Prediction of Wireless Network Signal Strength within a Building

J.N.Davies, V.Grout and R.Picking

Centre for Applied Internet Research (CAIR), University of Wales, NEWI
Plas Coch Campus, Mold Road, Wrexham, LL11 2AW, UK
e-mail: {j.n.davies|v.grout|r.picking}@newi.ac.uk

Abstract

With the increase in the provision of access to Wireless Local Area Networks and the abundance of user devices capable of utilising Wi-Fi, the design of the network infrastructure has introduced some significant problems. Prior to the installation of Access Points it is difficult to predict whether access can be guaranteed at specific locations. Additionally, to increase the level of security, it is often preferable, despite the use of security protocols, to ensure that the signal strength is not large enough to enable connection in areas other than those designated. By combining the theory of antennae and the measurement of the performance of devices, it is possible to predict whether access is likely and hence how secure the network design is. Additionally, the use of a simple application is proposed that enables the network designer to enter a configuration and produce an answer showing if WIFI will operate and a value to indicate the margin.

Keywords

Wireless networks, Wi-Fi, Signal strength, Prediction of signals

1. Introduction

The use of Wireless in Local Area Networks has increased dramatically since the development of the IEEE 802.11 set of standards. Its is anticipated that the use of Wi-Fi access will continue to increase for the foreseeable future due to the functionality being found as standard in mobile/cell phones. To cope with this requirement, the IEEE 802.11 Working Group (IEEE, 2007) are introducing new standards.

Additionally, Wi-Fi *Access Points* are being installed in almost every conceivable location from railway stations, airports, hotels, restaurants, coffee bars to private homes. A major UK service provider (O2, 2007) boasts over 7 000 locations where Wi-Fi access is available but this is increasing every day (Cunningham and Grout, 2007). Generally the access point is installed in a building; however there are instances were they are installed in lampposts or other open air locations. This paper is concerned with installations in a building.

One of the major problems facing Network Managers, who are tasked with providing access for to Wi-Fi, is associated with determining whether the signal strength from the access point is strong enough to enable a connection to be made. What makes this task more complex is that the signal strength is dependant on many factors including the physical attributes of the building, the contents (furniture) of the building and the restrictions on suitable installation sites.

There are many systems available to measure the strength once the access point has been installed (NetStumbler, 2007) or to even plot out maps of signal strength (AirMagnet, 2007); however to gain this information in advance of the installation requires a degree of prediction.

There are a number of reasons why it is necessary to know this information - the obvious being to know whether network service could be provided at that point; however, sometimes, for security reasons, it is more important to know that connections can *not* be made at certain points. This is particularly important in commercial environments, where it is essential to know that connection can not be made to the network from outside the building.

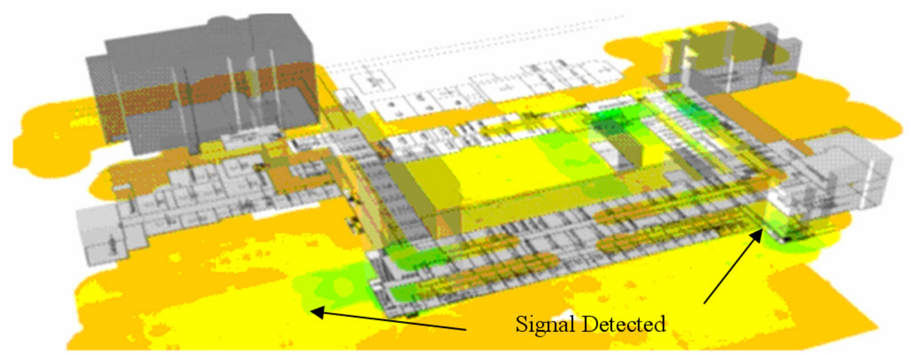


Figure 1: A building survey

From the security point of view, it is essential to ensure that the signal strength outside of the building should be low enough to prevent a connection to be made. Figure 1 shows an example of the results of a survey, which is colour-coded to aid the interpretation of the information. It can be seen that the signal from some access points can be detected outside of the building, which is a potential security problem.

Much of the work carried out on modelling wireless networks involves applying finite element models to ray trace (Ji et al., 2001). A great deal of work has been carried out in this area but they limit it to the operation in free air (Zhongqiang et al., 2004). One of the major problems is the losses associated with materials found within the building. Attempts have been made to take these issues into account in the models but the computational requirements are heavy (De La Roche et al., 2007).

A number of factors govern the signal strength at a given point and these are investigated in this paper. It is the intention to consider currently available technology to give the findings more credence. In addition to the network access point, some consideration is given to the user device.

This paper also considers, in section 4.2.3, the losses encountered with distance and when the signal passes through different materials, e.g. walls and windows, as the basis for a calculation. In section 5 a simple application is described which uses the results of the above investigation to provide a designer with an answer to the supplied configuration.

2. An Overview of Standards

The most widely used technology in this field is provided by the IEEE 802.11 series of specifications, which have been available since 2000. At the present time the predominant technology is IEEE 802.11g, which is backwards compatible with the earlier technologies. Equipment produced to IEEE 802.11n is starting to become available but since the technology is based on the same principles (it uses multiple channels to increase the bandwidth) then the same arguments will hold true. The IEEE 802.11 working group is working at present on a number of newer standards including IEEE 802.11k, IEEE 802.11s and IEEE 802.11w

3. Technology Involved

Most of the equipment used for this technology operates at around 2.4 GHz, which is an unregulated frequency. Depending on the type of modulation employed, the delivered data rate ranges between 1Mbps and 54Mbps.

A number of independent channels are provided with this type of technology. Based on clause 19 of IEEE 802.11g, there are 14 channels at 5MHz intervals from 2.142 GHz to 2.484 GHz. Since the protocol requires a separation of 25MHz to operate successfully, care needs to be taken in the selection of channels to use. This is made more complex since the number channels that can be used is regulated by individual countries and is not standardised throughout the world.

3.1. Basic operation

For the network to operate it requires a transmitter and a receiver at both ends to provide connection. Sometimes this technology is used for direct point to point links but more usually there is an access point with an omni-directional antenna allowing 360^{o} access. These are the link into a Local Area Network and this provides service for many other devices as shown in Figure 2. Each of these devices contains a wireless interface. To transmit and receive the 2.4 GHz signals, an antenna is required at each end.

There are many different types of antenna available depending on the type of transmission required. This paper addresses issues associated with the antennae found commonly in commercially available equipment.

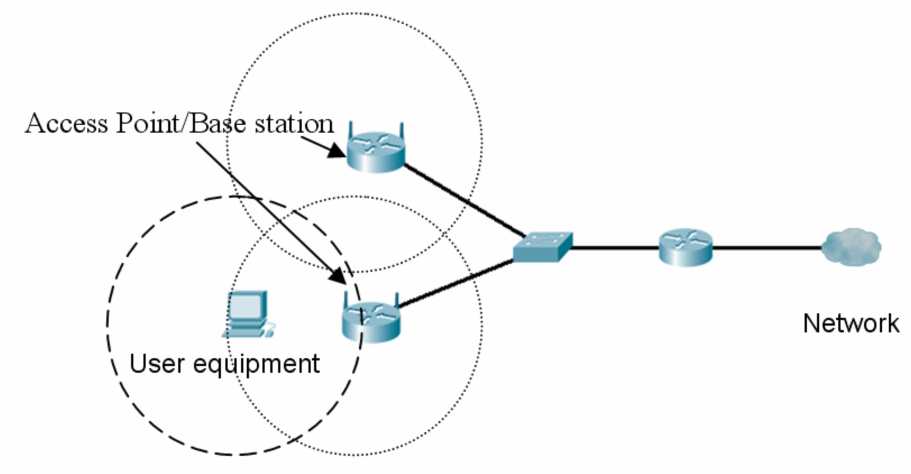


Figure 2: Typical Network Configuration

A great deal of theory is available in standard text books on the design of antenna (Balanis, 2000), which is based on general principals. Operation at various frequencies provides certain characteristics of the system. Typically the theory provides formulae for calculating the power at the receiver for particular frequencies, characteristics of antennae and defined transmission power. This paper confirms this theory and applies it to the particular characteristics found in IEEE 802.11g.

Normally, the antenna theory assumes that the medium that the signal passes through is air but this paper considers the signal passing through various materials. This is of particular interest when designing a network since every room in every building will have a unique characteristic depending on the materials used in construction, the physical shape, content of the room and the positioning of the access point.

802.11g:

Data rate	**Sensitivity**
1 Mbps	-95 dB
2 Mbps	-91 dB
5.5 mbps	-89 dB
6 Mbps	-90 dB

Table 1: Access point rate/sensitivity

What makes this interesting is the fact that domestic microwaves, cordless phones, Bluetooth, cable free keyboards and mouse and remote control devices operate in this frequency range and so there is scope for interference. For Health and Safety reasons, the power output is limited for IEEE 802.11g to 100 mW, i.e. 20 dB

3.2. Access points

Typically specifications of commercially available Access Points provide information to aid the design of networks. Table 1 shows the minimum power required to enable a connection to be made and how the range of operation can be extended by reducing the data rate. Often this is carried out automatically by the access point. Typical information for the maximum distance to connect for a given speed is shown in Figure 3.

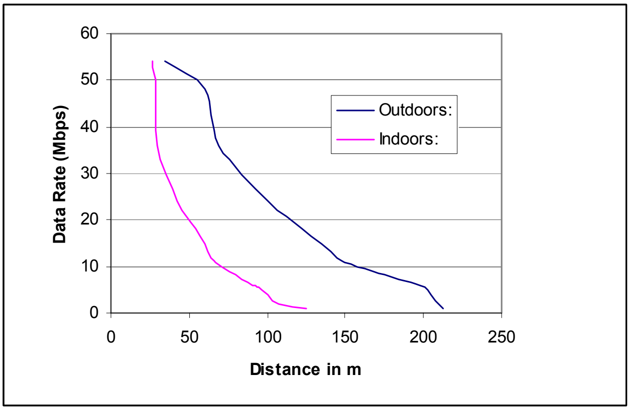


Figure 3: Graph of Maximum Connection Distances

This shows that the relationship is non-linear due to the change in modulation used at the varying data rates. Details of the way in which these values were obtained are not provided although additional comments are given as "*Ranges and actual throughput vary based upon numerous environmental factors, so may differ*" (Cisco, 2007), which is not particularly helpful!

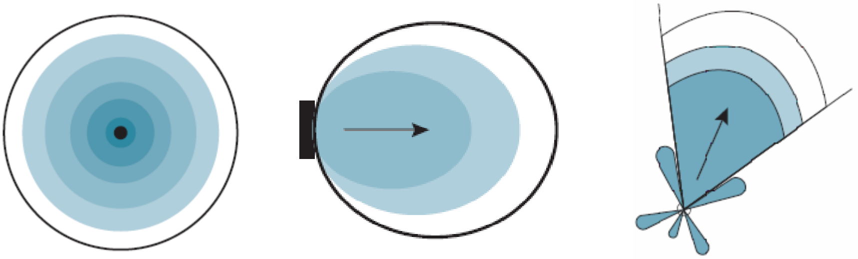


Figure 4: Typical radiation pattern diagrams for standard antenna

All the investigations in this paper were carried out assuming that an access point is to be used to support user connected devices, e.g. laptops, and that omni-directional antenna are utilised (Otyakmaz et al., 2004). Fig 4 shows the radiation pattern of typical antenna, the leftmost being an omni-directional pattern.

Since the transmission of the signal is via an antenna, the shape, positioning and orientation of the antenna at the transmitter and the receiver can have significant effects on the operation of the system. In reality, one side of the network - the user side - is relatively standard in so far as the system expects to be utilized either by a laptop or a desktop containing a wireless card. It is not always easy to interpret the results obtained from simple measurements in this type of scenario since the communication mechanisms are dependant on two dissimilar ends.

Unlike most point-to-point wireless applications, the antenna at either end are physically different. This is due to the physical shape, size and positioning. Since there is a limit to the power transmitted, the ability to operate successfully is dependant on the sensitivity of the receiver.

3.3. Laptops and desktops

Due to user requirements generally, laptops use omni-directional antenna since they are simple poles and can therefore be mounted relatively easily within a case. It is possible to fit external antenna but this is unusual.

4. Investigations

To predict the likely performance of a wireless network this paper takes two approaches: firstly, look at the theory behind the technology used and secondly, gain some empirical knowledge by making measurements under known conditions to see how they compare.

4.1. Theory of transmission in free air

Basic antenna theory for the transmission of electromagnetic waves is based on Maxwell's equation. However this can be simplified for transmission in free air when the accepted formula for the power received is given by the Friis Transmission Equation (Friis, 1946)

$$\mathrm{Pr} = GrGt\left(\frac{\lambda}{(4\pi d)}\right)^2 Pt \qquad (1)$$

where Pr = Power received, Pt = Power transmitted, Gr = receive antenna gain, Gt = transmit antenna gain, λ = wavelength and d = distance apart. This can be interpreted as, for a given access point communicating with a given laptop, operating at a predefined frequency then Gr, Gt, λ and Pt will all be constant so this equation simplifies to:

$$\mathrm{Pr} \propto \frac{1}{(4\pi d)^2} \qquad (1a)$$

i.e.

$$\mathrm{Pr} = K\frac{1}{d^2} \qquad (2)$$

where K is a constant.

4.2. Measured results

With relatively simple equipment it is possible to produce some interesting results when testing out the theory. This paper does not use any special equipment but uses equipment that would be utilized in normal operating environment. A Cisco base station and commercially available laptops that support IEEE 802.11g were used. A number of different measurement software were investigated and the freely available Network Stumbler (NetStumbler, 2007) was chosen for consistency.

4.3. Standardization of laptops

Initially the factor Gr, antenna gain shown in Equation 1, was investigated for different laptops. Since this reflects. in a real network the variation of the interface cards/antenna and mounting, it was essential to get an indication of the variation encountered. (Cho et al., 2000)

Measurements were taken in the middle of a field to ensure that there was little if any interference from other sources with the intention of following the transmission in free air principle (Guterman et al., 2007). Three different laptops were used at a distance of 10m horizontally to record the measurements as the base station was rotated around through 360^{o} as can be seen in Figure 5.

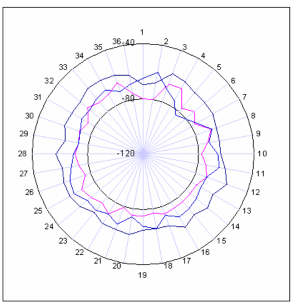


Figure 5: Measured signal strength around base station

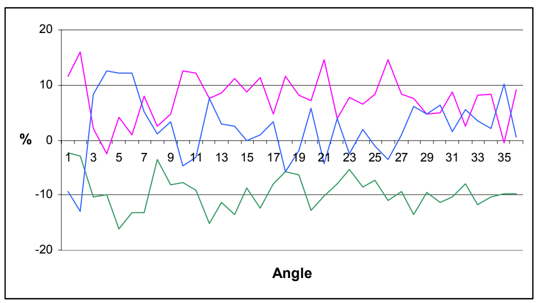
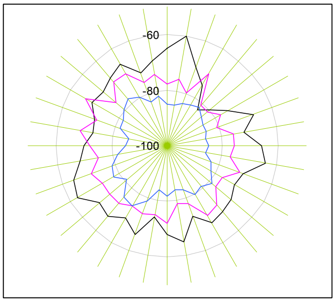


Figure 6: Laptop variation

An average value was then taken and the variance plotted on the graph shown in Figure 6. The maximum and minimum variation shown in the graph is between +15.9% and -16.2%, i.e. a variation of 30%, which gives concern particularly from the security point of view. This can be explained by the variation in design and manufacture of the laptops.

4.4. Variation by distance

Repeating the rotation measurements at varying distance provides the graph in Figure 7, which confirms that, as the distance from the access point increases then the strength of the signal decreases. The distances chosen for convenience were 10m, 20m & 30m.



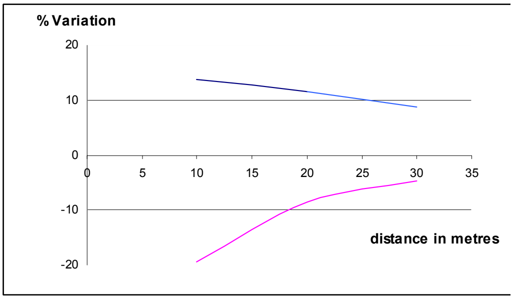


Figure 7: Variation with distance **Figure 8: % variation with distance**

The average at 10m is 69.5db, 20m is 74.6db and 30m is 82.1db. It is interesting to note that, as the distance from the access point increased, the percentage variation was less (Figure 8). It was noted that a minimum signal of -85dB was required for operation.

4.5. Variation by distance at fixed angle

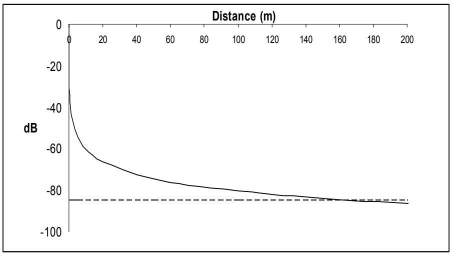
Measurements were then taken without rotating the antenna but by varying the distance. The results can be seen in Figure 9. To give credence to Friis Transmission (Equation 2), it is necessary to plot the log of the distance versus the log of the signal strength as shown in Figure 9a.

$Pr = K\frac{1}{d^2}$. Taking logs gives $Log(\Pr) = Log(K) + nLog(d)$

Comparing this with the equation of a linear graph, $y = m(x) + c$

The gradient of the graph gives the power to which the distance is raised, which Figure 9a gives as -19.98, which, allowing for the signal strength being in db, gives -1.998

i.e $\Pr = d^{-1.998} + c$ or $\Pr = \frac{1}{d^{1.98}} + c$ which is very close to d^2.



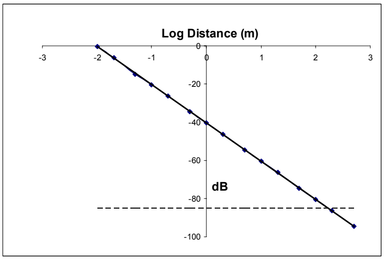


Figure 9: Distance versus signal strength **Figure 9a: Log Distance v signal strength in db**

4.6. Channel considerations

The above results were consistent when investigated on different channels. However it was found that certain channels were susceptible to interference from normal household devices such as microwave ovens. This was a very difficult fault to isolate due to the randomness of the usage (Yang et al., 2003). However changing to another channel removed the problem and so is a consideration to reflect upon since an installation normally involved selecting different frequencies throughout the network.

4.7. Measurements through a building

Measurements can be carried out similar to that described in section 4.4. By placing an access point inside the building and a laptop outside the building where there are no windows, or on the other side of a window and comparing it with the equivalent distance in free air, it is possible to obtain values for absorption by various materials.

There are many variables in building construction that affect 2.4GHz transmission. Each building will have its own characteristics depending on the materials used and the physical design. This can often be characterized by the era in which it was built. Older buildings tended to be made of brick, then there was a concrete phase and more modern buildings tend to have metal cladding and larger tinted windows. Some standard tables can be referenced to aid with the design, Table 2 for example.

Material	**Approximate Loss**
Plasterboard, single layer	3dB
Glass wall with metal frame	6dB
Window	3dB
Wire mesh safety glass window	8dB
Cinder block wall	4dB
Steel reinforced concrete floors	Up to 20dB
Solid core wall	Up to 10dB
Brick wall	8dB
Concrete Wall	Up to 15dB

Table 2: Materials Reference table

Often it is difficult to determine the exact make up of the building since bricks containing a high metal (iron) content, the plasterboard, foil wall paper, lead paint wire mesh safety glass can all have a significant effect on the absorption properties of the building. (WAG, 2007).

To show extreme values, the loss through an old brick building with plastered walls was measured which gave a loss of 25dB. Also a modern double glazed treated glass window was measured which gave a loss of 20.5dB.

Other household and office items which cause attenuation include filing cabinets, desks, fish tanks and water and heating pipe work. This is the subject of further study.

5. Predicting Signal strength

Careful investigation is required to specify the conditions and materials before trying to undertake a prediction.

5.1. Signal strength budget

An interesting concept is that of a signal strength budget, which can be produced to show the prediction. An example can be seen in Figure 10, which involves an access point (a) placed a distance x from a wall y from a window. The strength of the signal at a point (p) which is a distance z from the glass would be given by:-

$$S_p = S_a - (\mu_{x,y,z} + \mu_{Wall} + \mu_{Glass})$$

where S_p is received signal strength, S_a is transmitted signal strength , $\mu_{x,y,z}$ is the loss over the distance x,y,z in air, μ_{Wall} is the loss though the wall , μ_{Glass} is the loss through the glass.

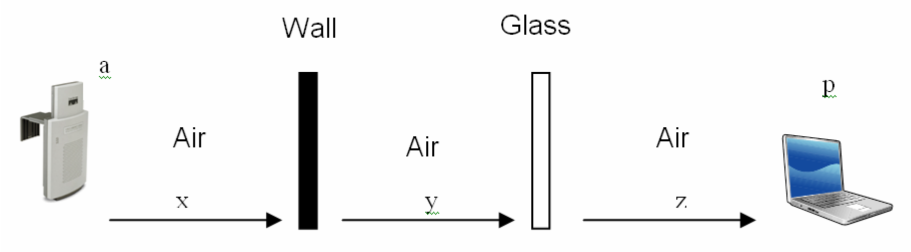


Figure 10: Example of budget calculation

Assume x = 5, y = 10, z = 5, total distance = 20m. Typical values give:-

$\mu_{x,y,z}$ = -66dB , μ_{Wall} = -8dB, μ_{Glass} = -6dB

So the loss would be as in Figure 11.

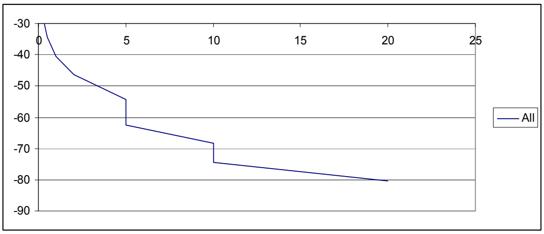


Figure 11: Budget calculation

This budget shows that there is a total budget of -80dB and, referencing Table 1, the receive sensitivity is 89dB, indicating that this installation would work.

5.2. Automatic calculator

This work allows software to be written to enable the user to enter characteristics of the proposed installation and then calculate the budget. As a result of this it can provide a yes/no answer whether the proposed scheme would operate successfully or not or how close to the margin it is. It would also be possible to create a budget graph as shown in Figure 11. The user would be able to enter distances for the portion of the network in air and then select the number of walls/ windows. A very basic user interface of such a calculator can be seen in Figure 12, along with the calculated result.

There is scope for improvement in the usability of this interface; for example, a series of pull-down boxes could be provided to allow the user to select the type of materials encountered. A set of predefined values as seen in table 2 would be provided with a suitable definition of the type. Additionally it would be possible for the user to carry out simple measurements as described in the paper and enter these for selection. Due to the varying performance of different materials this would improve the accuracy of the result.

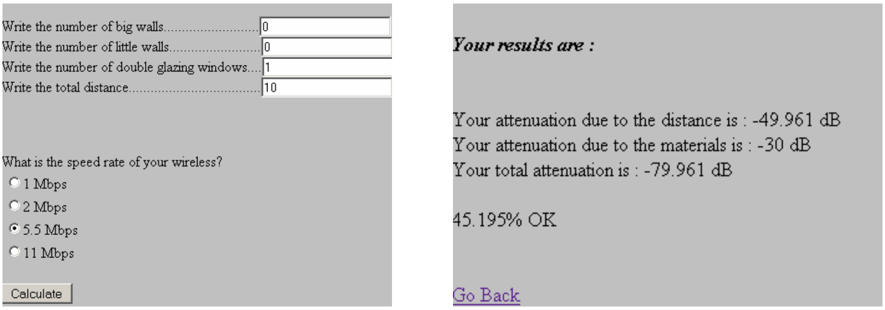


Figure 12: Signal strength calculator

6. Improvements in Performance of Antenna

Up to this point it has been assumed that an even distribution of signal strength around the access point is required. Often, in reality, this is not the case since the access points have to be mounted onto a surface to support it, e.g. screwed to a wall. Clearly, in this case, the distribution of the signal is no longer an even distribution due to the attenuation cased by the wall in that direction. The footprint of the antenna will look as in Figure 13.

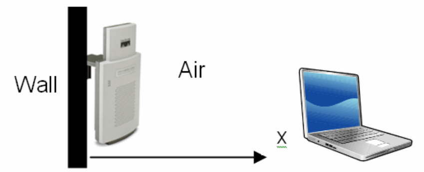


Figure 13: Effect of wall on signal

It can be seen that the signal in the surface away from the wall is unchanged. However due to the properties of the electromagnetic signal it may be possible to improve the signal strength in the direction away from the wall by using a suitable reflective surface. To this end some measurements were carried out with simple materials.

Placing the Access Point into a Cardboard box as seen in Figure 14 will have the effect of concentrating the signal through the gap. Since cardboard is not reflective then the gain associated with this setup is not significant, a difference of 2dB.

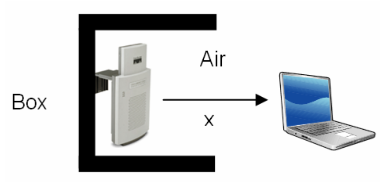


Figure 14: Effects of placing base station in box

The same measurements were carried out with the box lined with Aluminium foil. The results are recorded in Table 3. It can be seen that this gives a gain of 10 dB which is quite impressive. The advantage of this approach is that it utilises standard access points and laptops and so can be retrofitted to an existing installation.

Air	-16	db
Cardboard Hood	-14	db
Tin foil Hood	-6	db

Table 3: A comparison of gain

7. Conclusions

During the network design phase of a Wi-Fi installation it is not a simple process to know the best position to place access points due to the environmental conditions associated with area being considered. From the operational point of view it is important to know the limitations of the installation. This is required not only to ensure users can connect but also to ensure that non-authorized users could have no possibility of gaining access.

The usual mathematical approach to producing a model of the system based on the physics, which would enable the prediction of the signal strength within a building, involves a large amount of processing. This paper takes a balanced approach; it uses the physics supplemented by measurements made using system components.

An advantage of this is that some indication of the accuracy of the theory and the variation in the manufactured equipment can be gained.

From the theoretical point of view this paper shows that the technology used with WiFi follows the equations derived for antenna, i.e. the signal strength $\propto \frac{1}{d^2}$.

Users of WiFi will utilize a wide range of equipment, all manufactured to the IEEE standard but with slightly different characteristics due to the manufacturing process. This paper shows that the variation can be up to 30% which is much larger than one might expect. Clearly this can have a significant effect on the design considerations.

When planning a Wi-Fi installation, there are characteristics associated with the location that have to be considered. It is rare that the installation takes place in an open environment. Normally there are walls, windows and furniture that need to be considered. This paper provides an insight into the typical losses encountered by different types of walls and windows and indicates the importance of understanding the make up, since the losses can range from 8db to 25db. If the total budget is about 90db then this can be a considerable issue to be addressed. One of the conclusions of the paper is that, to ensure accuracy, the ideal situation would be to take measurements in the actual building prior to installation.

The antenna theory helps by suggesting ways in which the sensitivity of the standard access point can be altered. This can be carried out using very simple components, e.g. a shaped box lined with aluminium foil. A clear advantage is that this can be tailored to the installation requirements and can be retrofitted without having to make wiring and extensive alterations.

One of the major conclusions of the paper is that it is possible to produce a budget calculation dependant on the characteristics of the location. This can be automated with a software application and, if presented in graphical form, can be of great use to a network designer.

There is still future work to be carried out; the major area is to improve the three-dimensional aspects of the work. The results obtained were inconclusive due to the difficulties associated with reflections obtained from the floor. Clearly a different approach to the measurement needs to be taken.

The user interface of the software application was very simplistic but proved that the principle was viable. Again further work in this area with the inclusion of the three-dimensional aspects, and the ability to be more definitive about the characteristics of the building, would be advantageous. It is not anticipated that this will add to the complexity or the processing requirements of undertaking a finite-element model.

Even so, the results produced within the limited environment tested were accurate.

7.1. Further Work

There is a considerable amount of further work to do be done in most of the areas covered by the paper.

Measuring the effect in a 3dimensional rather than a 2d plane would give an insight into the positioning of Access Points and the effect between floors. This can be significant not only in availability but also for security where more than one company is situated in one building.

Further investigations are needed into the effects of the absorption and reflective nature of different materials and surfaces. There seems to be large variations which are not obviously accounted for without considering the make up of the material. Perhaps there will be a relationship between the wavelength and the molecular separation of materials. If a simple relationship could be found then the user interface for the automatic calculator could be simplified.

All this work would culminate in being able to calculate the optimum placement for Access Points to achieve predefined requirements within a specific physical area. These requirements could be to provide the largest overall coverage, or give optimum performance in a specified area or more importantly provide a risk assessment of the possibility of the signal outside of designate area being large enough for a connection to be made.

8. References

AirMagnet (2007), *AirMagnet Survey*, http://www.airmagnet.com/ (Accessed 20/12/2007).

Balanis, C.A. (2000), *Antenna Theory Analysis and Design*, John Wiley & Sons inc. ISBN – 0-471-59268-4

Cho, Y.J., Shin, Y.S. and Park, S.O. (2000) "Dual-band internal WLAN antenna for 2.4/5 GHz laptop PC applications", *Wiley InterScience*, Volume 48, Issue 11, pp2349–2354

Cisco (2007), ccmigration_09186a00800f9ea7, www.cisco.com, (Accessed 20/12/2007)

Cunningham, S. and Grout, V. (2007), "War and Peace: A practical study of Wi-Fi related issues", *Proceedings of the International Conference E-Activity and Leading Technologies* (*E-ALT'07*), Porto (Oporto), Portugal, 3-6 December, pp393-399.

De La Roche, G., Jaffrès-Runser, K. and Gorce, J.-M. (2007), "On predicting Indoor WLAN coverage with a fast discrete approach". *International Journal of Mobile Network Design and Innovation*, (in press)

Friis, H.T. (1946), *Proceedings of the IRE*, vol. 34, p.254.

Guterman, J., Rahmat-Samii, Y., Moreira, A.A. and Peixeiro, C. (2007), "Radiation Pattern of a 2.4/ 5.2GHz Laptop Internal Antenna: Near Field Spherical Range Measurements and Full Wave Analysis Antenna Technology *", Small and Smart Antennas Metamaterials and Applications, 2007. IWAT '07*. 21-23 March.

IEEE (2007), IEEE 802.11 Wireless Local Area Networks - The Working Group for WLAN Standards, http://www.ieee802.org/11/ (Accessed 20/12/2007).

Ji, Z., Li, B.-H. Wang, H.-X., Chen, H.Y. and Sarkar, T.K. (2001), "Efficient ray-tracing methods for propagation prediction for indoor wireless communications" *IEEE Antennas and Propagation Magazine*, Volume 43, Issue 2, April, pp41-49.

NetStumbler (2007), *NetStumbler: A Wireless networking tool*, http://www.netstumbler.com/ (Accessed 20/12/2007).

O2 (2007), *7000 O2 Wi-fi locations*, http://consumero2.directoryconnection.com/ (Accessed 20/12/2007).

Otyakmaz, A., Fornefeld, U., Mirkovic, J., Schultz, D.C. and Weiss, E. (2004), “Performance evaluation for IEEE 802.11G hot spot coverage using sectorised antennas”, *15th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC 2004*. 5-8 September.

WAG (2007), *What Antenna* Guide, http://www.allendale-hosting.co.uk/antenna/download/FAQ (Accessed 12/12/2007).

Yang, M., Kaffes, D., Mavrakis, D. and Stavrou, S. (2003). “The impact of environment variation on co-channel interference in WLAN”, *Twelfth International Conference on Antennas and Propagation*, (*ICAP 2003*). pp71-75.

Zhongqiang, C. and Bertoni, H.L. and Delis, A. (2004), “Progressive and approximate techniques in ray-tracing-based radio wave propagation prediction models”, *IEEE Transactions on Antennas and Propagation*, Jan. Volume: 52, Issue: 1, pp240-251