientation of the antenna elements. The more elements a Yagi has, the more gain it offers and the stronger its directionality is.

The *helix, or helical antenna* is quite a special case of antenna because it features circular polarization and looks pretty funny. Helix antennas have great bandwidth, are easy to construct and offer good noise immunity and immunity to phase cancellations due to the circular polarization.

They are often used for very long range links (satellite in particular) and other, difficult environments with lots of interference and reflections.

12. Power is nothing without control

We saw that according to inverse-square law, signal range and transmit power are directly related. We also remember that putting out more power is not always good to get more range. Increasing TX power above a certain limit might also be prohibited by local regulations.

But, how much power do we need anyways?

Basically, a good signal is around -60dB to -50dB on the receiving end. Note that too much received power may desensitize the receiver, or even destroy it by overloading. Anything above -40dB is no good no more, and at -30dB you'll slowly toast your gear.

On the other hand, if the signal's too weak, you'll find it difficult operating the link at higher rates or even establishing a connection.

[TABLE bitrate / signal level]

In any way, consider this one rule of thumb: Antenna gain is better than TX power.

Why? Because antenna gain works both ways, sending and receiving. Imagine you had a very distant client you want to associate with your access point. If you simply up TX power on the AP, the client might "hear" the AP. But that won't help as the AP can't hear the client transmitting at lower power. Adding a higher gain antenna to the access point will also increase the AP's "hearing range", picking up signals from farther away.

[Diagram AP -> client -> client out of range]

If you add a higher gain antenna to an AP, it will often be necessary to actually *lower* the TX power, as to stay compliant with spectrum regulations. How much depends on the antenna gain: The TX power in dB plus antenna gain in dB must be equal or less than max EIRP in dB.

$$TXPower_{dB} + AntennaGain_{dB} =< \max EIRP_{dB}$$