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WIRELESS NETWORKING OVER EXTENDED RANGE

Technology options for optimizing long range wireless connectivity

Technical Note

This paper has been compiled using 'real life' data collected over the last 5 years and research from conventional sources of information written about the more technical aspects of microwave transmission and propagation. The technical details have been kept to a minimum to aid the ease of understanding of this very in-depth subject. Instead, test examples with actual results have been used as working scenarios to show the capabilities and restrictions of networks based on wireless technologies commonly available today.

Overview

WiFi, WLAN, 802.11a/b/g are all terms used in the fast growing market of Wireless Networking. This generic term covers all areas of the market where one computer is connected to another or others, using radio signals. WiFi (short for 'wireless fidelity') is the popular term for a high-frequency wireless local area network (WLAN). High frequency in these terms refers to 2.4GHz (802.11b and g) and 5GHz (802.11a) microwave transmission of WLAN data.

Standard wireless Access Points (APs) and wireless network interface cards (WNICs) can create WLANs that traverse distances of 100m (328 ft.) to 300m (984 ft.) with a clear line of sight. By swapping the standard omni-directional antennas with directional antennas, these distances can be improved significantly. Using a matched pair of APs with directional antennas, a network 'bridge' spanning between 2 KM (1.2 miles) to 4 KM (2.4 miles) and further, can be easily created. This is particularly useful for linking disparate buildings together, crossing obstacles such as rivers or streams, or in place of traditional infrastructure where the cost to install is prohibitive. Once in place, traditional LAN activities such as shared file and print services, email, web access and even voice over IP, can be transmitted over great distances at a very low cost and be very quickly implemented. Wireless links using 2.4GHz equipment and dish antennas have achieved distances up to 50 KM (31 miles).

WiMAX (802.16) is the newer technology for longer range wireless networking and last mile links based on frequencies between 10GHz and 66GHz. Final ratification of this new standard has yet to be reached and therefore will not be included in this document.
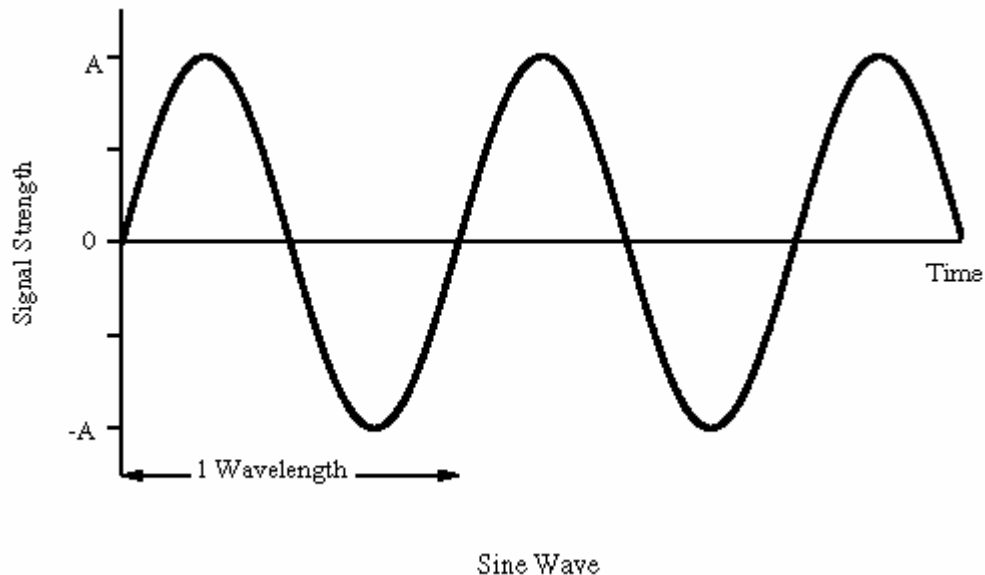
Some Basics

We are all familiar with radio waves. We use them every day to listen to the Radio News, watch TV and make calls on our mobile phones. More recently we have begun to use radio waves to connect PCs together without the use of cables or Wires.

Radio Waves are quite complicated in the way they are formed and travel through

the air (or any other medium for that matter). They can, however, simply be illustrated as a sine wave.

Fig 1.

Sine Wave

Wavelength is the distance of one complete sine wave. Frequency is how many of these wavelengths pass a point in 1 second. So 50 wavelengths per second (the frequency of the main electrical power in your house) is 50 Hertz or 50Hz.

Some examples of different frequencies used everyday are as follows:-

AM Radio	500-1500 KHz	802.11 b/g WiFi	2.4GHz
FM Radio	87MHZ- 107MHz	802.11a WiFi	5GHz
TV Broadcasts	500-700MHz	Satellite TV	12GHZ
Mobile Phones	900 MHz	Light	441THz

What are Microwaves?

Microwaves are radio waves with frequencies between 900 MHz and 300 GHz. Above this area of the radio spectrum, radio waves tend to start to behave like light. The waves can bounce off surfaces, particularly metals and a good example of this is a Satellite receiver dish. The signal from a satellite at 36,000 km (224 miles) geostationary orbit, travels down to your Satellite dish and is reflected back to the LNB (the receiver part of the dish), then to your Satellite receiver. Additionally microwaves at much higher power are used every day for heating food. Coincidentally, the operating frequency of a microwave oven is within the 2.4GHz part of the spectrum, the same as our popular WiFi standard. It should however be noted that more microwaves leak out of your microwave oven than are emitted from a WiFi antenna.
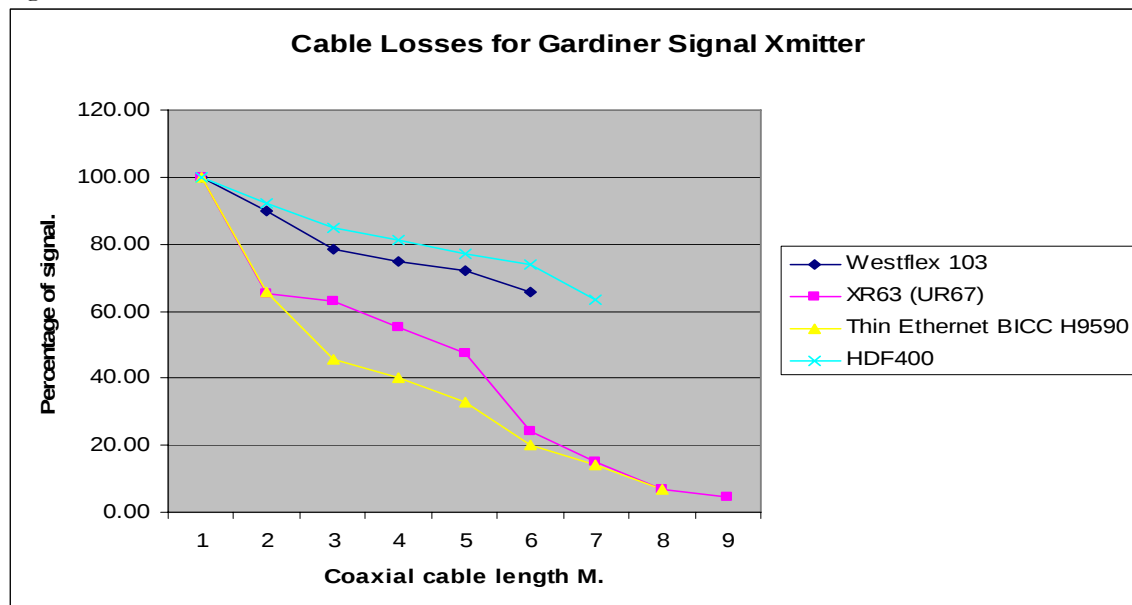
Microwaves – Generation and Transmission

In wireless networking equipment, the microwaves are generated by a microwave output transistor. The frequency is typically around 2.4 GHz, spanning from 2.402 GHz up to 2.482 for 802.11b/g, and output power is regulated by European (IEEE), North American (FCC), and UK (OFCOM) standards. This is about the same power output of the LED standby indicator on the front of your television.

The major problem with power limits as low as this is loss. Loss of power occurs in mismatch of cable (transmission lines) and connectors, and losses in the antenna and losses in the air (Free space loss).

The combination of high frequency and low power means that transmitting microwaves down even very high quality co-axial cables results in large losses in power. The signal dissipates as heat down the length of the co-axial cable which means the length of transmission lines must be kept to a minimum. In one test we carried out, a popular UK manufacturer was selling high quality 9m (27 feet) co-axial transmission line, which we found dissipated 87% of the signal power over its length.
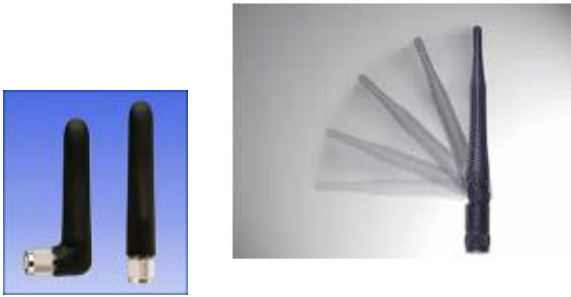
Fig 2.

The third component in the line of transmission is the antenna. Antennas essentially fall into two main types. Directional and Omni-Directional.

Omni- Directional antennas transmit signals in all directions (360 degrees). They are often recognized as a stick type of antenna pointing upwards (Vertically polarized). They are generally of the dipole style of antenna used on access points and network interface cards.
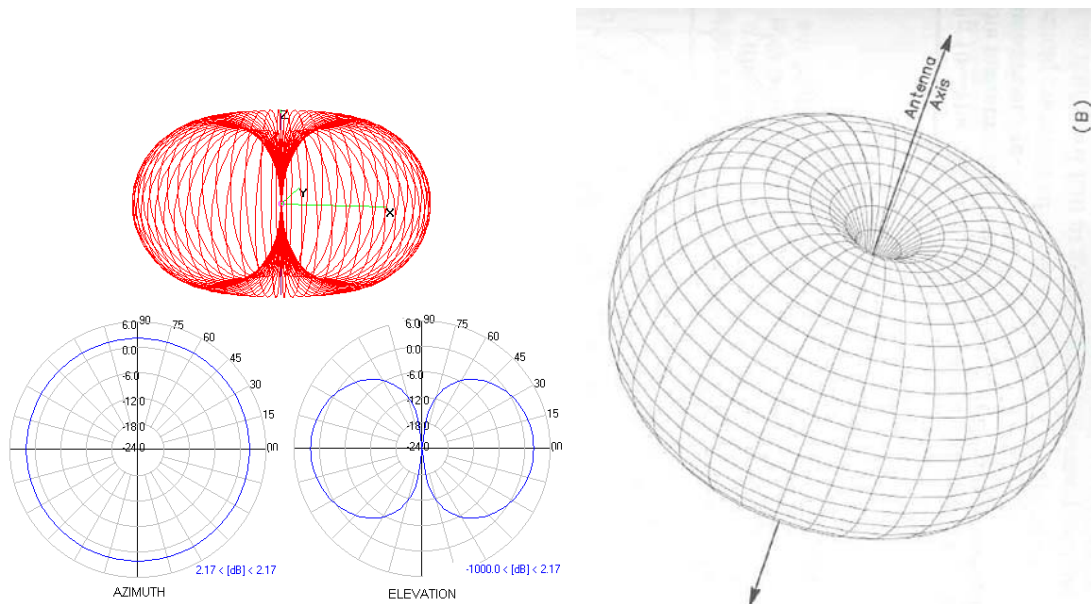
Fig 3.

The main reason a dipole antenna is used is that it is relatively efficient as well as being simple and inexpensive to construct. The size of the antenna is in direct relationship to the frequency being transmitted/received.
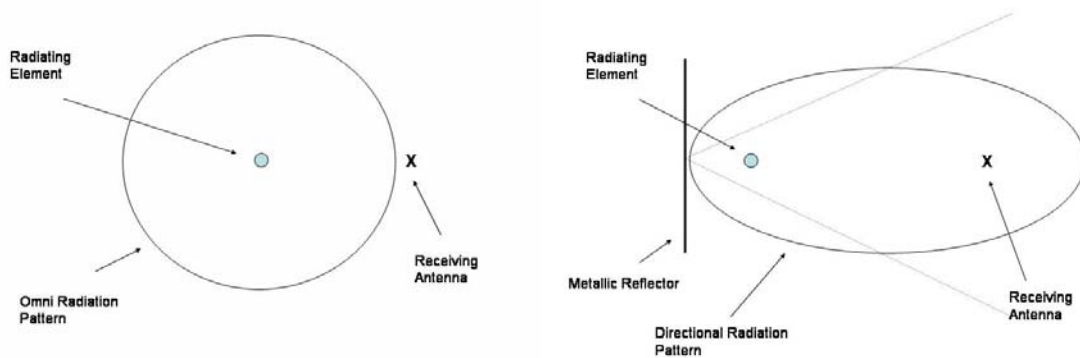
At 2.4GHz, the wavelength is around 13cm and knowing that fact means that divisions of this wavelength can be used effectively to reduce the length of the antenna. A very common design is to use a ¼ wavelength dipole which measures 3.25cm for each half of the dipole. Because of manufacturing defects and other losses, the radiation pattern of an omni-directional is never perfect but an ideal representation of the dough-nut shaped pattern is shown below.

Fig 4.

Directional Antennas generally use a radiating element (often a dipole) and then a reflector to modify the shape of the radiation pattern. In its simplest form a flat metallic reflector placed behind an omni-directional antenna will produce a basic directional antenna, see representation below.

Fig 5.

Omni Radiation Pattern   **Directional Radiation Pattern**

By 'squeezing' the radiation pattern into a much narrower beam, using the reflections from the plate the power at X can be significantly increased. The dotted line shows the reduced radiation pattern (beam) from 360 degrees in the omni directional pattern.

The increased power at X is known as a gain and is measured in decibels (dB) and is effectively amplification of the power from the transmitter/receiver. dB is a logarithmic measurement, so as an example a drop in power of 1dB equals approximately 20% drop of the original power output. And a 3dB drop represents a 50% drop of the original power output. Conversely doubling the original power represents a 3dB gain and quadrupling shows a 6dB gain.
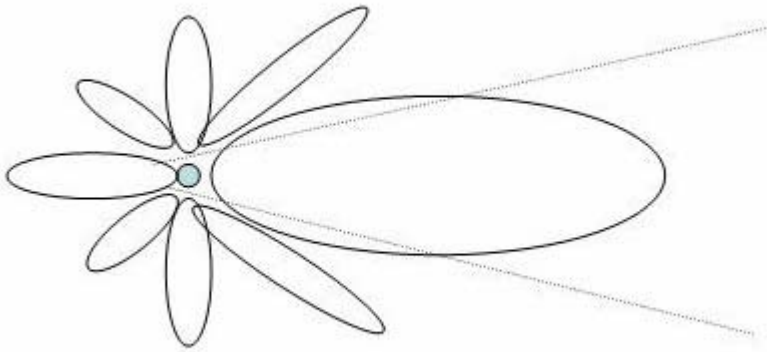
Directional antennas are often designed in other ways to enhance the radiation pattern further than that in figure 5. These designs are formed from helixes and combinations of reflecting plates to achieve more gain and directionality.

Fig 6.
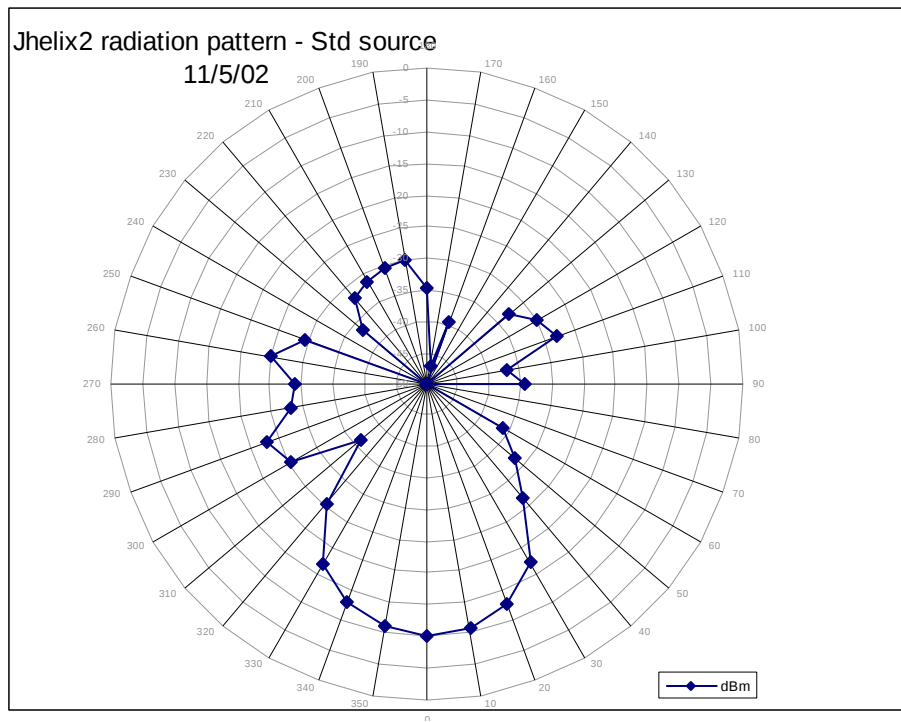
All of these designs are not, however, perfect so the radiation pattern can often look like the following representation.
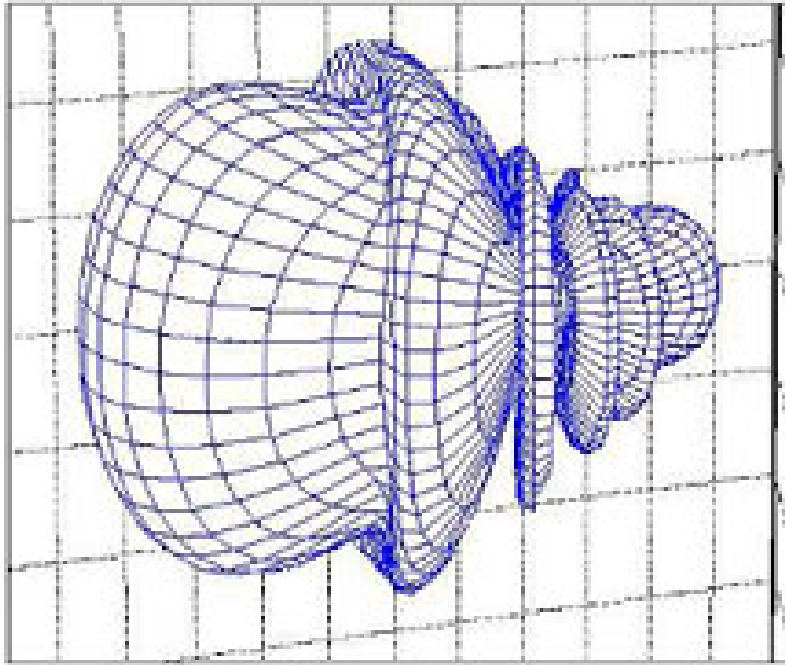
Fig 7.

The 'lobes' of the radiation pattern show the main lobe which is where most of the radiation is 'focused' and then the side lobes which represent the inefficiencies of the antenna design. The beam width is the angle of the area covered by the main lobe.
Actual radiation patterns often appear as follows:

Fig 8.

Directional Antenna Applications & Installation

There are 2 main reasons to use directional antennas. The first is to create a 'link' or 'bridge' between two locations. Using the increased distances achieved with directional antennas, these links can easily extend many Kilometres or miles with a clear 'line-of-sight' (LOS).

The other reason to use directional antennas is to 'Push' the signal into a specific location rather than 'flood' a whole area with signal. Again the focussed radiation pattern allows the signal to be 'pushed' further than it would using an omni directional antenna.

When using directional antennas that have a narrow beam width, alignment becomes an important factor. Over LOS links between 1-2 km, alignment by eye is quite easy to achieve with a little 'trial and error'. With LOS links greater than 2km, it is necessary to use special alignment equipment and expertise to achieve the maximum performance from the wireless network link

Polarisation and Antenna Matching

As mentioned earlier, polarisation is effectively the orientation of the antenna. Using the simple dipole as an example. The dipole pointing straight up is vertically polarised and at 90 degrees horizontally polarised.
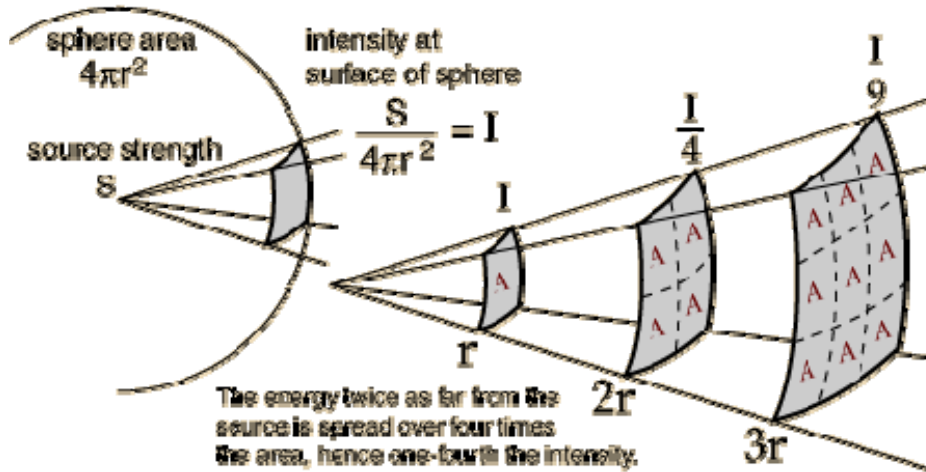
It is very important when using antennas together their polarisation is matched. Failure to match polarisation has very significant effects on the performance of the antennas.

Matched antennas of exactly the same design can also give massive gains in performance. When creating bridges over any significant distance using wireless networking equipment, it becomes critical to use matching antenna pairs.

Range

Radio waves propagate through space using the inverse square law. This means as the distance doubles the signal reduces by 75%, see below.

Fig 8.

Range is dictated by transmitter power in dB, plus receiver gain in dB, minus losses. As described earlier, losses include transmission line loss, antenna inefficiencies and alignment and polarisation deficiencies. The major loss, however, is the 'free space loss' or the signal loss over distance as described above.

Other factors that could affect range include weather and LOS obstruction. The first factor – Weather- undoubtedly has an effect on performance. However the effect is so small we have not managed to measure it accurately and so can be treated as insignificant.

Obstructions do however pose a significant problem. We have seen high sided vehicles, dense foliage in summer, mobile billboards and large signs, kill perfectly functioning wireless links in seconds or over a period of months (trees contain lots of water that soak up microwaves).

Good planning will help overcome these issues before they arise.

Security

With the prevalence of Wi-Fi networks, it cannot be emphasised too much that security is an absolute requirement of every private network. In our local town, in just one hour we detected 390 separate WiFi networks, and 30% of these had no protection at all. What this means is that anyone within range of the network can connect to it generally undetected. At the least these interlopers will piggyback your broadband bandwidth (which is illegal in many places), or with a little extra knowledge they can break into any PCs you have connected to the same unsecured network. A simple firewall like Zone Alarm on your PC and a little security such as MAC address filtering or WEP encryption can prevent all but the most dedicated hackers (War Drivers as they are known in the Wi-Fi arena). We have tried to measure the performance degradation as a result of using WEP and other encryption but have failed to measure any real loss in performance, so this can be assumed to be insignificant.

Performance

As with all types of networking, cabled or otherwise, the quoted 'maximum theoretical throughput' of the network differs greatly from the actual capacity of the network connection. Wireless as a rule of thumb is about 4 to 6 times slower than conventional cabled networks. While this is fine for small file data transfer, email and web access, backing up 1Gb of data across a wireless LAN can be painfully slow. This should be taken into consideration when planning a wireless LAN particularly if the applications to be used on the PC workstations involve database files or require many files to be opened and closed in quick succession.

Summary

Wireless networking can provide high performance connectivity where cabling is impractical or undesirable. It can be made secure with very simple changes to the 'out-of-the-box' configuration. Using directional antennas, great distances can be bridged at a very low cost in comparison to alternative technologies. Using our data over the last 4-5 years, these links can provide 'up-times' better than 99.5%, which exceeds those of mission critical components of the LAN in most organisations.

Real Life Test Results

The base line tests were conducted using the standard dipole antenna that is included with the USR5450 Access Point (AP). This was then attenuated down with 20dB at both ends, so a fair comparison between the antennas could be made within the space available for the testing. Distance is measured between matching pairs of antennas and attenuators before the AP bridge is lost. Perf (performance) is the presumed performance increase over the baseline antenna. Assumed Distance is the assumed maximum distance calculated from the baseline figure, but excludes a safety margin (See appendix for details). Note: The assumed figure can be substantially affected by alignment and quality of LOS.

Test #	Antenna	Gain dBi	Atten. dB	Distance (M).	Perf.	Assumed Distance (M).	
1	std	5	0	1931		1931	
2	std	5	6 (x2)	379.6		1931	
3	std	5	20(x2)	175.3	baseline	1931	
4	USR5482	9	20(x2)	557.9	3.2	6145	
5	USR5484	14	20(x2)	740.7	4.2	8159	
6	SCR9-2400	9	20(x2)	389	2.2	4285	Alignment
7	SCR9-2400	9	20(x2)	463	2.6	5100	difference
8	SCR14-2400	14	20(x2)	489	2.8	5387	
9	SCR14-HX	14	20(x2)	636	3.6	7006	

Conclusions

It should be noted that the original/standard antenna included with the USR5450 AP performed very well and way above our expectations. Both the USR patch antennas performed well and provide a good choice of antenna for distances of 5KM (3 mi) and 7KM (4.3 mi) respectively. The corner reflector antennas performed worse than expected and there is little benefit to be seen in performance between the 9dBi and 14dBi. This may be due to alignment which seemed to be more crucial with the corner reflector antennas. The Helix performed well, and considering this antenna has provided connectivity over a distance of 6.9KM (4.2 mi), it would suggest that the attenuated

assumed distances are very close to reality. The long Helix was not tested as even using 20dB attenuators it would easily exceed the distance available in the test area.

Note: These tests were carried out in 'real life' conditions and alignment was purely by eye. The use of 2 20dB attenuators plus the 4 sets of adaptor cable probably give a total of around 41-42dB loss.

Free space loss

Free space loss is one of the initial measurements to be calculated in order to develop distance estimates for wireless solutions.

"Spreading" is the principle contributor to signal loss for line of sight signal propagation. As a signal radiates it "spreads" or expands into a spherical surface. The available RF power is distributed over this surface and weakens with increasing range. The signal is reduced by 6 dB every time the distance from the source doubles. To compute the loss path between the source radiators with spherical patterns use the following equation:

$$Lp= 92.45 + 20Log10F + 20Log10d$$

Lp= path loss in decibels
F= frequency in GHz
dB= decibels
d= distance in kilometers

Free Space Loss Example

A distance of 6 kilometers provides a free space loss of -115.67 dB.

Distance/Km	Gain Loss/dB
0.5	94.0
1.0	100.0
1.5	103.5
2	106.0
3	109.5
4	112.0
5	114.0
10	120.0
15	123.5
20	126.0

The link budget
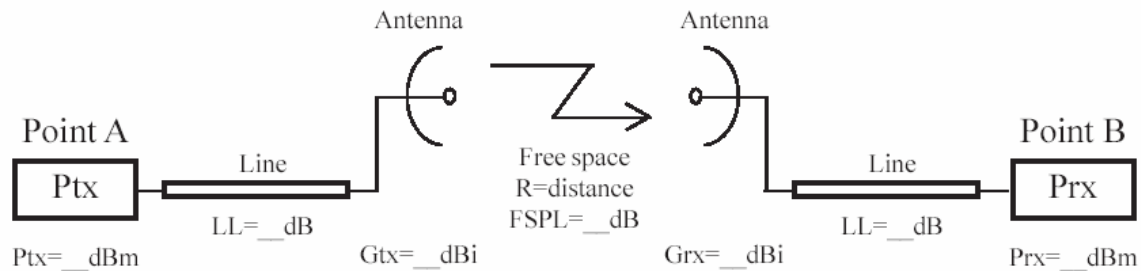
For each link a ""link budget" needs to be made. The link budget will calculate the signal level through the link and predict the signal level at the receiver's side. Within the "link budget" there are a few parameters that are influenced by the location of the link: humidity and terrain roughness. The length of the link also has a major influence on the "link budget".

It is best to consider the link in three stages:

1. The transmitting end: Consisting of the transmitter (e.g. access point, router etc.), the antenna cable and the antenna.
2. The middle bit: This is considered the distance between the two sites.
3. The receiving end: The receiver (e.g. access point or wireless device), the antenna cable and the antenna.

The link budget calculation is as follows:

Link budget= Ptx – LL + Gtx + FSPL – LL + Grx –Prx

Where:

Ptx = Output power of transmitter in dBm

LL = Antenna and cable losses at transmitter in dB

Gtx = Transmitter Antenna gain in dBi

FSPL = "Free Space Loss" propagation loss in dB (negative number, see table on previous page)

LL = Antenna and cable losses at receiver in dB

Grx = Receiver antenna gain in dBi

Prx = Receiver sensitivity in dBm (negative number)

Link Budget Example

This example is based on the need to bridge a point-to-point distance of 1 Km over average terrain in a dry climate. The bridge must perform at full speed (e.g. 54Mbps).

To be able to do this, we first select the components we need. Assume that the wireless connections use "standard" access power devices (i.e.32mW or 15dbm) and 9dbi gain USR5482 antenna at each end.

These are the values to be used in the calculation:

Ptx = 15 dBm (Output power of the transmitting access point)
LL = 3 dB (Cable + connector attenuation for a CO 100 cable of 5m at 2.45 GHz)
Gtx = 9 dBi (Antenna gain)
FSPL = -100 dB (see table on page 4 for 1 km)
Prx = -80 dB (Receiver sensitivity value for a typical access point at 54 Mbit/s)
LL = 3 dB (Cable + connector attenuation for a CO 100 cable of 5m at 2.45 GHz)
Grx = 9 dBi (Antenna gain for USR5482)

<u>**This gives:**</u>
15-3+9-100-3+9+80=7 dB

This means a margin of about 7 dB on the link. This is a good margin with which to work, providing confidence that the connectivity required will be achieved. In general a margin of 5 dB is the lowest level that will provide acceptable results.

This signal is a calculation under ideal circumstances, however, the radio path can be disturbed by weather conditions or antennas can suffer degradations. The user must also ensure that the installation does not infringe upon any local or national laws.

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