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# Broadband Wireless Communication in an Occupied Frequency Band

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# ABSTRACT

The wireless environment is becoming a crucial medium for communication. The demand for such systems is growing constantly. Due to increased user bandwidth requirements, in the near future the frequency bands available for wireless communications may be insufficient. This report shows a study of how two different systems can use the same frequency band in the same area and cause minimal interference to each other. It provides theoretical analysis on the interference issues. It examines different parameters that affect the area coverage. It also points out steps to be taken such that the interference to the other system is minimal, and thus the area coverage is maximized.

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# CHAPTER 1

## 1. INTRODUCTION

### 1.1 Motivation

In only ten years, the Internet has changed the telecommunication world. Old-fashioned "3 minute average" phone calls are now replaced by Internet sessions that last up to a few hours, with large amounts of data being transferred back and forth. On the commercial side, the popularity of local area networks and their inter-operability increased the demand for bandwidth, as well. According to [1], the majority of data carried across the telecommunication networks today is non-voice data. With all of the positive changes that the networking revolution has produced, it also has brought huge problems for service providers.

One such problem was replacing the voice channel with a new fast data connection for all users. Technologies like Integrated Services Digital Network (ISDN), [2], Asynchronous Transfer Mode (ATM), [3], and Digital Subscriber Line (xDSL), [4], enabled much faster traffic than before. There is no question that a lot has been done to overcome these problems. Also, a user's desire to be connected at all times in all places introduced a new technology, cellular. The introduction of cellular systems drastically improved a user's mobility. In cellular systems, the whole coverage area is divided into smaller service areas called cells. Each cell has one central access point that serves all the users in that cell. Decreasing the cell area enables an increase in the number of mobile users, [5].

In practice, the cell size varies depending on the area. It can be as small as 1 mile in urban areas, or up to 10 miles in rural areas [6]. The cell under consideration in this report is one with a radius of 5 km, or 3.125 miles. This allows for a large enough cell, one that is economically justifiable, and, at the same time, small enough to be able to increase the number of users in an urban area. The 5 km cell size also matches the cell size given in the specifications given by the BWLL group.

When these technologies are implemented, there are two primary areas of interest, the backbone and the "last mile." The last mile deals with the problem of bringing the fast connection to the actual users. Before the Internet evolved, telecommunication systems were used predominantly for telephone calls. Since voice channels do not require high-speed bit transfer, copper wires were great medium for transport. However, when the popularity of the high-speed data transfer increased, the old copper wires proved to be not a good medium for high bit rate transfers, [4]. Even though the introduction of modems increased the bit rates that could be handled by the copper wires, it was obvious they will become obsolete really soon. In the beginning it seemed that fiber optic lines would replace copper wires. However, although this may be feasible for the backbone, it may be too expensive when it comes to the last mile.

This report is based on the idea of using broadband wireless system to connect the end user. Primarily, the idea is to implement a wireless connection to the customer premises and still be able to provide high speed Internet connection to users. Basically, the wireless connection is established by using cells. In order to increase the user capacity, the cell size is kept relatively small. The reason for using a wireless connection for the end users is to avoid the high cost of installing a wire line connection to the user site.

Two main differences between the broadband wireless system and the cellular phone system should be considered. In the case of a broadband wireless system, the user is not mobile. The wireless environment is only used to reduce expenses when installing the physical connection. The other difference is bandwidth size. In cellular phone systems, the user has bandwidth that is only enough for one voice channel. In a broadband wireless system, the user has a much higher bandwidth that enables high speed Internet access.

Today, most of the wireless Internet providers use allocated frequencies for the connection. This means that they have the right to a specific range of frequencies, and no one else can use the same frequency in that area. However, the limitations of frequency bands for service providers and the ever-increasing demand for bandwidth by users impose a limit to the number of users that may be serviced in a certain cell. It is in the providers' best interest to increase the number of users in a cell.

There are several ways of increasing the capacity of a cell. One is by reducing the cell-size and using a frequency reuse pattern. However, at some point it is not economically acceptable to reduce the cell size further. Another method would be to increase the number of frequency bands available, which can be accomplished by utilizing non-allocated frequencies for commercial use. This way a whole spectrum of frequencies can be used. The greatest problem with using non-allocated frequencies is the interference that the system may cause for the existing users who use the same frequency but do not belong to that system. Another scenario would be if two or more providers are allowed to use the same allocated frequency. This would decrease the price for the use of the frequency; it will create competition between providers and possible make it cheaper at the end user.

This introduces an important question: how far/close can a provider position its users from an existing system, such that it can guarantee services to its users and at the same time not cause harmful interference to the already existing systems that use the same frequency. This type of interference is known as co-channel interference.

There are different ways of preventing interference, depending on what needs to be accomplished and what kind of system is implemented. For example, [7] deals with a case where multiple users, randomly distributed, share the same frequency and thus cause co-channel interference to a certain transmitter-receiver link. The primary interest in [7] is the increase or decrease in the bit error rate depending on the distribution of the users. On the contrary, this report deals with a case of Time Division Multiple Access / Time Division Duplex (TDMA/TDD) type of model. In this model only one user at a time can use the channel, and, therefore, only one user can cause interference to the existing systems. Also, rather than concentrating on the effects of the interference in the bit error rate, the primary interest is to increase the area coverage. Namely, the assumption is that the broadband wireless system components (access point and the user) will be positioned in such a location that they will not cause harmful (some specified level) interference to existing systems. Therefore, the interest is not the bit error rate, but the area coverage in the cell.

In [8] and [9] there are two different methods of interference cancellation. Basically, these technical papers describe additional equipment used for interference cancellation. In this report, however, the emphasis is on the effects of the simple physical parameters (location, height, power level, etc) rather than introducing additional equipment for suppressing noise. In [10] and [11] a similar problem is introduced: interference between line-of-sight radio relay systems and broadband satellite systems. However, the primary interest in those papers is the distortion caused by the interference in the analog carrier, not the area coverage within a cell.

There are number of studies that describe antenna technology and how to produce an antenna with side lobes as low as possible. However, this report deals with a case where the antenna pattern is theoretically determined. In order to make it a more realistic case, the maximum gain and the physical shape of the antennas are assumed from antennas already used on the market for a similar type of system. Except for Section 4.6, the specifications for the maximum gain used for the calculations are based on the parameters given by the antenna supplier and BWLL group

Another way to avoid interference would be to try to find a frequency channel that nobody else uses in that cell. In [12] and [13] an algorithm for finding the frequency reuse pattern is introduced when a spectrum of allocated frequencies is used. As mentioned earlier, this report deals with the case where either non-allocated frequencies are used or more than one provider use the same allocated frequency. Therefore, it is very possible that someone else in the area is using the same frequency. Hence, the provider must deal with interference and, by finding proper parameters, should be able to establish the best area coverage possible.

Fig 1.1 graphically depicts the problem researched in this report. The access point (AP) antenna and the user antennas are part of the same system. The access point communicates with all the users in a particular cell. Within a cell the access point is divided into 6 sectors, each of them 60° wide. Since it is assumed that this system operates in an area where someone else may use the same frequency, it is possible that it may cause co-channel interference. Therefore, for the purpose of the report this system is going to be called the Interfering System (IS). As mentioned before, at any given point in time only one user antenna can transmit; consequently, the user antenna will be called the Interfering System Antenna (IS antenna). It is assumed that the AP antenna does not cause interference. This assumption is justified in later chapters. On the other hand, the system that has already been in place and may suffer interference because of the IS will be called the Interfered-with System (IWS). The concept of 6 sectors in a cell was also suggested by the BWLL group.

In this report the assumed IWS system is, basically, a receiver antenna from a satellite system that uses the same frequency as the IS. As can be seen from the figure, the IS antennas always point straight towards the AP antenna. In general, they will not point toward the IWS antenna, but because of the side lobes, it is possible to cause interference to the IWS antenna. In order not to cause interference, the IS antenna should be positioned in a place that is far enough from the IWS antenna and is guaranteed not to cause harmful interference. This creates an area around the IWS antenna where no IS antenna should be placed. This area is called the forbidden zone. The point of this report is to find out what can be done to minimize this forbidden zone.

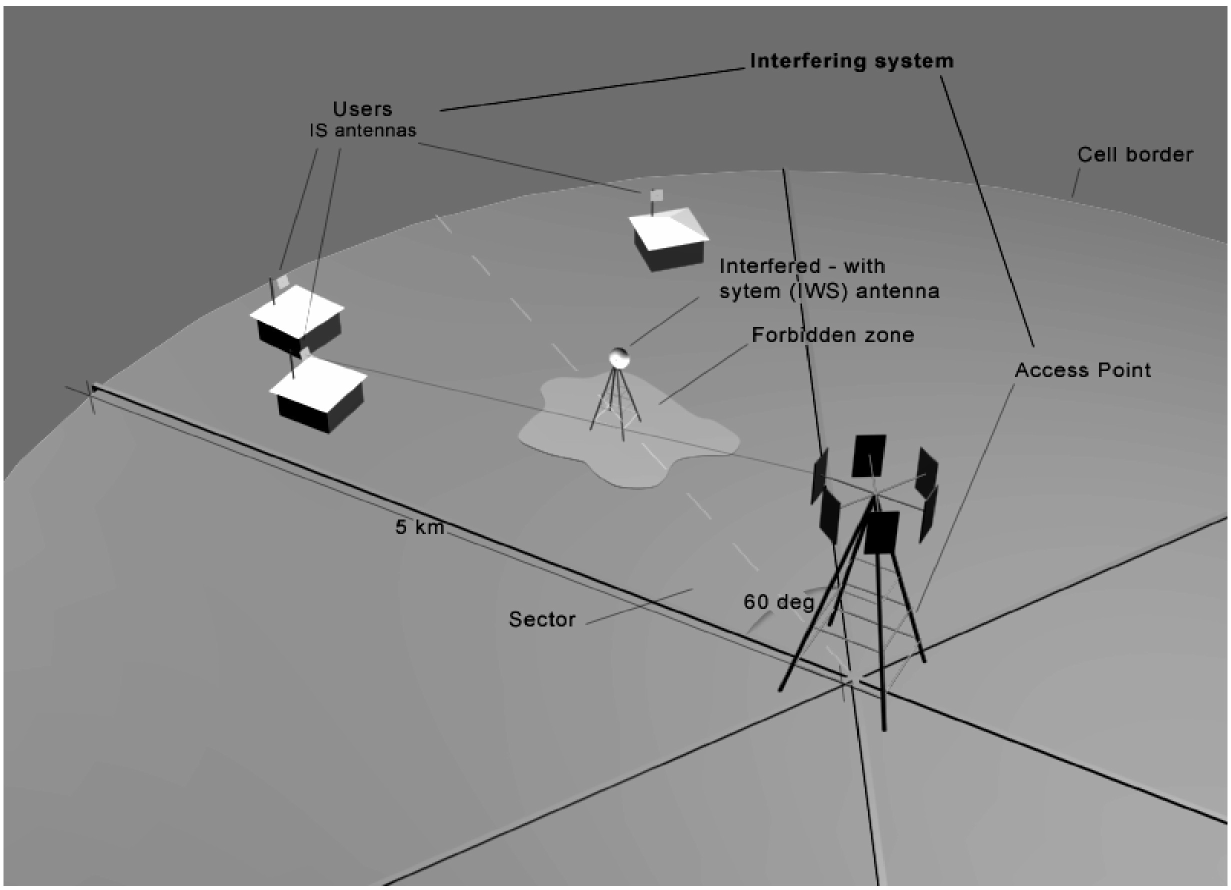


Fig 1.1 Cell site

## 1.2 Report Organization

The first part of the report, Chapter 2 and Chapter 3 explain the theoretical formulas used for the computer calculations. Section 2.1 introduces the interference analysis and the relations used for determining the allowed interference level. It introduces all the parameters that may be varied in order to increase area coverage. After all the parameters are introduced in Section 2.1, Sections 2.2, 2.3 and 2.4 offer a closer examination of each of the parameters individually. Section 2.2 explains the propagation model used. It gives the relations that describe the two-ray propagation model. Section 2.3 deals with the antenna pattern formulas. It gives the antenna pattern relations for circular and rectangular aperture antennas. Section 2.4 explains the link calculations for the access point-user link. It gives the power levels that are used in both cases, with power control and without. Section 3.1 gives mathematical derivations of the antenna gain angles that are used for the computer algorithm, in order to calculate the forbidden zone. The algorithm is described in Section 3.2. Chapter 4 gives all the results received by changing some of the parameters in the simulation. Section 4.1 introduces the Forbidden Area Ratio. Section 4.2 deals with the case of adjusting the azimuth angle of the access point. Section 4.3 deals with adjusting the direction of the access point. Section 4.4 explains the effects of increasing the access point antenna height. Section 4.5 discusses the effects of varying the distance between the access point and the user. Section 4.6 gives the simulation results when power control is used. Section 4.7 deals with the trade-off between a more directional antenna and the power level at the user site. Section 4.8 shows how the provider can adjust the position of the AP antenna such that it does not cause interference to the IWS antenna. Finally, based on the simulation results, some general conclusions are drawn and explained in Chapter 5. Also, in this part the steps for minimizing the coverage area are introduced based on the conclusions. This chapter contains suggestions for possible future research, as well.

# CHAPTER 2

## 2. THEORETICAL ANALYSIS OF THE INTERFERENCE

### 2.1 Interference Relations

The analysis of interference is based on the assumption that both systems, the interfering and the interfered-with, are digital. So the measure for the quality of the received signal is the bit energy divided by the noise power spectral density, $E_b/N_o$. The assumption is that before the interfering system was installed, the interfered-with system was properly operating at some desired level of $E_b/N_o$. In further analysis that level will be called $(E_b/N_o)_{IWS\_Nointerference}$. According to [14], the following relationship holds:

$$(\frac{E_b}{N_0})_{IWS\_NO\text{int}erference} = \frac{S}{N}\frac{W}{R} \tag{1}$$

where

$E_b$ is the bit energy;

$N_o$ is the noise power spectral density;

$S$ is the signal power;

$N$ is the noise power;

$W$ is the bandwidth of the Interfered-with signal (filter bandwidth in the receiver);

$R$ is the bit rate.

When the new system that uses the same frequency is installed in the area, it causes co-channel interference. As far as the IWS antenna is concerned, the entire additional signal from any interfering antenna is just additional noise power. The installation of the interfering system will cause some change in the quality of the IWS signal. In that case the new $E_b/N_o$ would be as follows:

$$(\frac{E_b}{N_0})_{IWS\_interference} = \frac{S}{(N+N_1)}\frac{W}{R} \quad (2)$$

in which

$$N_1 = P_{IS\_antennas} + P_{AP\_antenna} \quad (3)$$

Basically, $N_1$ is the additional power that the interfered-with system is going to receive due to the new transmitters in the area. In general, this additional power is from all the users that transmit at the same time, $P_{IS\_antennas}$, plus the power from the access point, $P_{AP\_antenna}$. However, in the model discussed in this report, only one user at a time can transmit (including the access point). In that case:

$$N_1 = \begin{cases} P_{IS\_antenna,} & \textit{when an IS antenna transmits} \\ P_{AP\_antenna,} & \textit{when the AP antennatransmits} \end{cases} \quad (4)$$

The primary interest will be the co-channel interference that is caused by the IS antenna. The assumption is that the provider would be able to ensure that there is no interference from the access point. This assumption is discussed in Section 4.8.

When a digital system is installed. The propagation loss between the transmitter and the receiver can be divided in two parts [15].

$$\textit{Maximum acceptable loss} = \textit{Predicted loss} + \textit{Fade margin} \tag{5}$$

The predicted loss is calculated based on the different parameters that may affect the signal in that particular link. This would include: the path loss, body and matching loss of the antennas, receiver noise figure, average rainfall, etc., as explained in [14] and [15]. The predicted loss is normally calculated in the link budget calculations.

The fade margin is allocated for the signal fading that may occur due to any other influences that were not predicted in the original budget calculations, [15]. Therefore, part of this fade margin will be used to place the new system in the same area, and, at the same time, not to cause harmful interference to the existing system. In the newly designed systems the fade margin can be up to 5 db [14]. It would be nice if that entire margin was available for the IS antenna. However, the fade margin should compensate for any other unexpected influences like extreme weather, some additional interference, etc. In order to be conservative in using the margin, all the calculations are performed using only 1 db of the fade margin. This would leave 80%

of the margin for any other unexpected influences. As a matter of fact, if another provider decides to implement a similar system in the area, with a conservative use of the margin, additional implementation would also be possible. Some of the older systems may have lower fade margins. This is due to the fact that they have already been tested for a longer period of time and their signal fading can be predicted with a lot less uncertainty. But, even in such systems, there is at least 1db of fade margin that can be used for the interference of the IS system. Furthermore, the part of the fade margin used for the IS antenna interference will be referred to as simply the margin with M=1db.

In mathematical terms this means that there is always margin between the required $E_b/N_o$ level and the operational $E_b/N_o$. According to [14] the margin level is defined as:

$$M(dB) = \left(\frac{E_b}{N_0}\right)_{operationd}(dB) - \left(\frac{E_b}{N_0}\right)_{required}(dB) \tag{6}$$

In order for the interfering system not to cause harmful interference to the IWS, the interfering signal should not decrease the IWS $E_b/N_o$ level for more than the allowed margin. The margin level varies depending on the system deployed. But, in general, there should be enough margin allocated in order to achieve a desired signal-to-noise ratio under any working conditions. In this case, the difference between the SNR when the IS system is present and when it is not should not be more than the margin allowed in the IWS system. Expressing that in a mathematical relationship is as follows:

$$M(dB) > 10\log\left(\frac{E_b}{N_0}\right)_{IWS\_NOinterference} - 10\log\left(\frac{E_b}{N_0}\right)_{IWS\_interference} \tag{7}$$

Using the equation given in Eqn. (2), Eqn. (7) changes to the following:

$$M(dB) > 10\log\left(\frac{\frac{S}{N}\frac{W}{R}}{\frac{S}{(N+N_1)}\frac{W}{R}}\right) \tag{8}$$

After a few algebraic cancellations Eqn. (8) simplifies to:

$$M(dB) > 10\log\left(\frac{N+N_1}{N}\right) \tag{9}$$

Rearranging Eqn. (9) leads to an equation for the upper bound of $N_1$.

$$N_1 < N(10^{M/10} - 1) \tag{10}$$

The above equation shows that the additional power that the interfered-with system is going to receive should not be higher than a certain level. That level depends on the margin, $M$, and the noise power, $N_1$. Furthermore, the additional received power level of the interfered-with system will be called $P_{received}$. Therefore:

$$P_{received} < N(10^{M/10} - 1) \tag{11}$$

Eqn. (11) shows the upper bound of the power level that the IWS antenna may receive due to the transmission of the interfering system.

As mentioned earlier, $N$ is the noise power. According to [14],

$$N = kT_0WF \tag{12}$$

where $k$= 1.380622 J/K is the Boltzman constant;

$T_0$=290° is the room temperature;

$F$ is the noise figure. In order to make a conservative assumption the value of the noise figure is used as $F$=1.

$W$ is the bandwidth of the signal in the IWS.

For this work, the assumption is that the IWS is a broadband satellite system with $W$=36 MHz, [16].

The only unresolved parameter in Eqn. (11) is the power that the IWS antenna will receive from the interfering antenna. There are several models that describe the propagation of microwave energy from one antenna to another. The model used in this report is discussed in the following section.

## 2.2 Propagation Model

Finding the proper propagation model for a certain system is not an easy task. Normally, the free space propagation model is used for satellite communications. There are several models that are developed for cellular systems. Most of them are based on some experimental measurements. Such models include the Okomura Model, Hata Model, and the Wideband PCS Microcell model. A short description of each of these models can be found in [5]. However, these models are effective at frequencies up to 1.5 GHz. The PCS Extension to Hata Model is an extension of the Hata Model, and can be used for frequencies up to 2 GHz.

For this report the assumption is that the frequencies used are higher than 2 GHz. So the current experimental models may not be so effective. Using the free space model also may not be the proper choice, since at least one of the systems (the interfering system) is a cellular type system. The propagation model used in this report is known as the two-ray model. The two-ray model takes into account the fact that the received signal is attenuated due to the reflection and multiple paths that it takes to reach the receiver. In this report, only a general overview of the two-ray model is given, as well as the final relationships used for the computer-simulated results. The complete derivation of the two-ray model propagation formulas is given in [5] and [17]. Fig 2.2.1 shows the two different paths that the signal takes on its way to the receiving antenna. Notice that the receiving antenna receives two signals, one from the line of sight, and the other one reflected from the ground. Due to the different path lengths, there is a phase difference between the two, causing attenuation or amplification of the signal.

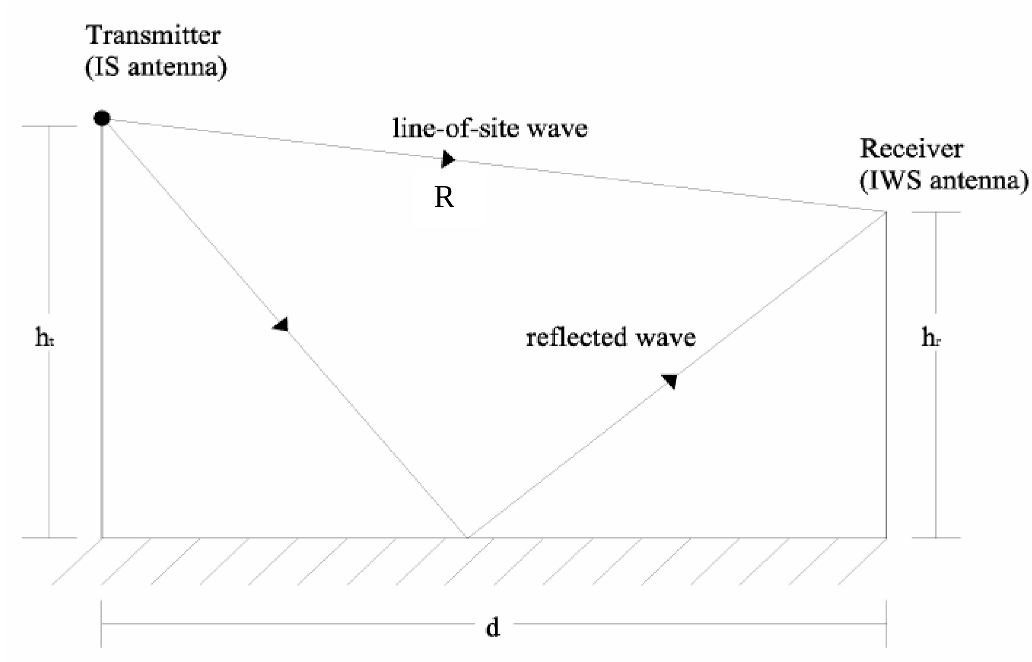



Fig 2.2.1 Two-ray model, signal is attenuated due to the phase difference of the reflected wave

The signal power received by the receiving antenna is given by the following formula, [17]:

$$P_{received} = \frac{P_{transmitte} g_t g_r g_m}{\left(\frac{4pR}{l}\right)^2} \quad (13)$$

where $P_{transmitter}$ is the signal power at the transmitter (power level of the transmitter);

$g_r$ is the antenna gain of the receiver in the direction of the transmitter;

$g_t$ is the antenna gain of the transmitter in the direction of the receiver;

$g_m$ is the multi path factor;

$\lambda$ is the wavelength of the signal;

$R$ is the distance between the two antennas.

From Fig 2.2.1 one can see that $R^2=(h_r-h_t)^2+d^2$, where $h_r$ and $h_t$ are the heights of the receiver and transmitter antennas, respectively, and $d$ is the ground distance between the receiving and the transmitting antenna.

The wavelength of the signal, $\lambda$, is reciprocal to the frequency.

$$l = \frac{c}{f} \tag{14}$$

where $c$=3x10$^8$ m/s is the speed of light.

$f$=4GHz.

The multi-path factor, $g_m$, is defined as follows, [17]:

$$g_m = 1 + 2r\cos\left(\frac{2p\Delta R}{l} + f\right) + r^2 \tag{15}$$

In Eqn. (15), *DR* is the path difference between the direct wave and the reflected wave. Using Fig 2.2.1, the mathematical representation of *DR* is given in the following formula:

$$\Delta R = \sqrt{(h_r + h_t)^2 + d^2} - \sqrt{(h_r - h_t)^2 + d^2} \tag{16}$$

The other two parameters in Eqn. (15), $r$ and $f$, are the amplitude and the phase of the reflection coefficients. Mathematically they are defined as following, [17]:

$$y = \arctan\left(\frac{h_r + h_t}{d}\right) \tag{17}$$

$$\Gamma_h = \frac{\sin(y) - \sqrt{e_c - \cos^2(y)}}{\sin(y) + \sqrt{e_c - \cos^2(y)}} = r_h e^{-jf_h} \tag{18}$$

$$\Gamma_v = \frac{e_c \sin(y) - \sqrt{e_c - \cos^2(y)}}{e_c \sin(y) + \sqrt{e_c - \cos^2(y)}} = r_v e^{-jf_v} \tag{19}$$

$G_h$ and $G_v$ are reflection coefficients when the carrier is polarized horizontally or vertically, respectively. As the distance increases, their value approaches –1. For this report the worst case is assumed, that both systems, IWS and IS, have the same polarization. Furthermore, for the sake of simplicity, horizontal polarization is assumed. $e_c$ is the dielectric constant of the reflecting surface. In [17] values of $e_c$ are listed for different types of surfaces. In this report an urban (residential) surface is assumed. Therefore, $e_c$=5-j0.002x60x$\lambda$.

Eqn. (13) is normally used in link calculations for a receiver-transmitter link from the same system. However, in this case, the transmitter is the interfering antenna from IS, and the receiver is the antenna of the IWS. Therefore, $P_{transmitter}$ is the power level of the IS antenna, $g_t$ is the antenna gain of the IS antenna in the direction of IWS antenna, and $g_r$ is the antenna gain of the IWS antenna in the direction of the IS antenna. For that reason $g_t$ will be labeled as $g_{IS\_IWS}$ and $g_r$ as $g_{IWS\_IS}$.

Keeping in mind the discussion above, Eqn. (12) is as follows:

$$P_{received} = \frac{P_{transmitter}\, g_{IS\_IWS}\, g_{IWS\_IS}\, g_m}{\left(\frac{4\pi}{\lambda}\right)^2 ((h_r - h_t)^2 + d^2)} \tag{20}$$

The power level of the transmitter will be discussed in chapter 2.4, where the link calculation of the system is discussed. The antenna patterns, $g_{IWS\_IS}$ and $g_{IS\_IWS}$, will be discussed in more detail in the following section.

## 2.3 Antenna Gains and Patterns

One of the most important parameters that explains the functionality of an antenna is the antenna gain. As described in [18], antenna gain is defined as the ratio of the radiation intensity in a given direction to the radiation intensity that would be obtained if the power was radiated by an isotropic antenna. An isotropic antenna is an antenna that radiates equally in all directions. Mathematically the gain is represented as:

$$gain = 4\pi\alpha \frac{radiation\ \ in\ certain\ \ direction}{P_{IN\_isotropic\ \ \_source}} \tag{21}$$

where $\alpha$ is the efficiency of the antenna and accounts for all the losses that occur in the antenna.

In the far field, the antenna gain does not depend on the distance, but only on the direction. In polar coordinates this would mean that the gain is only a function of the polar angles, $\theta$ and $\varphi$, and not on the radius *r*.

Most of the time, the gain of an antenna is considered to be the maximum value of the gain for any direction. In link calculations for a receiver-transmitter link from the same system, the maximum gain has a major role. This is so because it is assumed that the transmitter and the receiver antenna look straight at each other, and therefore the gain of both antennas is maximum. However, in this report, this is not necessarily the case. Here the transmitter and the receiver are from different systems and, in general, their antenna position relative to one another can vary enormously. Therefore, the antenna gain in certain directions will play a major role in the interference calculations. The normalized antenna gain in a certain direction is known as the antenna pattern. In general, finding the antenna pattern is not an easy problem. There are numerous methods of calculating the antenna pattern; however, often in practice, the antenna pattern is determined by conducting measurements.

The purpose of this report is not to try to calculate the antenna patterns, nor to find better ways of shaping the pattern. This report deals with a case where the antenna patterns are already theoretically predetermined. Based on requirements that are discussed later in this section, it is appropriate to use a rectangular aperture antenna for the IS antennas. Since the IWS system is assumed to be a part of a satellite system, a circular aperture antenna is the most appropriate choice for the IWS antenna.

This chapter shows the formulas used for the antenna patterns, as well as their graphical presentation. It should be pointed out that these formulas are strictly theoretical and may differ somewhat in actual implementation. But since all the work in this report is based on theoretical analysis, the theoretical gains of the antennas are assumed to be an appropriate choice for the interference calculations. The expectation is that the conclusions drawn from these theoretical formulas will be general and hold for different types of antenna patterns.

As mentioned in the previous section, there are two parameters of interest: $g_{IS\_IWS}$ and $g_{IWS\_IS}$. $g_{IS\_IWS}$ is the antenna gain of a rectangular aperture antenna in the direction of the IWS, and $g_{IWS\_IS}$ is antenna gain of a circular aperture antenna in the direction of the IS antenna.

It is important to note that antenna gain formulas may be simplified as the distance from the antenna increases. Based on the size of the antenna, three different regions of interest can be established: the reactive near-field region, the radiating near-field (Fresnel) and the far-field region (Fraunhofer), [18]. In this report the far-field region is assumed, i.e., it is assumed that the distance between the IWS and IS antennas is far enough to use the far-field formulas. In order to use the far-field relations, the distance from the antenna should be greater than $2D^2/l$. $D$ is the maximum overall dimension of the antenna. The antenna gain formulas used in this report are presented in [19]. The following shows only a few steps of deriving the gain formulas as well as the final formulas used in the simulations.

As presented in [19] and Fig 2.3.1 the gain of an aperture antenna is given by:

$$g(q,f) = \frac{p}{l^2}\frac{\left|\int_A F(x,h)(\cos q + 1)e^{jk\sin q(e\cos f + h\sin f)}dxdh\right|^2}{\int_A \left|F(x,h)\right|^2 dxdh} \qquad (22)$$

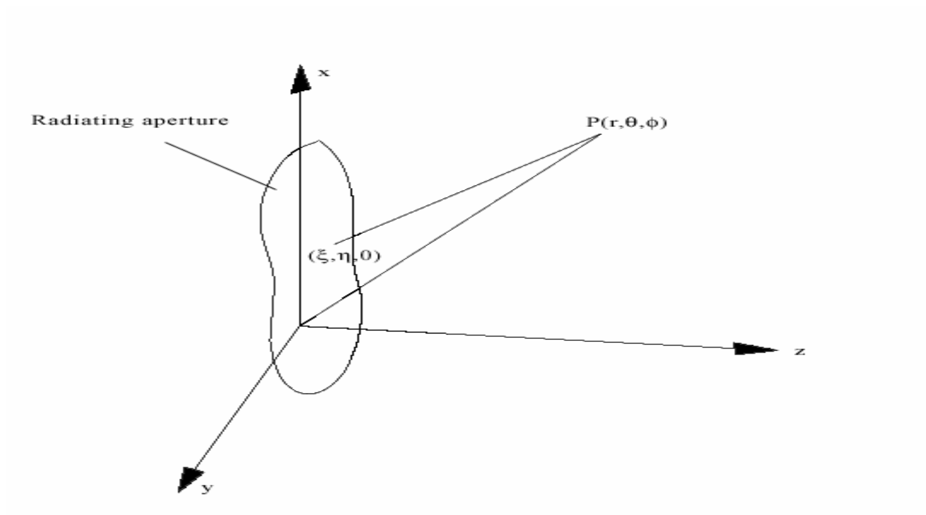



Fig 2.3.1 Derivation of the antenna gain of a radiating aperture

where $q$ and $f$ are the polar coordinates in the $x,y,z$ coordinate system presented in Fig 2.3.1 and $x$ and $h$ are the polar coordinates in the $x,y$ plane. $A$ is the radiating area of interest. $F(x,h)$ is the field distribution over the aperture, and for the purpose of this report is assumed to have a uniform amplitude and phase distribution; therefore, $F(x,h)=1$. In addition, $k$ is defined as $k=2p/l$. Notice in Fig 2.3.1 that $q$ and $f$ define a line and all the coordinate points that lie on that line (in that direction) have the same gain value.

The rectangular aperture antenna will be analyzed first. In reference to Eqn. (22), this means that aperture $A$ is a rectangular in the $x,y$ plane. The size of the rectangle on the $x$-axis is $a$ (length), and the size in the $y$ direction is $b$ (width). As presented in [19], the following holds:

$$\int_{-\frac{a}{2}}^{\frac{a}{2}}\int_{-\frac{b}{2}}^{\frac{b}{2}} F(\xi,\eta)e^{jk\sin\theta(\xi\cos\phi+\eta\sin\phi)}d\xi d\eta = ab\left[\frac{\sin(\frac{\pi a}{\lambda}\sin\theta\cos\phi)}{\frac{\pi a}{\lambda}\sin\theta\cos\phi}\right]\left[\frac{\sin(\frac{\pi b}{\lambda}\sin\theta\sin\phi)}{\frac{\pi b}{\lambda}\sin\theta\sin\phi}\right] \tag{23}$$

Therefore, for a rectangular aperture antenna with size *a* x *b*, the gain function is:

$$g(\theta,\phi) = \frac{\pi ab}{\lambda^2}(1+\cos\theta)^2\left|\frac{\sin(\frac{\pi a}{\lambda}\sin\theta\cos\phi)}{\frac{\pi a}{\lambda}\sin\theta\cos\phi}\frac{\sin(\frac{\pi b}{\lambda}\sin\theta\sin\phi)}{\frac{\pi b}{\lambda}\sin\theta\sin\phi}\right|^2 \tag{24}$$

This is the theoretical gain of the rectangular aperture antenna. In practice, however, the gain is often multiplied with an efficiency coefficient ($0<\alpha<1$) to compensate for all the losses that occur in the antenna.

Using the size of the antenna and the efficiency coefficient, the parameters of the IS antenna and the access point antenna were adjusted such that they meet the specifications for the cell. The access point antenna is a rectangular aperture antenna. Referring to Fig 2.3.1, the aperture is positioned in the xy plane. Its main lobe is 60° wide in the azimuth plane (yz plane) and 7° wide in the elevation plane (xz plane). The center of the main lobe is the z-axis. The 60° wide lobe in the azimuth plane corresponds to the width of a sector. On the other hand, the 7° wide lobe in the elevation plane serves few purposes. Being relatively quite directional, it allows a longer distance from the customer and the access point antenna, and it also causes less interference to the antennas that are not from that system and are not located on the same height as the access point antenna. Also, it ensures that as the AP antenna changes in height, the cell coverage will not be affected much. The desired width of the lobe is accomplished by proper selection of the physical dimensions of the antenna. As the dimensions of the antenna become longer, the main lobe becomes more directional. In order to achieve a 60° x 7° lobe, the width of the antenna must be proportionally larger than the height. This design services all customers located in a particular sector. For the purpose of the interference calculations, the access point antenna does not play a major role, as explained earlier. Referring to Fig 2.3.1, the maximum gain of the access point antenna is 18dBi in the direction of the z-axis, using an isotropic antenna as a comparison level. Fig 2.3.2 and Fig 2.3.3 show the access point antenna gain in the azimuth plane ($f$=0°) and elevation plane ($f$=90°) for -180°<$q$<180°.

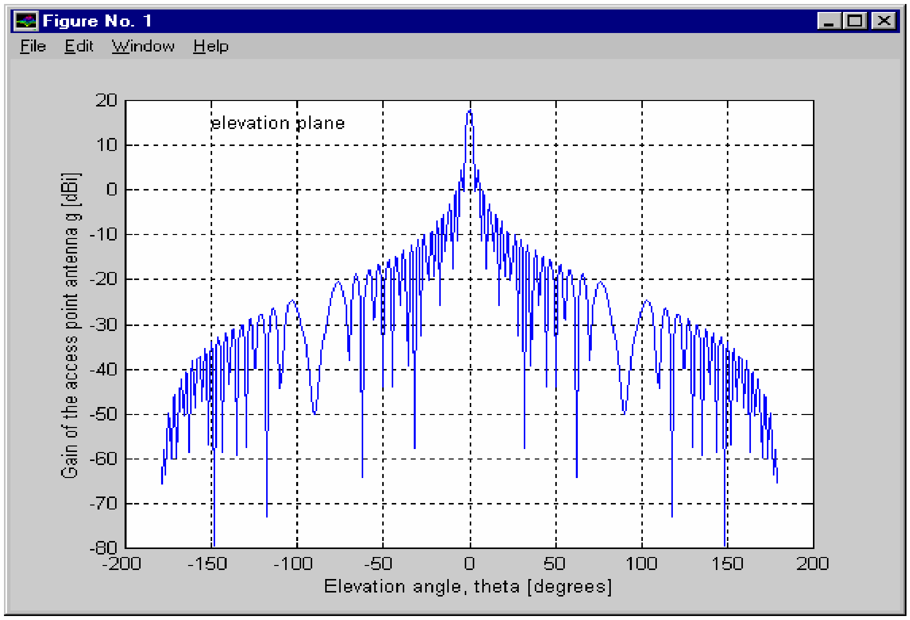



Fig. 2.3.2 Access Point antenna gain pattern in the azimuth plane, max_gain=18dBi

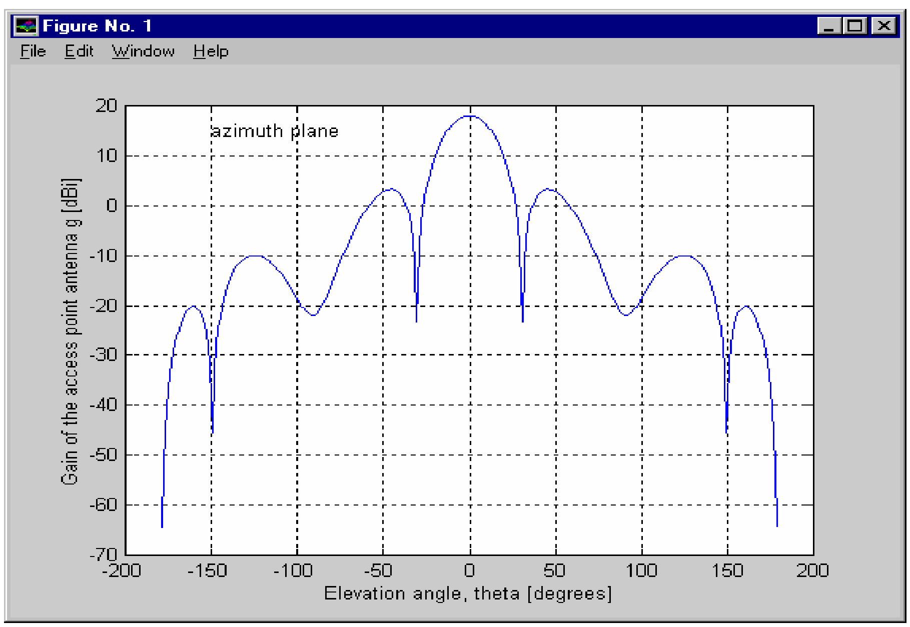



Fig. 2.3.3 Access Point antenna gain pattern in the elevation plane, max_gain=18dBi

The gain of the antenna, as well as the width of the main lobe used in this report corresponds to the specification given by the BWLL group.

The IS antenna has a rectangular aperture as well. However, it is square in shape, and, for the most part, except for Section 4.6, its maximum gain is 18 dBi (compared to an isotropic antenna), and the main lobe is 20° x 20°. Since not all the customers will have clear view towards the AP antenna, alowing the main lobe to be not so directional can be helpful in practical implementations of such systems. Referring to Fig 2.3.1, the maximum gain is in the direction of the z–axis. In order to make a more realistic case, the gain and the shape of the antennas are taken as parmeters from existing antennas used in a similar environment. However, the pattern is theoretically calculated based on the antenna type. In Section 4.6 the gain and the main lobe of the IWS antenna are varied in order to see what kind of effect such change has on interference. Fig 2.3.4 shows the antenna pattern of the IWS antenna with a maximum gain of 18 dBi and a 20° x 20° main lobe. This antenna pattern is used for most of the measurements. In Fig 2.3.5 the maximum antenna gain is increased by changing the size of the antenna. Note that this causes the main lobe to shrink. The antenna gain in this case is 22 dBi. This and some other maximum gain values are used in Section 4.6. Since the antenna is square, the azimuth and elevation plane have the same shape. The gain and the lobe dimensions of this antenna also correspond to the specification provided by the BWLL group.

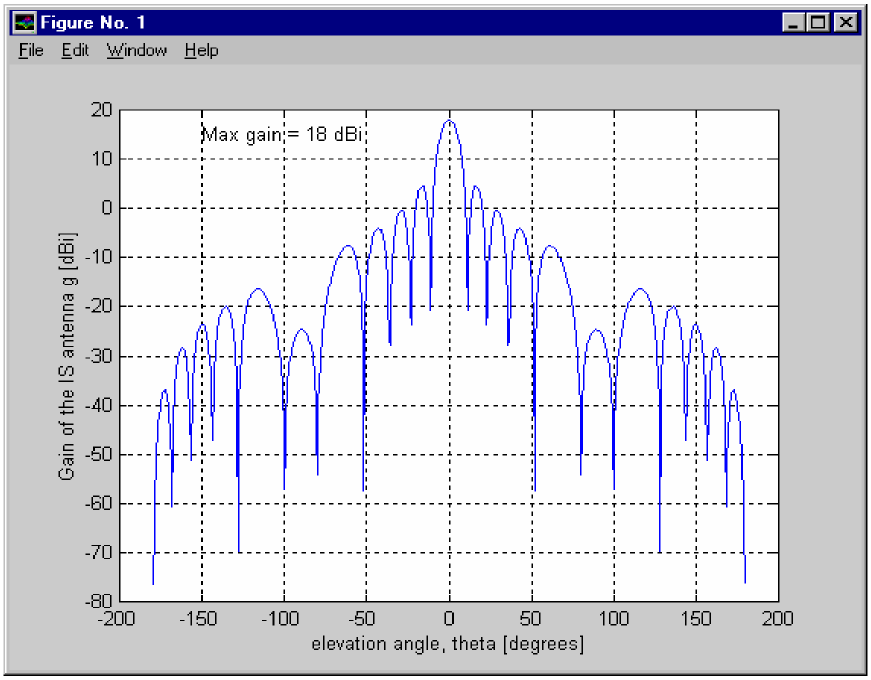



Fig 2.3.4 IS antenna gain pattern, max_gain=18dBi, rectangular aperture

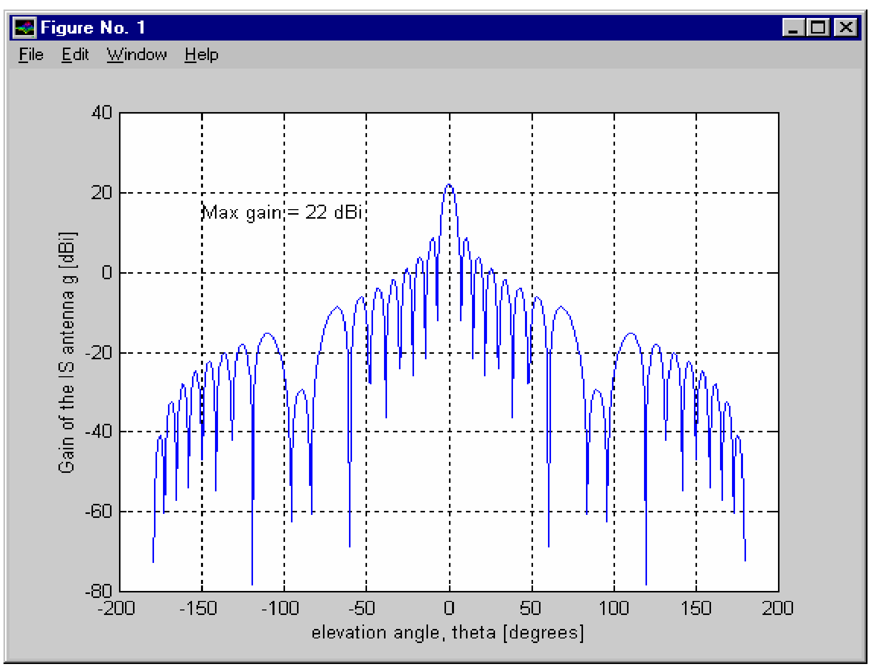



Fig 2.3.5 IS antenna gain pattern, max_gain=22dBi,rectangular aperture,increased size

The IWS antenna is assumed to be part of a satellite system. However, that may not always be the case. Again, the expectations are that the conclusions at the end will be general and hold for any antenna type. The assumed IWS antenna is a circular aperture antenna. The exact derivation of the antenna pattern is given in [19]. Because the aperture is uniformly illuminated and the radius of the aperture is *a*, the following holds:

$$\beta\int_0^{2\pi}\int_0^{a} F(\rho,\varphi)\, e^{jk\rho\sin\theta\cos(\phi-\varphi)}\,\rho\, d\rho\, d\varphi = 2\pi a^2\,\frac{J_1\!\left(\frac{2\pi a}{\lambda}\sin\theta\right)}{\frac{2\pi a}{\lambda}\sin\theta} \tag{25}$$

where $x = \rho\cos\varphi$, $\eta = \rho\sin\varphi$, and $J_1$ signifies the Bessel function. The above formula represents only the normalized antenna pattern of a circular aperture antenna with radius *a*. A three-dimensional picture of the pattern presented by Eqn. (25) is given in [18]. These types of antennas are designed to have high gain in a certain direction. This is necessary since the very long distances between the receiving antenna and the satellite causes large path loss. In such circumstances any additional gain that can be achieved by the antenna design is important.

The formula given in Eqn. (25), however, does not take into account the blockage that is caused by the feed of the antenna. To make it more realistic, the following formula, Eqn. (26), gives the actual antenna gain of a circular aperture antenna, with radius *a*, that uses a circular feed, with radius $a_1$. This formula is derived based on the interpretations given in [19] explaining the effects of the feed over the antenna pattern.

$$g(q) = \frac{a(1+\cos q)^2}{l^2 a^2} \left| \frac{2pa^2 J_1(\frac{2pa}{l}\sin q)}{\frac{2pa}{l}\sin q} - \frac{2pa_1 J_1(\frac{2pa_1}{l}\sin q)}{\frac{2pa_1}{l}\sin q} \right|^2 \qquad (26)$$

where α is the efficiency of the antenna.

The gain does not depend on the polar coordinate $f$. For the purpose of this report, the radius of the aperture is $a$=0.875m, the radius of the feed is $a_1$=0.1m and, the efficiency is α=0.55. The dimensions of the antenna are determined based on the calculations given in [20]. This is approximately the size of the dish antenna that would be used in order to communicate with one of the satellites of Telstar in the orbit if the antenna was to be positioned in the vicinity of Lawrence, Kansas. The value of the efficiency of 0.55 is also taken as the most common value used in the practice, as explained in [21]. The gain formula used for the calculation of the interference is given in Fig 2.3.6. For the purpose of this report it will be assumed that the far field for such an antenna starts somewhere around $2D^2/\lambda$ = 80m from the IWS antenna. Therefore, all the analysis will be valid outside of that area.

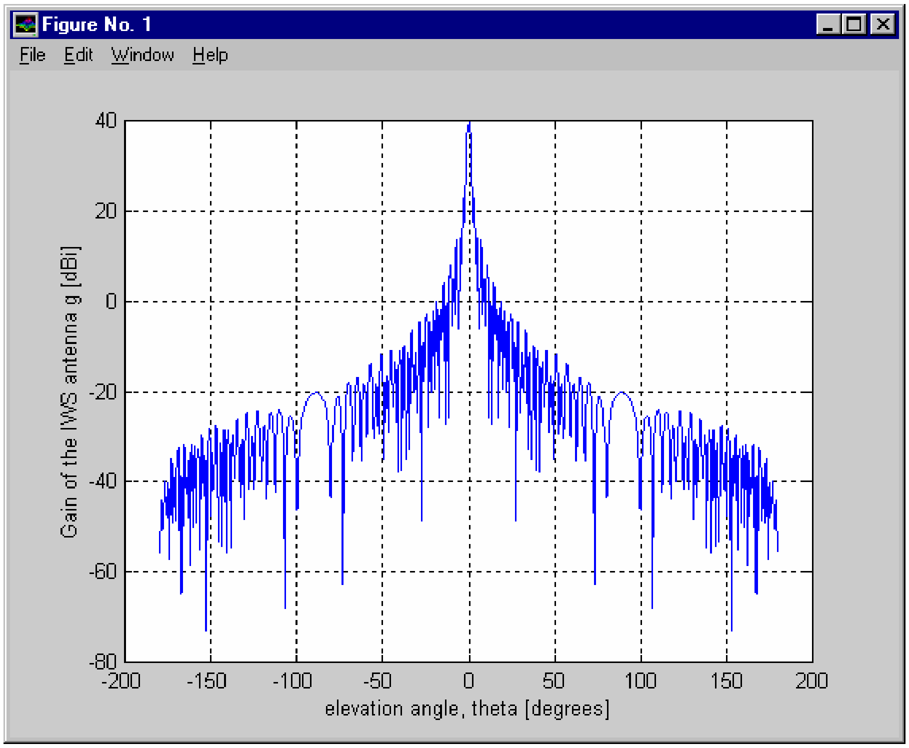


Fig 2.3.6 IWS antenna gain pattern, circular aperture with circular feed

## 2.4 Link Calculations and Determining the Power Level of the *IS* Antenna

The only parameter from Eqn. (13) that has not been completely explained is the $P_{\text{transmitter}}$. In this report $P_{\text{transmitter}}$ is, basically, the power level of the IS antenna. Therefore, from this point on it will be referred as $P_{IS\_antenna}$. The question here is how high that power level should be. The assumption for this system is that the signal-to-noise ratio for the access point-user link should at all time be 10 dB. That would mean that no matter where the IS antenna is located, its power level should be high enough to establish a 10 dB SNR link with the AP antenna. It is normal to expect that the IS antenna located at the end of the sector, 5 km away from the AP antenna, will have the highest power level. In order to determine the desired power level of the IS antenna, it is necessary to perform some link calculations. The link calculations in this report are not extensive and take into account only those parameters necessary for simple link calculations. The procedure for link calculations is described in [22].

The calculations to determine what should be the power level in order to achieve 10 dB SNR are as follows:

$$SNR(dB) = P_{received}(dBm) - N(dBm) \tag{27}$$

where, $P_{received}$ is the power that the AP antenna should receive, and $N$ is the noise power.

$$N(dBm) = 10\log\left(\frac{kT_0BF}{1mW}\right) \tag{28}$$

*B* is the bandwidth for the IS system, and, for the purpose of this report is assumed to be *B*=20 MHz. *F* is the noise figure of the receiver and it is set to *F*=10 dB, [13]. Therefore:

$$N(dBm) = 10\log(\frac{kT_0}{1mW}) + 10\log B + 10\log F = -174dBm + 73 + 10 = -91dBm$$

$$P_{received}(dBm) = SNR(dB) + N(dBm) = 10 - 91 = -81dBm \tag{29}$$

The last value is basically the power that the AP antenna should receive in order to have 10dB SNR. In Section 2.2 the two-ray propagation model was presented. That model takes into consideration the attenuation that occurs due to reflection. For the purpose of the link calculations, a simplified formula for the two-ray model will be used. The simplification in the formula comes from the fact that the calculations are performed at large distances. The simplified formula is given in [6]. So, using the two-ray propagation model, the following holds:

$$P_{received}(dBm) = P_{IS\_antenna}(dBm) + g_{IS\_AP}(dBi) + g_{AP\_IS}(dBi) - PathLoss_{total}(dB) \tag{30}$$

As mentioned earlier, $P_{IS\_antenna}$ is the power level of the IS antenna, $g_{IS\_AP}$ is the gain of the IS antenna in the direction of the AP antenna. $g_{AP\_IS}$ is the gain of the AP antenna in the direction of the IS antenna. $g_{IS\_AP}$ is the maximum gain of the IS antenna, and therefore $g_{IS\_AP} = G_{IS}$. $G_{IS}$ is maximum, because the assumption is that the IS antenna always looks straight at the AP antenna. Another simplification will be made with the $g_{AP\_IS}$. Since the antenna pattern of the AP is wide, it will be assumed that $g_{AP\_IS}$ is also the maximum gain of the AP antenna. Therefore, as shown in Section 2.3, $g_{AP\_IS}=G_{AP}$=18 dBi.

$PathLoss_{total}$ (dB) accounts for two losses. One is the actual path loss and the other one is the additional loss that may be caused by weather, diffraction, buildings, etc.

$$PathLoss_{total}(dB) = PathLoss(dB) + AddiLoss(dB) \tag{31}$$

The path loss can be calculated according to the following formula, [5]:

$$PathLoss(db) = 40\log d - 20\log h_{transmitter} - 20\log h_{receiver} \tag{32}$$

In the worst-case $d$=5000m. The height of the antennas are $h_{transmitter}$=25m and $h_{receiver}$=5m. The additional loss compensates for losses such as: body loss (around 3db), building penetration loss (12 to 20db), shadowing allowance (6 to 15db), etc.,[6]. The values for such losses are determined by measurements for every individual cell. In these calculations, the assumption for the additional loss is $AddiLoss$=20 dB. Putting everything together, the power level of the IS antenna should be:

$$P_{IS\_antenna}(dBm) = P_{received}(dBm) - G_{IS}(dBi) - G_{AP}(dBi) + PathLoss(db) + AddiLoss(dB)$$

$$P_{IS\_antenna}(dBm) = -81 - G_{IS}(dBi) - 18 + 106 + 20 = 9dBm \tag{33}$$

Besides Sections 4.5 and 4.6, all the other results are calculated for $G_{IS}$=18 dBi. So, according to the link calculations the power level of the IS antenna is assigned to be the one calculated in Eqn. (33), $P_{IS\_antenna}$=9 dBm. This calculated transmit power corresponds to the transmit power level provided by BWLL group.

In two instances the power level of the IS antenna is not as specified above. Section 4.5 examines the effects of power control. In all other chapters users have the same power level of 9 dBm. Since the link calculations were done for the worst case, at the border of the sector, it is assured that the 9 dBm power level is high enough for all other locations of the IS antenna. However, the relationship for the path loss shows that the power level can be decreased as the distance to the AP decreases. The adjustment of the power level is called power control. The power level is adjusted in such manner that as the distance to the AP antenna decreases, he power level also decreases. The decrease is directly proportional to the decrease in the path loss. On the other hand, in Section 4.6 the antenna gain of the IS antenna $G_{IS}$ increases. Therefore, the power level of the IS antenna can be decreased for as many dBm as the dB of the IS antenna gain is increased.

# CHAPTER 3

## 3. ALGORITHM FOR COMPUTING THE FORBIDDEN ZONE

### 3.1. Mathematical Derivation of the Antenna Directions

In Section 2.2 Eqn. (20) represents the propagation model used in this report. In Sections 2.3 and 2.4 the antenna gains and the IS antenna power level were discussed. With this in mind, the Eqn. (20) from Section 2.2 becomes the following:

$$P_{received} = \frac{P_{IS\_antenna} g_{IS\_IWS}(q_{IS\_IWS}, f_{IS\_IWS}) g_{IWS\_IS}(q_{IWS\_IS}) g_m}{\left(\frac{4p}{l}\right)^2 ((h_{IS\_antenna} - h_{IWS\_antenna})^2 + d^2)} \qquad (34)$$

$g_{IS\_IWS}(q_{IS\_IWS}, f_{IS\_IWS})$ is the gain of the IS antenna in the direction of the IWS antenna. That direction is determined by $q_{IS\_IWS}$ and $f_{IS\_IWS}$. Similarly, $g_{IWS\_IS}(q_{IWS\_IS})$ is the gain of the IWS antenna in the direction of the IS antenna. In general, that direction is determined by $q_{IWS\_IS}$ and $f_{IWS\_IS}$; however, since the IWS antenna has a circular aperture, its gain does not depend on $f$. $h_{IWS\_antenna}$ and $h_{IS\_antenna}$ are the antenna heights, and $d$ is the ground distance between the two antennas. In order to use the algorithm presented in the following chapter, it is necessary to express $q_{IS\_IWS}, f_{IS\_IWS}$

and $q_{IWS\_IS}$ through some other parameters. These parameters are presented in Fig 3.1.1.

As it can be seen from the Fig 3.1.1, $Q_{AP}$ represents the ground polar angle that determines the ground direction of the AP antenna relative to the IWS antenna. $Q_{IS}$ represents the ground polar angle that determines the ground direction of the IS antenna relative to the IWS antenna. $d_a$ is the ground distance between the AP antenna and the IWS antenna. The term "ground" means that the angle, or the distance, is not between the actual antennas but between the bottoms (ground level) of the antenna poles.

The idea is to express $q_{IS\_IWS}$, $f_{IS\_IWS}$ and $q_{IWS\_IS}$ as functions of the above parameters:

$$q_{IS\_IWS} = f_1(d, h_{IS\_antenna}, h_{IWS\_antenna,}, h_{AP\_antenna}, \Theta_{AP}, \Theta_{IS}, d_a)$$

$$f_{IS\_IWS} = f_2(d, h_{IS\_antenna}, h_{IWS\_antenna}, h_{AP\_antenna}, \Theta_{AP}, \Theta_{IS}, d_a)$$

$$q_{IWS\_IS} = f_3(d, h_{IS\_antenna}, h_{IWS\_antenna}, h_{AP\_antenna}, \Theta_{AP}, \Theta_{IS,} d_a) \tag{35}$$

The above functions, $f_1$, $f_2$, and $f_3$, can be derived through some geometrical formulas. In order to derive the desired functions, two different methods will be used. The derivation of all $q$ angles is calculated with the Law of Cosines, [23]. On the other hand, all $f$ angles are derived by using vector algebra, [24].

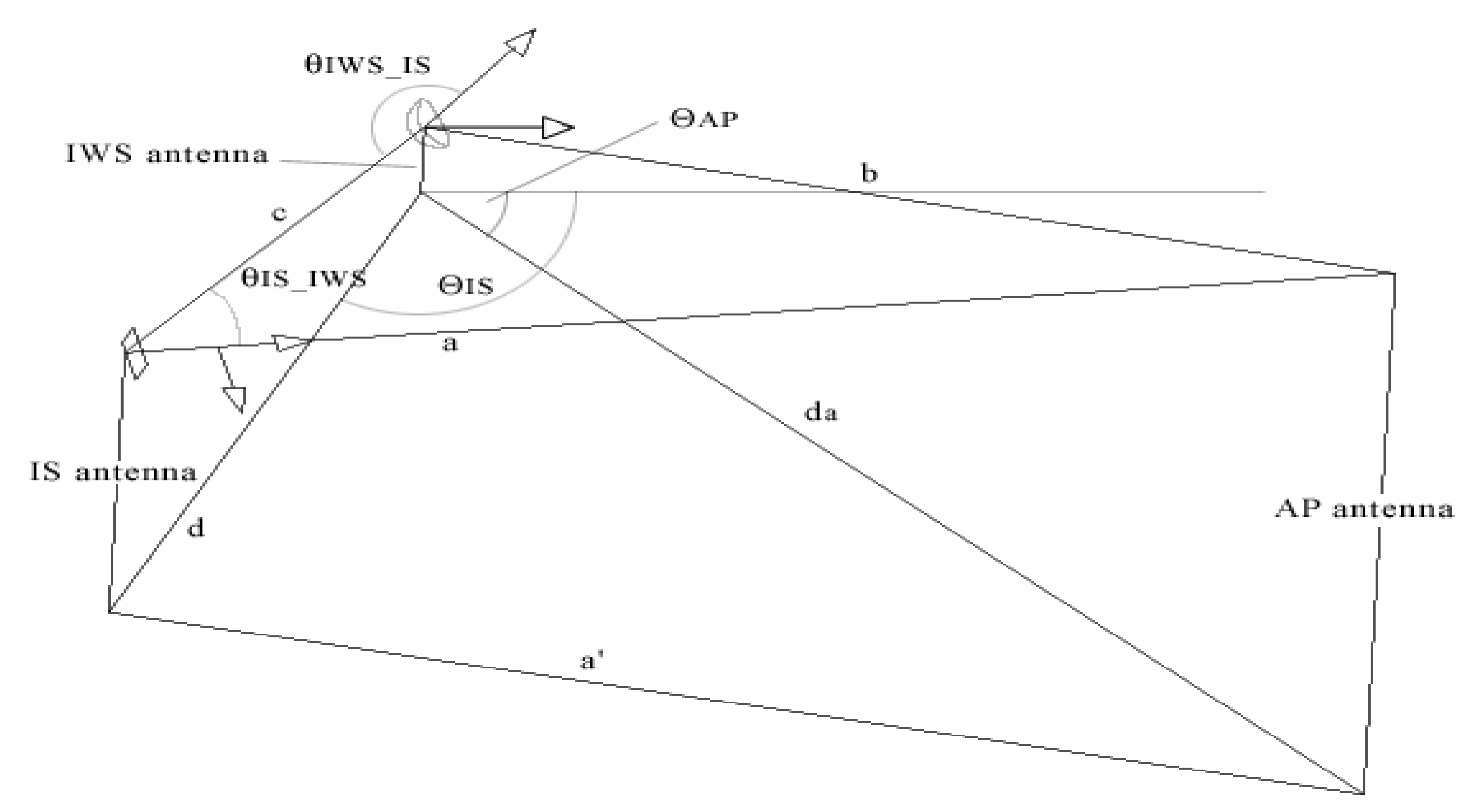



Fig 3.1.1 Parameters used for algorithm for computing the forbidden zon

The derivation of $q_{IS\_IWS}$ and $f_{IS\_IWS}$ will be done in detail, but all other $q$ functions can be derived in a similar manner as $q_{IS\_IWS}$, and all $f$ functions similarly to $f_{IS\_IWS}$.

Using the Pythagorian Theorem, [23] and Fig 3.1.1, the following relations hold:

$$
\begin{aligned}
a^2 &= a'^2 + (h_{AP\_antenna} - h_{IS\_antenna})^2 \\
b^2 &= (h_{AP\_antenna} - h_{IWS\_antenna})^2 + d_a^{\ 2} \\
c^2 &= (h_{IS\_antenna} - h_{IWS\_antenna})^2 + d^2
\end{aligned}
\tag{36}
$$

Referring to Fig 3.1.1 and using the Law of Cosines, [23], the following can be derived:

$$
\begin{aligned}
a'^2 &= d^2 + d_a^{\ 2} - 2dd_a \cos(\Theta_{IS} - \Theta_{AP}) \\
b^2 &= a^2 + c^2 - 2ac\cos(q_{IS\_IWS})
\end{aligned}
\tag{37}
$$

Expressing $q_{IS\_IWS}$ from Eqn. (37) leads to the following expression:

$$
q_{IS\_IWS} = \arccos\left(\frac{a^2 + c^2 - b^2}{2ac}\right) \tag{38}
$$

Finally, substituting Eqn. (36) and Eqn. (37) in Eqn. (38), the desired function is derived. Therefore, the final formula for $q_{IS\_IWS}$ is as follows:

$$
q_{IS\_IWS} = \arccos\left(\frac{A + 2d^2 - 2dd_a\cos(\Theta_{IS} - \Theta_{AP})}{B}\right) \tag{39}
$$

where the formulas for $A$ and $B$ are:

$$A = (h_{AP\_antenna} - h_{IS\_antenna})^2 + (h_{IS\_antenna} - h_{IWS\_antenna})^2 - (h_{AP\_antenna} - h_{IWS\_antenna})^2$$

$$B = 2ac = 2\sqrt{(h_{AP\_antenna} - h_{IS\_antenna})^2 + d_a{}^2 + d^2 - 2dd_a\cos(\Theta_{IS} - \Theta_{AP})} * \\ * \sqrt{(h_{IS\_antenna} - h_{IWS\_antenna})^2 + d^2} \tag{40}$$

Using a similar procedure as above, all the θ angles can be found by using the Law of Cosines. The procedure for finding the ϕ angles is a bit more complicated but involves simple vector algebra [24]. The procedure for deriving $f_{IS\_IWS}$ is based on finding the *x* and *y* value of the position of the IWS antenna in a coordinate, whose origin is in the center of the IS antenna. This is represented in the figure on the following page, Fig 3.1.2. Using Fig 3.1.2 and vector algebra, the following holds:

$$\vec{c} = \vec{d} + \vec{f} = |d|\vec{i}_d + |f|\vec{i}_f \tag{41}$$

where $i_d$ and $i_f$ are unit vectors in the direction of *d* and *f* respectively. For the magnitude of vector *f*,

$$|f| = h_{IS\_antenna} - h_{IWS\_antenna} \tag{42}$$

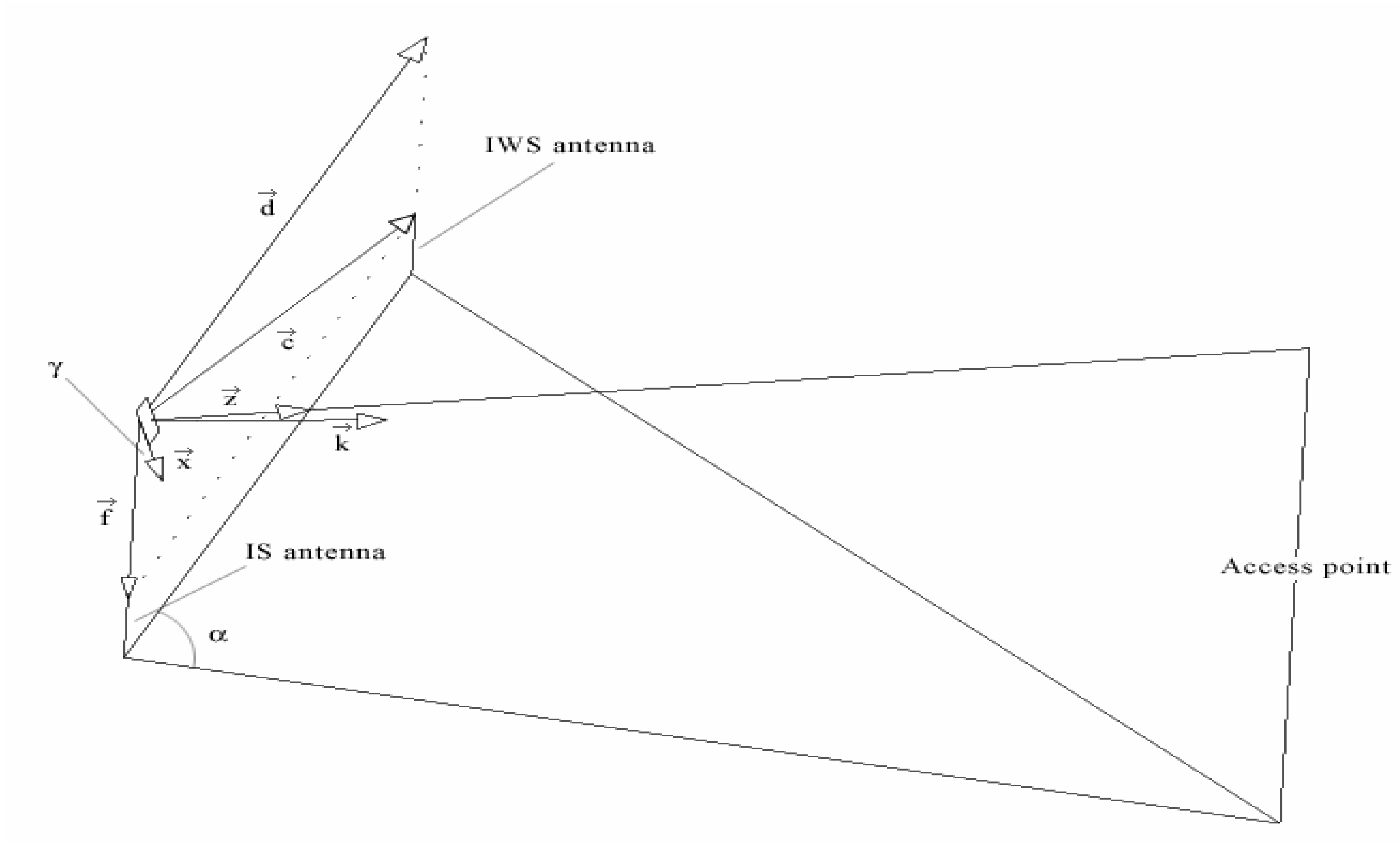



Fig 3.1.2 Parameters used to find the azimuth angle of the IS antenna towards the IWS antenna. The procedure is based on finding the x and y coordinates of the IWS antenna in a coordinate system with origin in the US antenna.

On the other hand, by adding the two vectors, the vector $i_d$ can be represented as a sum of two vectors. Mathematically that is represented as

$$\vec{i}_d = \cos a \vec{i}_k + \sin a \vec{i}_y \tag{43}$$

$\alpha$ can be expressed using the Law of Cosines as

$$a = \arccos\left( \frac{d - d_a \cos(\Theta_{IS} - \Theta_{AP})}{\sqrt{d^2 + d_a{}^2 - 2dd_a \cos(\Theta_{IS} - \Theta_{AP})}} \right) \tag{44}$$

Using the same procedure for vector $i_f$, the following formula can be derived.

$$\vec{i}_f = \cos g \vec{i}_x - \sin g \vec{i}_z$$

$$g = \arctan\left( \frac{h_{AP\_antenna} - h_{IS\_antenna}}{\sqrt{d^2 + d_a{}^2 - 2dd_a \cos(\Theta_{IS} - \Theta_{AP})}} \right)$$

$$\vec{i}_k = \cos g \vec{i}_z + \sin g \vec{i}_x \tag{45}$$

Finally, substituting Eqn. (42), Eqn. (43), Eqn. (44) and Eqn. (45) for the variables in Eqn. (41), the vector $c$ can be expressed as:

$$\begin{aligned} \vec{c} &= d \cos a \vec{i}_k + d \sin a \vec{i}_y + (h_{IS\_antenna} - h_{IWS\_antenna})(\cos g \vec{i}_x - \sin g \vec{i}_z) = \\ &= d \cos a (\cos g \vec{i}_z + \sin g \vec{i}_x) + d \sin a \vec{i}_y + (h_{IS\_antenna} - h_{IWS\_antenna})(\cos g \vec{i}_x - \sin g \vec{i}_z) \end{aligned} \tag{46}$$

Since the vector $c$ is expressed through its basic components, $x$, $y$ and $z$, the $x$, $y$ and $z$ values can be found with some rearrangement in Eqn. (46). From Eqn. (46) the values of $x$ and $y$ are as follows.

$$
\begin{aligned}
x &= d \cos a \sin g + (h_{IS\_antenna} - h_{IWS\_antenna}) \cos g \\
y &= d \sin a
\end{aligned}
\tag{47}
$$

Since the $x$ and $y$ coordinates are now known, the relationship for $f$ is determined by using the formulas for polar coordinates:

$$
f_{IS\_IWS} = \arctan(\frac{y}{x}) \tag{48}
$$

A similar derivation can be made for $q_{IWS\_IS}$. However, the derivation process is not presented in the report. The derived formula is:

$$
q_{IWS\_IS} = \arccos\left( \frac{(A_1 - B_1)\cos(ElevAngle_{IWS})}{2d\sqrt{(h_{IS\_antenna} - h_{IWS\_antenna})^2 + d^2}} \right) \tag{49}
$$

where $A_1$ and $B_1$ are defined as follows:

$$
\begin{aligned}
A_1 &= (h_{IS\_antenna} - h_{IWS\_antenna})^2 + d^2\left(1 + \frac{1}{\cos^2(ElevAngle_{IWS})}\right) \\
B_1 &= (h_{IWS\_antenna} + d\tan(ElevAngle_{IWS}) - h_{IS\_antenna})^2 + 2d^2(1 - \cos\Theta_{IS})
\end{aligned}
\tag{50}
$$

$ElevAngle_{IWS}$ is the elevation angle of the IWS antenna. Since it is assumed that IWS is a satellite system, the value of the $ElevAngle_{IWS}$ is set to 60°.

It is interesting to point out that, although for this particular research only $q_{IWS\_IS}$, $q_{IS\_IWS}$ and $f_{IS\_IWS}$ are relevant for the interference calculations, in some cases (when another model is used or other antennas are used), other angles may be of interest, too. For the purpose of future work, Appendix A contains the derived formulas for the other angles.

## 3.2 Algorithm for Computing the Forbidden Zone Around the IWS Antenna

In chapter 3.1 Eqn. (34) shows the power that the IWS antenna will receive as a result of the radiation from the IS antenna. Also, in the same chapter, the gain functions were expressed as functions of the ground distance, *d*, between the IWS and IS antennas. If all the parameters other than *d* are kept constant, the above relationship will have the following form.

$$P_{received}(d) = \frac{P_{IS\_antenna}\, g_{IS\_IWS}(d)\, g_{IWS\_IS}(d)\, g_m(d)}{\left(\frac{4p}{l}\right)^2 ((h_{IS\_antenna} - h_{IWS\_antenna})^2 + d^2)} \tag{51}$$

Keeping all the parameters constant means that the location of the AP antenna is predetermined. That location is specified by $Q_{AP}$ and $d_{a..}$ Also, all the antenna heights are kept constant. $Q_{IS}$ is also constant, which means that the direction of the IS antenna is also specified. The idea is to find the minimum distance at which the IS antenna will not cause interference to the IWS antenna in that particular direction.

In Section 2.1, Eqn. (11) specifies the power level that will cause interference to the IWS antenna. Let $P_{border}$ be the power level that will cause harmful interference to the receiver. According to Eqn. (11) that level will be determined by the following formula:

$$P_{border} = N(10^{M/10} - 1) \tag{52}$$

The power received by the IWS antenna has to be under the border level. This means that the new user should be positioned in a location such that:

$$P_{received}(d) < P_{border} \tag{53}$$

The question is: what is the shortest distance, $d_{min}$, from the IWS antenna that will guarantee no interference from that point on?

Finding the $d_{min}$ may seem like an easy problem, but, due to the complexity of the gain functions, it can cause some difficulties. The following explains the algorithm used for finding the minimum distance. The product of the gain functions and the multi path factor is replaced with one function, *F(d)*:

$$F(d) = g_{IS\_IWS}(d) g_{IWS\_IS}(d) g_m(d) \tag{54}$$

Replacing Eqn. (54) in Eqn. (34) leads to the following equation:

$$P_{received}(d) = \frac{P_{IS\_antenna} F(d)}{\left(\frac{4p}{l}\right)^2 ((h_{IS\_antenna} - h_{IWS\_antenna})^2 + d^2)} \tag{55}$$

In order to proceed with the algorithm, another function, *G(d)*, is defined:

$$G(d) = P_{received}(d) - P_{border} \tag{56}$$

In further analysis *G(d)* will be referred to as interference function. Substituting Eqn. (52) and Eqn. (55) in Eqn. (56) leads to the following equation for *G(d)*:

$$G(d) = \frac{P_{IS\_antenna} F(d)}{\left(\frac{4p}{l}\right)^2 ((h_{IS\_antenna} - h_{IWS\_antenna})^2 + d^2)} - N(10^{\frac{M}{10}} - 1) \tag{57}$$

In order not to cause interference, *G(d)*<0. If the zeros of *G(d)* are found, then all of the interference area in that particular direction, $Q_{IS}$, can be determined. This is represented on the following figure, Fig 3.2.1.

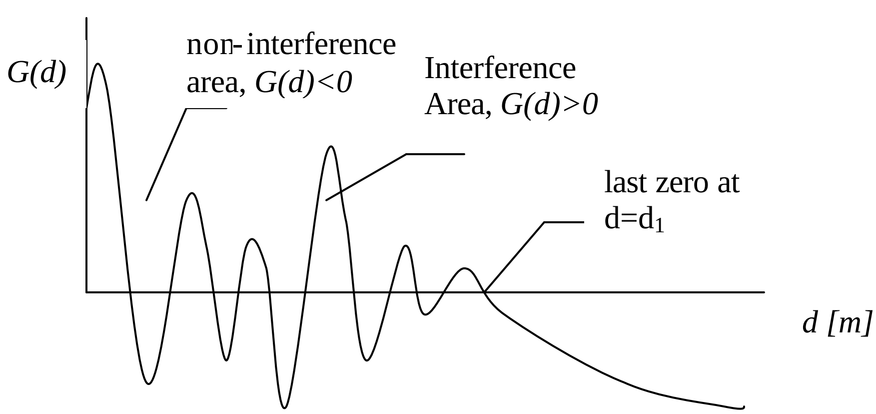



Fig 3.2.1 Interference function *G(d)*. The areas above zero is where harmful interference occurs. The areas below zero are non-interference areas.

If the last zero of *G(d)* is found, there is a guarantee that from that particular distance forward, the user will not cause interference to the receiver. The problem then, is to find the last zero in *G(d).* If *F(d)* is some simple function, finding all the zeros of *G(d)* is straightforward. However, in most cases the antenna patterns are represented by complex functions and finding the zeros is not so straightforward. Then, the existing computer algorithms can be used for finding a zero of a single-variable function.

One such algorithm was originated by T. Dekker, [25]. A computer version of the algorithm is given in [26] and [27]. There are two variants of this algorithm. One is finding a zero in a given interval, and the other is finding a zero close to a single specified value. Both variants can be useful in a given situation.

Using the second variant, if a value for $d_2$ is found such that $d_2>d_1$, then, using $d_2$ as a starting guess, the use of the algorithm should be able to locate the last zero. It needs to be pointed out that it is possible for the algorithm to determine some zero other than the last one. However, with proper parameters in the algorithm, it is possible to eliminate the occurrence of such cases so that it does not affect the final result. The problem now is to find a value $d_2$, such that $d_2>d_1$, keeping in mind that $d_1$ is unknown. This can be done by finding the maximum value of *F(d)*:

$$\max(F(d)) = \max(g_{IS\_IWS}(d)g_{IWS\_IS}(d)g_m(d)) = F_{\max} \qquad (58)$$

Therefore, if max($F(d)$) can be found, then a new function $Pmax_{received}(d)$ can be formed:

$$P\max_{received}(d) = \frac{P_{IS\_antenna} F\max}{\left(\frac{4\pi}{\lambda}\right)^2 ((h_{IS\_antenna} - h_{IWS\_antenna})^2 + d^2)} \tag{59}$$

$Pmax_{recived}(d)$ function is represented in the following figure, Fig 3.2.2:

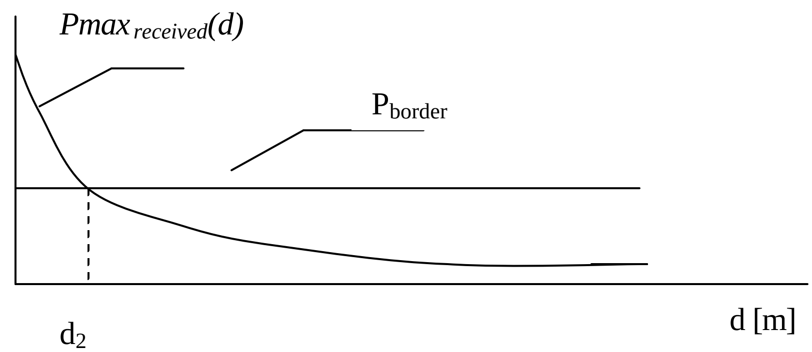



Fig 3.2.2 $Pmax(d)$ is the maximum possible received power by the IWS antenna. At distance $d_2$ the maximum received power becomes lower than the border level. For $d>d_2$ there is no interference.

Notice that $Pmax_{recived}(d)$ and $P_{border}$ intersect for $d=d_2$. The following relationships give the value of $d_2$:

$$P\max_{received}(d) = P_{border}$$

$$d_2 = \sqrt{\frac{P_u F_{\max}}{(\frac{4\pi}{\lambda})^2 P_{border}} - (h_{IS\_antenna} - h_{IWS\_antenna})^2} \tag{60}$$

Finding $d_2$ in this manner guarantees that the new value will truly be greater than $d_1$. This can be seen from the above figure. $Pmax_{received}(d)$ represents the maximum power that the receiver could possibly receive. It can be seen that for $d \geq d_2$, the maximum power will definitely be under the border level. Since $d_1$ was defined (Fig 3.2.1) as the last point where the $P_{received}(d_1)=P_{border}$, or $G(d)=0$, this guarantees that $d_2 \geq d_1$. Once $d_2$ has been found, the algorithm for finding a zero close to $d_2$ can be utilized.

The only other issue left is how to find the $F_{max}$. Finding $F_{max}$ is straightforward. First of all, the $g_m$ part of $F(d)$ only depends on $d$ and it is periodic. The maximum value of $g_m$ is really easy to find by examination of the $g_m$ function. Finding the maximum of the other product, $g_{IS\_IWS}(d) \cdot g_{IWS\_IS}(d)$, is a bit more complex. However, given that the gain of the antenna in most cases increases by increasing the distance from the antenna, it can be concluded that the maximum value of the product will be toward the end of the interval [0, $d_{end}$]. By using an algorithm for calculating the maximum in a smaller interval [$d_{end}$-$d_k$ $d_{end}$], the maximum can be found:

$$F\max = \max(g_m(d)) \max(g_{IWS\_IS}(d) g_{IS\_IWS}(d)) \tag{61}$$

This can be useful when the area that has been examined has no boundaries. If the area that has been analyzed is not too small, then the value of $d_{end}$ can be set to some large value. However, if the area of interest is only one cell or a sector within a cell, the whole procedure can even be simplified. Instead of finding $F_{max}$, the border of the cell in a certain direction, $d_{max}$, can be found. Once $d_{max}$ is found, a test for interference is conducted. If $P_{received}(d_{max})^{3}P_{border}$, then the whole interval [0 $d_{max}$] is considered a forbidden zone. However, if $P_r(d_{max})<P_{border}$, then the last zero of the interval [0 $d_{max}$] needs to be found, and the distance corresponding to the last zero would be the end of the forbidden zone. This is represented in the following figure, Fig 3.2.3:

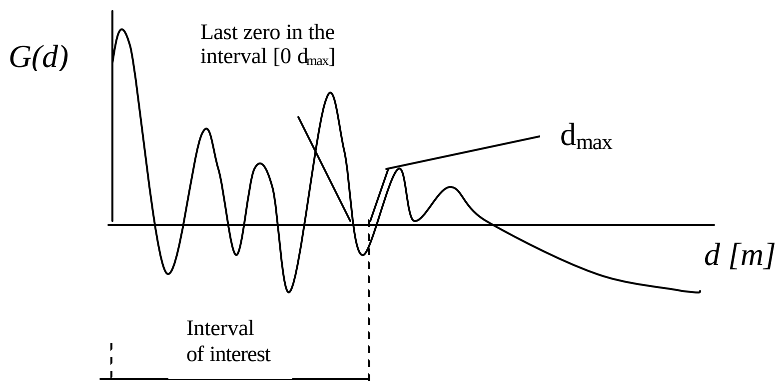



Fig 3.2.3 If the border of the sector is greater than d1, there is no need to find $d_1$. Instead, the first variant of Dekker's algorithm is used.

It is obvious that in either of the two cases, the algorithm is used to find the end of the forbidden area only for a certain direction. In order to form a forbidden zone around the receiver, the procedure is repeated for all directions, from $Q_{IS}$=0 to $Q_{IS}$=360°.

The above algorithm theoretically determines the shortest distance that guarantees no interference in a certain direction. If the algorithm is repeated for 360 degrees, a forbidden area around the receiver can be computed in a relatively fast and precise manner. This could be helpful when determining the cell and access point position in order to have a minimum forbidden area. This algorithm is used for all the measurements presented in Chapter 4. The only modification is in Section 4.5, where the power level of the IS is also a function of *d*. But other than the formula for the $P_{IS\_antenna}=P_{Is\_antenna}(d)$, the algorithm does not change.

# CHAPTER 4

# 4. COMPUTER CALCULATED RESULTS FOR MINIMIZING THE FORBIDDEN ZONE

## 4.1 Forbidden Zone and Forbidden Area Ratio

Section 3.2 explains the algorithm for determining the forbidden area around the IWS antenna. As presented in Fig 3.2.1, the interference function, generally, has a complex form. It is possible that the interference function *G(d)* can cross the *x*-axis in several places. As explained in the previous chapter, this means that in a certain direction, $Q_{IS}$, it is possible to have areas with interference and areas without interference. Depending on the cell size, the last zero (for $d=d_1$) may or may not be in the sector of interest. If $d_1$ falls within the sector borders, then $d_1$ will be considered the minimum distance at which an IS antenna can be positioned. However, since the whole area is limited by the sector size, it may happen that $d_1$ is farther away than the sector border. In that case, as explained on Fig 3.2.2, the distance of interest is the last zero of the interference function within the sector. As explained in the previous chapter, the algorithm from Section 3.2 is used to find the last zero of *G(d)*. This step is repeated for every direction from $Q_{IS}=0°$ to $Q_{IS}=360°$ around the IWS antenna, with increments of 1°, and therefore a forbidden zone around the IWS antenna is formed. The area of the zone is calculated and compared with the total area of the sector, thus calculating the percentage of forbidden zone of the total area. This ratio is called Forbidden Area Ratio (FAR).

$$FAR\ [\%] = \frac{area\ \ of\ \ the\ \ forbidden\ \ zone}{area\ \ of\ \ the\ \ sector} 100 \tag{62}$$

The goal of this report is to find ways to minimize the FAR by adjusting some of the parameters. The results are presented in the following sections.

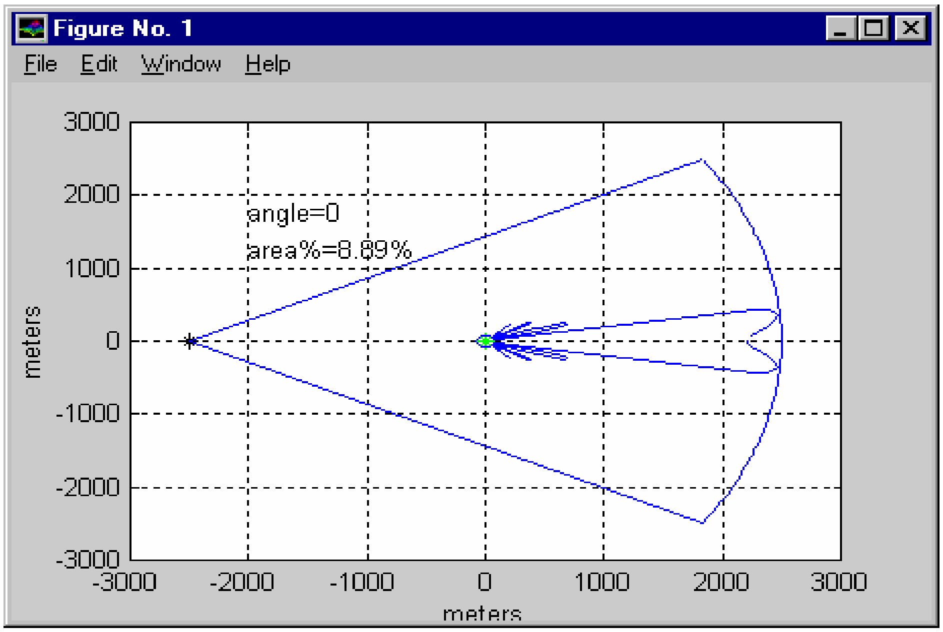
## 4.2 Adjusting the Azimuthal Pointing of the AP Antenna

The results presented in this section are not significant in terms of the improvement of the forbidden area ratio. However, they are important for two other reasons. One is the visualization of the forbidden zone and the other is to show that the forbidden zone does not depend on the azimuth angle of the AP antenna. As presented in Fig 4.2.1, 4.2.2, and 4.2.3, it is possible to see the effect of the azimuth angle adjustment. If the forbidden zone is completely inside the sector (Fig 4.2.1 and 4.2.2), the adjustment in the azimuth angle does not play a role. This should be expected since the formula for the interference function *G(d)* does not involve the azimuth angle of the AP antenna in any of the parameters. However, if we keep rotating the AP antenna as the forbidden area starts reaching the edge of the cell, the coverage area becomes larger due to the fact that part of the forbidden zone goes to the other sector. The part of the forbidden zone that goes to the other sector is no longer a forbidden zone, since the assumption is that the frequency used by the users in other sectors can not cause interference to the sector of interest. This is represented in Fig 4.2.3. As the forbidden zone starts reaching the sector border, the forbidden zone becomes smaller; therefore, the percentage of the forbidden zone relative to the area of the whole sector becomes smaller. This is represented in Fig 4.2.4. In this particular case the FAR is constant up to rotating the azimuth angle to 24° (for a 60° sector), and then it starts to decrease. As long as the forbidden zone is completely in the sector, it remains the same in size and shape. The moment the IWS antenna is located close to the border of the sector, some parts of the forbidden zone fall under a different sector, and, therefore, FAR decreases. As can be seen in Fig 4.2.4, once FAR starts to decrease, the decrease is linear.

The improvement of the area coverage, as presented in Fig 4.2.4, may be misleading. The improvement is achieved only because part of the forbidden zone falls into another sector. This could be justified only in certain situations. However, it brings up other issues as well. One can make an argument that if the AP antenna is rotated even further, then the whole forbidden zone will fall into the other sector and there will not be any interference. This would be similar to a case where the frequencies used in each sector are arranged according to some algorithm that will enable no interference in any of the sectors. As explained in Chapter 1, it is possible that such an algorithm may not always be possible. Therefore, the assumption in this report is that no matter what algorithm was used to assign the frequencies in the sectors, the provider always has a case where he needs to deal with the interference in one of the sectors. Also, a negative consequence of adjusting the azimuth angle of the AP antenna is the fact that by rotating the AP antenna in one direction, it is possible that the new sector may include another IWS antenna that was not in the sector prior to the rotation. In this report, however, only one IWS antenna per sector is being analyzed. For these reasons the improvement of the area coverage by adjusting the azimuth angle, even though it is an intuitive way of increasing the area coverage, may not have importance from a practical point of view. But the importance of the results presented in this section is that they give an idea of what the forbidden zone looks like. Although adjusting the azimuth angle of the access point antenna may not always be practical in terms of reducing the forbidden area, it could have importance when making sure that the AP antenna does not cause interference to the IS antenna. This is helpful due to the fact that the rotation of the AP antenna, for the most part, does not cause any change to the forbidden zone. The assumption that the AP antenna does not cause interference is discussed in Section 4.8. The conclusion that the forbidden zone does not change with the rotation of the AP antenna depends only on the physical structure of the system, and not on the propagation model, antenna pattern or any other RF parameter in the system. Therefore, the same principle can be implied for any system, regardless of the type of the antennas or propagation model used.

Despite the consequences explained above, it is that possible in some cases rotating the antenna would be a good solution for decreasing the forbidden zone. It is obvious that there are two choices when deciding at which borderline to position the IWS antenna, one being rotation to the right and the other one to the left. Which one is better depends on the shape of the forbidden zone. If the shape of the forbidden zone is symmetric, like in Fig 4.2.1, it does not make a difference which way the AP antenna is rotated in the azimuth plane. Either a left or a right rotation will give the same results. However, Fig 4.2.5 shows a case in which the forbidden zone is not symmetric. Therefore, rotating the AP antenna to one or the other side gives different results. The adjustment of the azimuth angle should be done once the location of the AP antenna is selected.

*Distance form the IWS antenna in the y- direction*




*Distance form the IWS antenna in the x- direction*

Fig 4.2.1 Forbidden zone around the IWS antenna. The star located at (0,0) represents the IWS antenna. The IWS antenna is facing in the positive direction of the x-axis. Its elevation angle is 60°. The star located at (-2500,0) represents the AP antenna, facing directly towards the IWS antenna.

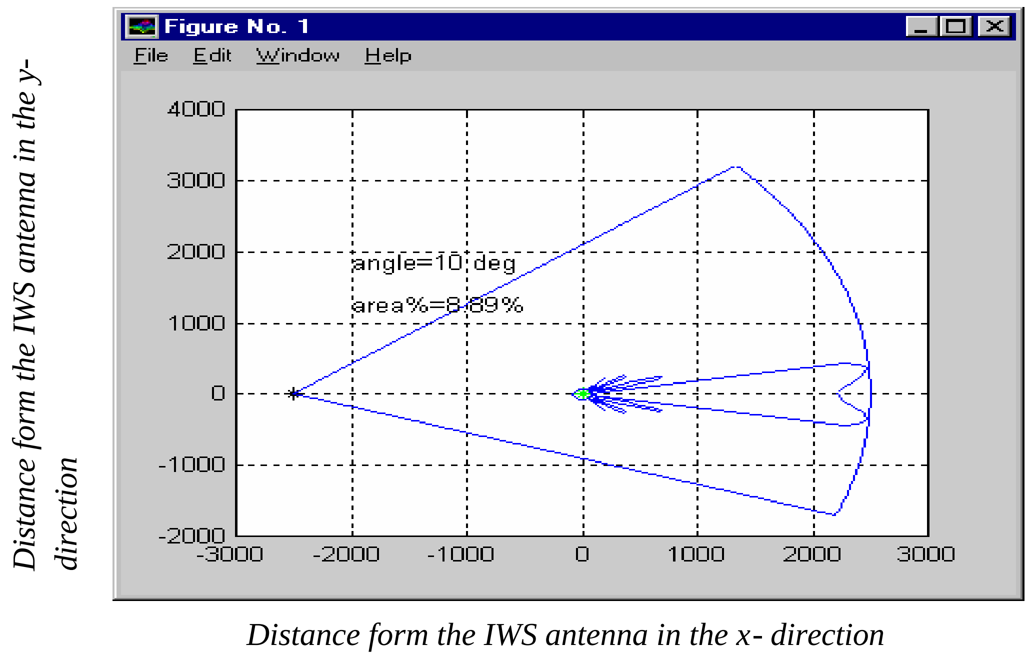
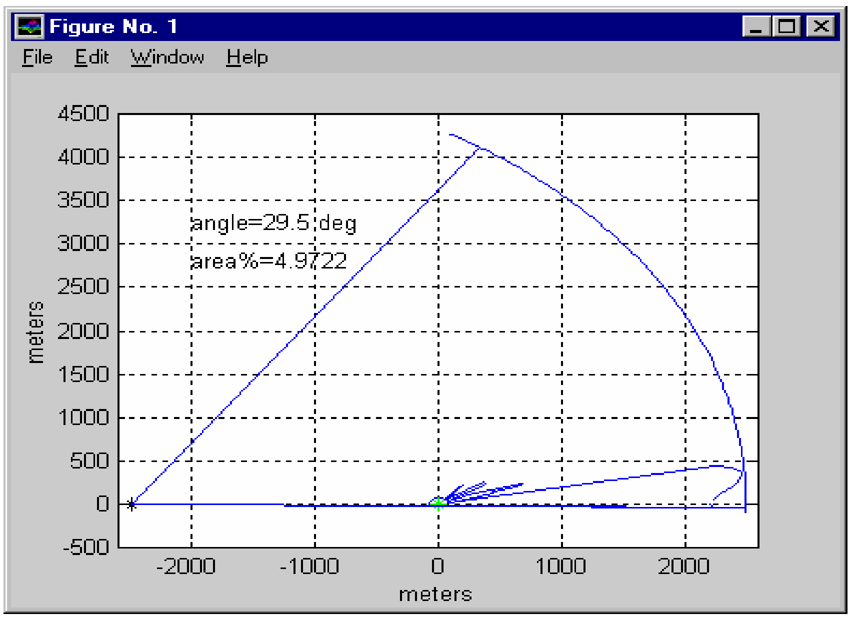



Fig 4.2.2 Forbidden zone around the IWS antenna. The star located at (0,0) represents the IWS antenna. The IWS antenna is facing in the positive direction of the x-axis. Its elevation angle is 60°. The star located at (-2500,0) represents the AP antenna, facing 10° off the direction to the IWS antenna.




*Distance form the IWS antenna in the y-direction*

*Distance form the IWS antenna in the x- direction*

Fig 4.2.3 Forbidden zone around the IWS antenna. The star located at (0,0) represents the IWS antenna. The IWS antenna is facing in the positive direction of the x-axis. Its elevation angle is 60°. The star located at (-2500,0) represents the AP antenna, facing 29.5° off the direction to the IWS antenna.

| $T_{azimuth\_AP}$ [°] | 24.5 | 25 | 25.5 | 26 | 26.5 | 27 | 27.5 | 28 | 28.5 | 29 | 29.5 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| FAR [%] | 8.89 | 8.85 | 8.67 | 8.30 | 7.86 | 7.45 | 7.02 | 6.47 | 5.98 | 5.41 | 4.97 |

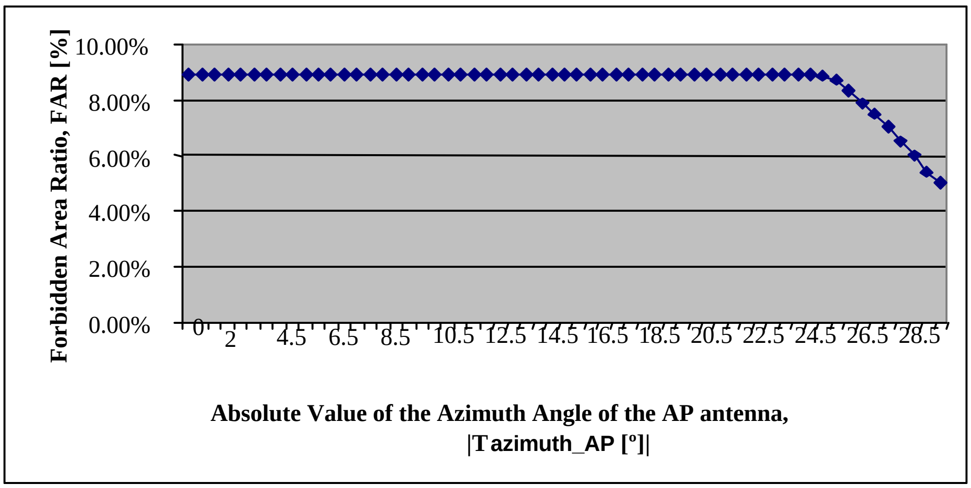
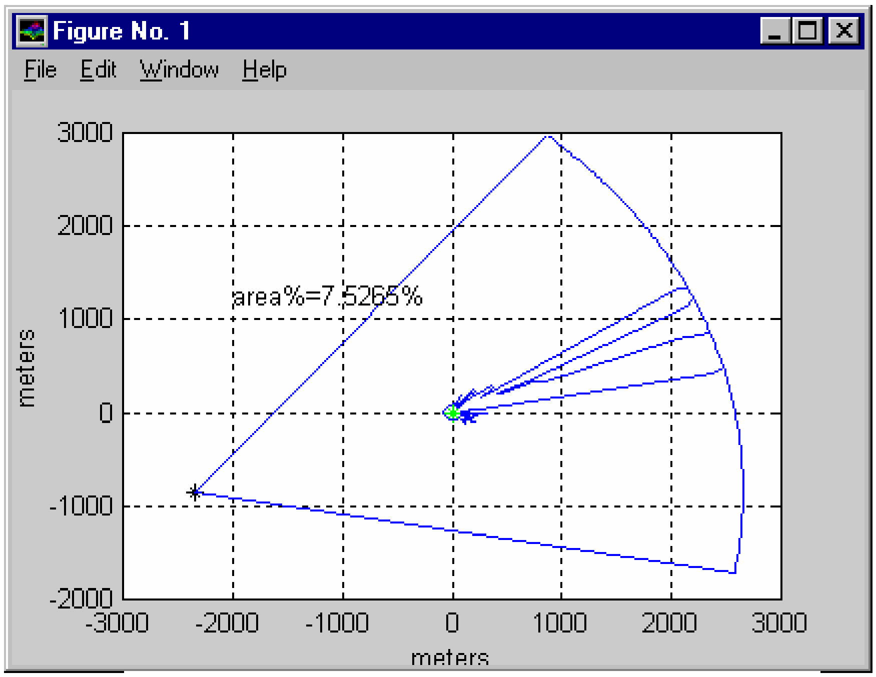



Fig 4.2.4 FAR dependence on the azimuth angle of the AP antenna. Except for the case when the forbidden zone starts reaching the end of the sector, FAR remains constant.




*Distance form the IWS antenna in the y-direction*

*Distance form the IWS antenna in the x- direction*

Fig 4.2.5 Non-symmetric forbidden zone. Rotating the AP antenna in the azimuth plane to the left or right will give different results for the FAR

## 4.3 Adjusting the Ground Direction of the AP Antenna Relative to the IWS Antenna

As will be shown in the following discussion, a proper selection of the location of the AP antenna relative to the IWS antenna can drastically improve the area coverage. In this analysis the assumptions are that the antenna heights remain the same and that the ground distance, $d_a$, between the IWS antenna and the AP antenna remains the same. In other words the AP antenna is rotated around the IWS antenna. The idea is to see what position of the AP antenna minimizes the forbidden zone. Another assumption made is that, in any of the positions, the AP antenna always looks straight at the receiver antenna in the azimuth plane. Also, it is assumed that the AP antenna does not cause interference to the IWS antenna.

The FAR is calculated every 5° as the AP antenna is being rotated around the IWS antenna, starting from 0° (IWS and the AP antenna look straight at each other), up till 180° (the AP antenna looks straight at the back of the IWS antenna in the azimuth plane). As shown earlier in Fig 3.1.1, the ground distance between the AP and IWS antennas, $d_a$, and the ground direction of the AP antenna relative to the IWS antenna, $\Theta_{AP}$, are basically polar coordinates of the AP antenna in a coordinate system with origin at the ground level of the IWS antenna. These two parameters define the position of the AP antenna relative to the IWS antenna. Based on that, the results are given in the following table:

The results are obtained for AP antenna height of $h_{AP\_antenna}$=30m.

| $\Theta_{AP}$[°] | Forbidden Area Ratio, FAR[%] | | | |
|---|---|---|---|---|
| | $d_a$=500m | $d_a$=1500m | $d_a$=2500m | $d_a$=3500m |
| | | | | |
| 0 | 1.4764 | 1.0592 | 0.9586 | 0.9388 |
| 5 | 1.3817 | 1.0169 | 0.9584 | 0.9105 |
| 10 | 1.2945 | 0.9426 | 0.8705 | 0.8323 |
| 15 | 1.4159 | 0.7952 | 0.7257 | 0.7125 |
| 20 | 1.3084 | 0.8673 | 0.7478 | 0.6794 |
| 25 | 1.5796 | 0.7846 | 0.7407 | 0.7305 |
| 30 | 1.675 | 1.2844 | 1.2474 | 1.0518 |
| 35 | 2.0535 | 1.3078 | 1.0441 | 0.9053 |
| 40 | 1.9525 | 1.2802 | 0.9355 | 0.8855 |
| 45 | 2.3532 | 1.6862 | 1.5092 | 1.0702 |
| 50 | 2.2254 | 1.6977 | 1.3931 | 0.964 |
| 55 | 1.9121 | 1.0446 | 0.9359 | 0.9039 |
| 60 | 4.1534 | 0.9063 | 0.8648 | 0.8504 |
| 65 | 7.2888 | 1.0157 | 0.9006 | 0.8716 |
| 70 | 9.3649 | 1.2144 | 1.0313 | 0.9823 |
| 75 | 11.0571 | 4.4757 | 2.9672 | 1.5921 |
| 80 | 11.7356 | 7.2079 | 5.6293 | 2.2789 |
| 85 | 12.4858 | 9.1788 | 6.9513 | 2.6288 |
| 90 | 12.873 | 10.0959 | 7.4202 | 2.8022 |
| 95 | 13.9397 | 9.7195 | 7.1633 | 2.8006 |
| 100 | 16.0463 | 7.9767 | 6.1677 | 2.4415 |
| 105 | 17.118 | 6.0474 | 4.3196 | 1.9693 |
| 110 | 17.9273 | 5.3166 | 2.9083 | 1.7164 |
| 115 | 19.4283 | 3.9066 | 3.6543 | 1.961 |
| 120 | 19.3666 | 7.271 | 4.7146 | 2.0012 |
| 125 | 17.0596 | 8.0896 | 5.9003 | 2.6232 |
| 130 | 17.7299 | 8.9303 | 4.5597 | 2.1333 |
| 135 | 19.7774 | 10.7142 | 6.3682 | 2.4345 |
| 140 | 21.0582 | 12.3001 | 7.4852 | 2.9566 |
| 145 | 21.1256 | 11.0473 | 6.5018 | 2.403 |
| 150 | 21.564 | 10.701 | 5.1502 | 2.4723 |
| 155 | 22.0573 | 12.864 | 7.8306 | 3.0063 |
| 160 | 24.5148 | 13.2927 | 7.5249 | 2.5808 |
| 165 | 26.6891 | 11.6154 | 6.5495 | 2.8083 |
| 170 | 27.2683 | 10.7439 | 6.2935 | 2.8324 |
| 175 | 28.4937 | 11.7623 | 6.8478 | 2.7072 |
| 180 | 29.8923 | 13.9867 | 8.8896 | 3.348 |

Table 4.3.1

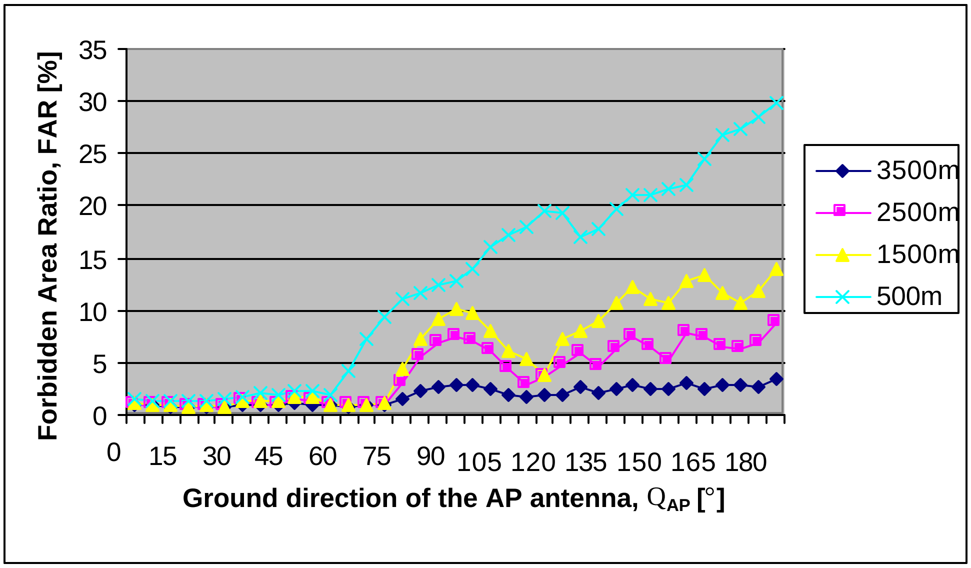



Fig 4.3.1 Dependence of FAR on the direction of the AP antenna. The measurements are taken for different distances between the AP and the IWS antennas

For this particular case the best area to position the AP antenna in reference to the IWS antenna is between $\Theta_{AP}$= 0° and $\Theta_{AP}$=30 °. At a distance of 2500 m, the improvement between the worst case (180°) and best case (15°) is around 8%. Fig 4.3.1 represents the dependence of FAR on the direction of the AP antenna relative to the IWS antenna.

An important point that needs to be made is that the variation in the area coverage because of the rotation of the AP antenna is only due to the antenna pattern of the IS antenna. Therefore, knowing the IS antenna pattern will be vital in determining the best place for the AP antenna. It is even easier if the antenna pattern only depends on elevation angle and not on azimuth angle, as is the case here, with an assumed square aperture antenna for the IS antenna.

Also, another thing that is noticeable, as the distance between the AP and IWS antennas increases, is that the basic shape of the curve remains the same. This is shown on the following figure, Fig 4.3.2:

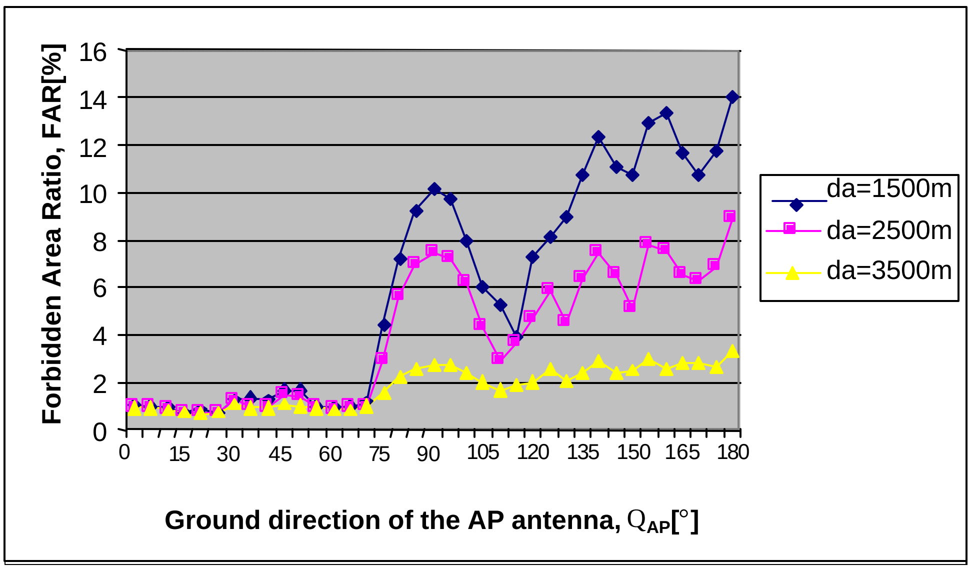



Fig 4.3.2 Similarity between the curves for $d_a$>1000m

This may be useful when determining the best position for the AP antenna. This shows that only by examining the IWS antenna pattern, the best direction for the AP antenna can be determined regardless of the distance between the two of them. Once the direction is determined, the distance can be adjusted accordingly.

## 4.4 Effects of the AP Antenna Height on the Coverage Area

The results of the effects of the antenna height are given in Table 4.4.1, Table 4.4.2, and Fig 4.4.1. Notice that the height of the AP antenna does improve the area coverage. However, the improvement is not very significant. The same conclusion holds for any direction of the AP antenna in reference to the IWS antenna (Table 4.4.1), as well as for any distance between the IWS and the AP antennas (Table 4.4.2).

The results in Table 4.3.1 are for $d_a$=2500m.

| | Forbidden Area Ratio , FAR [%] | | | | |
|---|---|---|---|---|---|
| $\Theta_{AP}$[°] | $h_{AP\_antenna}$ =30m | $h_{AP\_antenna}$ =40m | $h_{AP\_antenna}$ =50m | $h_{AP\_antenna}$ =60m | $h_{AP\_antenna}$ =70m |
| 0° | 0.9586% | 0.9564% | 0.9537% | 0.9505% | 0.9461% |
| 50° | 1.3931% | 1.3869% | 1.3714% | 1.3597% | 1.3436% |
| 90° | 7.4202% | 7.411% | 7.4035% | 7.3929% | 7.3794% |
| 140° | 7.4852% | 7.4801% | 7.4714% | 7.4639% | 7.4542% |
| 180° | 8.8896% | 8.8617% | 8.8224% | 8.7505% | 8.6922% |

Table 4.4.1

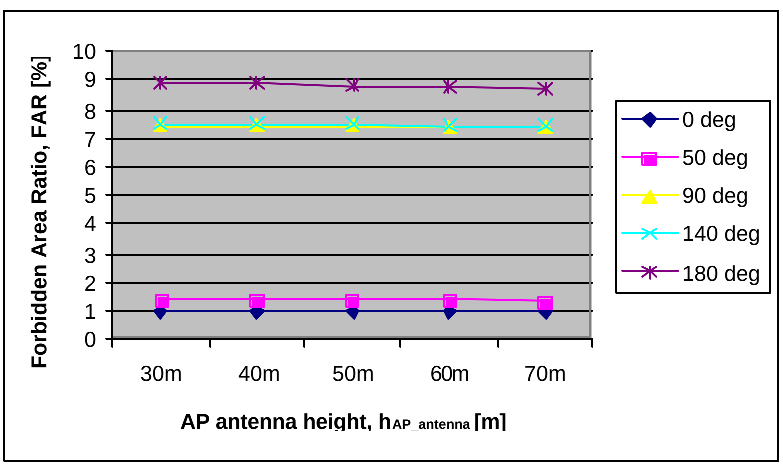



Fig 4.4.1 Effects of the AP antenna height on FAR. In this case the distance between the AP and the IWS antennas is kept constant, $d_a$=2500m.

In order to insure that the conclusion is valid for all distances between the IWS and AP antennas, the following table shows the improvement in the area coverage for distances other than 2500m:

The results in Table 4.3.2 are for $\Theta_{AP}$=180°.

| | Forbidden Area Ratio, FAR [%] | |
|---|---|---|
| $d_a$ | $h_{AP\_antenna}$ = 30m | $h_{AP\_antenna}$ = 70m |
| 500m | 29.8923% | 28.8895% |
| 1000m | 18.5038% | 17.9143% |
| 1500m | 13.9867% | 13.6926% |
| 2000m | 11.101% | 10.8422% |
| 2500m | 8.8896% | 8.6922% |
| 3000m | 6.2122% | 6.0421% |
| 3500m | 3.3482% | 3.3288% |
| 4000m | 1.6023% | 1.5893% |
| 4500m | 0.6801% | 0.6761% |

Table 4.4.2

The reason that the increase of the AP antenna height does not cause significant improvement in the coverage area is due to the fact that an increase of 10 to 40 meters of the access point antenna height does not cause a large change in the gain function of the IS antenna. For example, an increase of Δh meters in height of the AP antenna would only cause an increase of the angle between the IS and IWS antennas by:

$$Dq=atan((h+Dh)/d)-atan(h/d) \qquad (63)$$

For $d$=500m, $h_{AP\_antenna}$=30m and $Dh$=40m the difference is approximately 4.5°. In addition, the gain function of the IWS antenna does not change with the increase or decrease of the AP antenna height.

Although the AP antenna height does not have much influence over the area coverage, it does have an important role when it comes to making sure that the access point does not cause interference to the IWS antenna. Specifically, it is easy to show, Section 4.8, that by adjusting the AP antenna height, it is possible to select a desired distance between the AP antenna and the IWS antenna such that the AP antenna does not cause interference to the IWS antenna. Why adjusting the distance is important for enlarging the coverage area will be shown in the following section.

## 4.5 Effects of Increasing the Distance Between the AP and IWS Antenna on the Coverage Area

As presented in the following figures and tables, increasing the distance between the AP and the IWS antennas can enlarge the area coverage, especially if the ground direction angle, $\Theta_{AP}$, is relatively large. The results for three different angles are given in the Table 4.5.1 and Fig 4.5.1:

| | Forbidden Area Ratio, FAR [%] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| $\Theta_{AP}$ | $d_a$=500m | $d_a$=1000 | $d_a$=1500 | $d_a$=2000 | $d_a$=2500 | $d_a$=3000 | $d_a$=3500 | $d_a$=4000 | $d_a$=4500 |
| | | | | | | | | | |
| 0° | 1.4764 | 1.2018 | 1.0592 | 1.0002 | 0.9586 | 0.9489 | 0.9753 | 0.8951 | 0.4525 |
| 90° | 12.873 | 11.427 | 10.096 | 9.3852 | 7.4202 | 4.9982 | 2.8022 | 1.3428 | 0.5527 |
| 180° | 29.892 | 18.504 | 13.987 | 11.101 | 8.8896 | 6.2122 | 3.3482 | 1.6023 | 0.6801 |

Table 4.5.1

Notice that increasing the distance between the AP antenna and the IWS antenna improves the area coverage. However, the improvement is most significant for the case when the AP antenna looks at the back of the IWS antenna in the azimuth plane, $\Theta_{AP}$=180°. One conclusion that could be drawn is that, as the distance approaches 4500m, FAR becomes smaller and smaller and does not depend much on the ground direction angle, $\Theta_{AP}$, between the AP and the IWS antennas. To understand why this happens, Fig 4.5.2 and Fig 4.5.3 show the forbidden zone at 180° for $d_a$=500m and $d_a$=4500m.

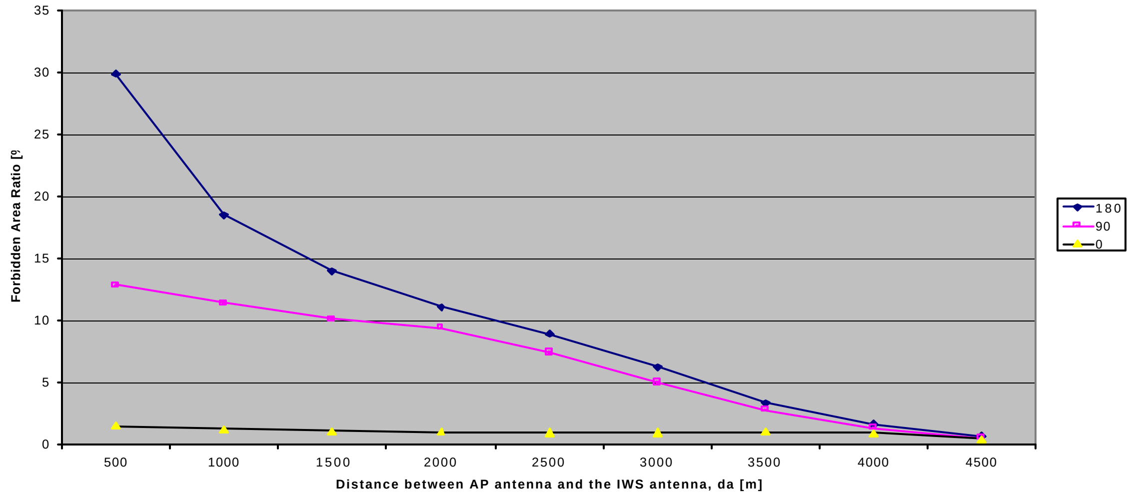
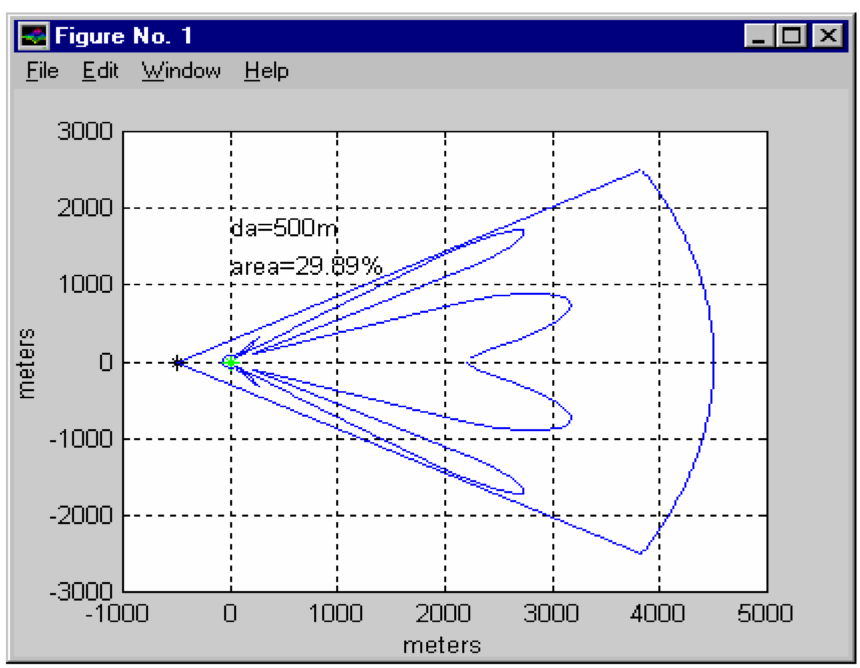



Fig 4.5.1 FAR dependence on the distance between the AP antenna and IWS antenna. Notice the best results for the $\Theta_{AP}$=180°.

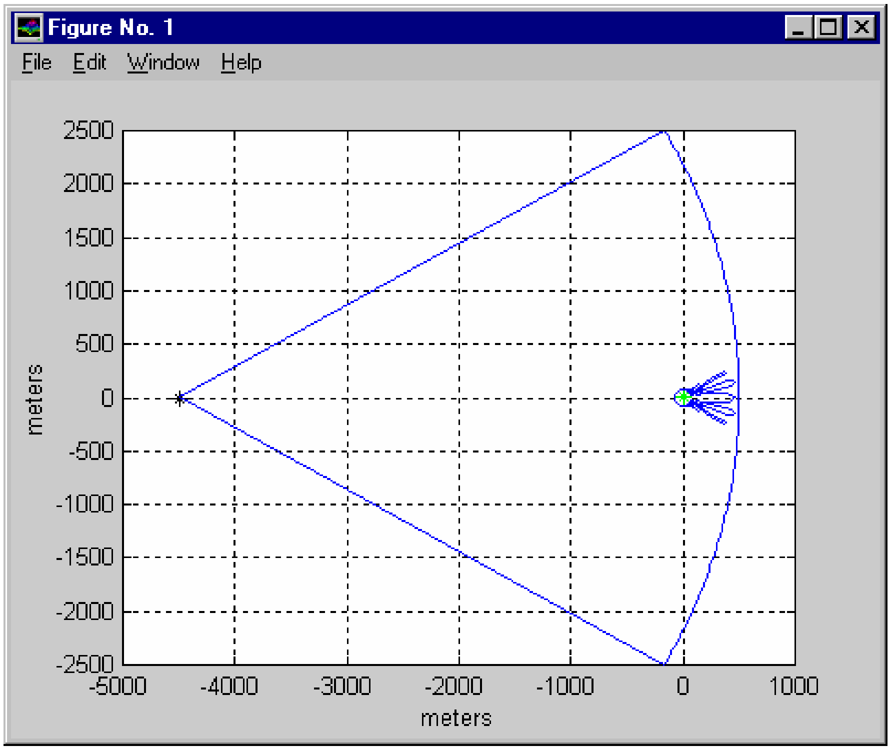
*Distance form the IWS antenna in the y-direction*




*Distance form the IWS antenna in the x- direction,*

Fig 4.5.2 Forbidden zone around the IWS antenna when $d_a$=500m. The star located at (0,0) represents the IWS antenna. The IWS antenna is facing in the positive direction of the x-axis. Its elevation angle is 60°. The star located at (-500,0) represents the AP antenna.

*Distance form the IWS antenna in the y-direction*




*Distance form the IWS antenna in the x- direction,*

Fig 4.5.3 Forbidden zone around the IWS antenna when the $d_a$=500m. The star located at (0,0) represents the IWS antenna. The IWS antenna is facing in the positive direction of the x-axis. Its elevation angle is 60°. The star located at (-4500,0) represents the AP antenna.

## 4.6 Effects on the Coverage Area by Using Power Control

In the analysis conducted so far, the power emitted by the IS antenna is constant no matter where in the sector the antenna is located. The power level of each IS antenna is calculated based on the fact that the user at the far end of the sector (5Km) has to have a power level high enough to ensure 10db SNR in the link. All other IS antennas in the sector have the same power level. Thus, it is guaranteed that all other IS antennas will also have at least 10db SNR, since they are closer than 5 km.

However, as the IS antenna gets closer to the access point antenna; there is no need for such a high power level. The 10db SNR can be achieved with a smaller power level. Since all the IS antennas are stationary, it would be easy to calculate the desired power level for a certain antenna. If it is possible to adjust the power level at the IS antenna site, the expectations are that the interference to the IWS antenna could be reduced, and, therefore, the coverage area increased. As will be shown by the results, this will be especially helpful if the distance between the access point and the IWS antenna is small. This analysis is presented in the following graphs and tables. The adjustment in the power level is done based on the two-ray model for a far field region and Eqn. (30) presented in Section 2.4. Using the two-ray model for a far field region will simplify the calculations and will not take away from the general conclusions.

The following tables and figures, Table 4.6.1, Fig 4.6.1, Fig 4.6.2 and Fig 4.6.3, show the improvement in the area coverage achieved by using power control for different directions between the access point and the receiver.

$h_{AP\_antenna}$=30m.

| | Forbidden Area Ratio, FAR [%] | | | | | |
|---|---|---|---|---|---|---|
| $d_a$ | $\Theta_{AP}$=0 ° | | $\Theta_{AP}$=90° | | $\Theta_{AP}$=180° | |
| | No power control | Power Control | No power control | Power control | No power control | Power control |
| 500m | 1.4764 | 0.1558 | 12.873 | 0.5723 | 29.8923 | 0.2463 |
| 1000m | 1.2018 | 0.1862 | 11.4266 | 0.8982 | 18.5038 | 0.2726 |
| 1500m | 1.0592 | 0.2921 | 10.0959 | 5.0156 | 13.9867 | 0.29 |
| 2000m | 1.0002 | 0.4765 | 9.3852 | 7.5007 | 11.101 | 2.6559 |
| 2500m | 0.9586 | 0.6253 | 7.4202 | 6.7275 | 8.8896 | 7.8407 |
| 3000m | 0.9489 | 0.7397 | 4.9982 | 4.957 | 6.2122 | 5.7417 |
| 3500m | 0.9753 | 0.8248 | 2.8022 | 2.7301 | 3.3482 | 3.0627 |
| 4000m | 0.8951 | 0.8673 | 1.3428 | 1.3204 | 1.6023 | 1.5558 |
| 4500m | 0.4525 | 0.4395 | 0.5527 | 0.5482 | 0.6801 | 0.681 |

Table 4.6.1

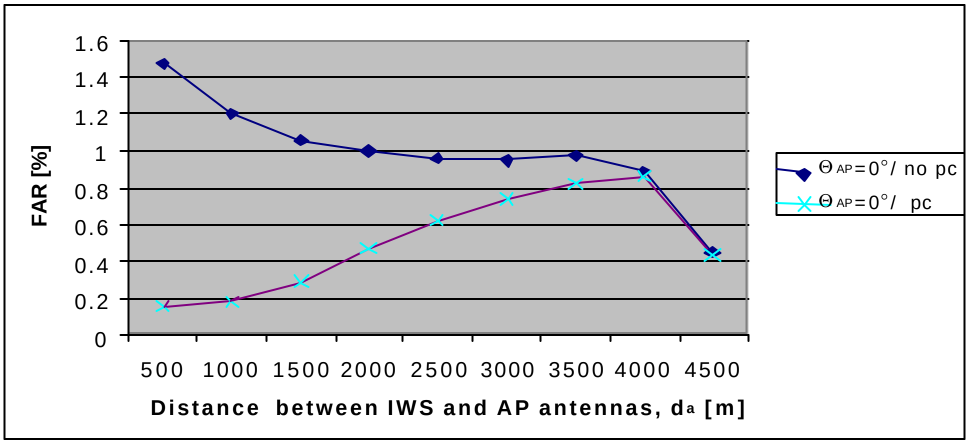



Fig 4.6.1 Comparison of the area coverage when no power control is used and when power control is used. This is for the case when $\Theta_{AP}$=0°.

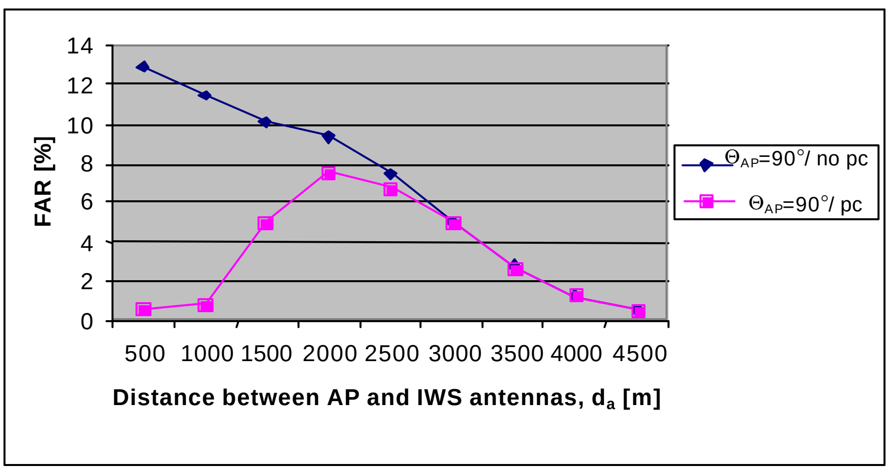



Fig 4.6.2 Comparison of the area coverage when no power control is used and when power control is used. This is for the case when $\Theta_{AP}$=90°.

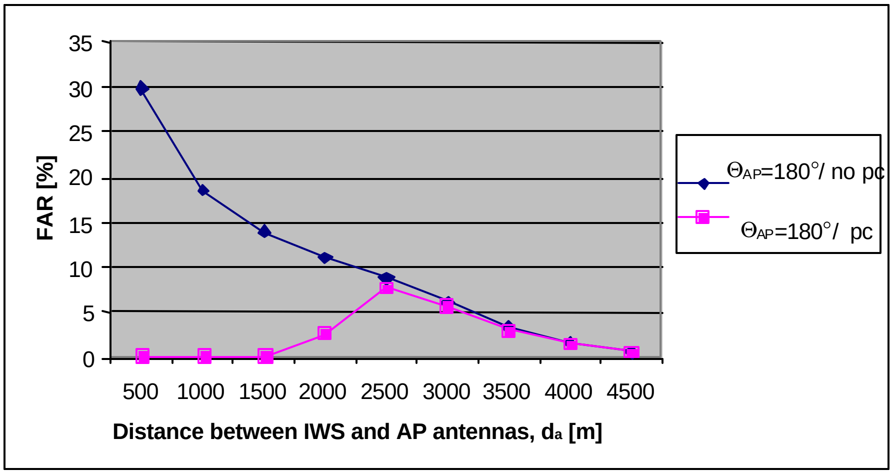



Fig 4.6.3 Comparison of the area coverage when no power control is used and when power control is used. This is for the case when $\Theta_{AP}$=180°.

There are several things that can be concluded from these figures. The first is that the improvement of the area coverage due to the power control becomes more and more significant as the distance between the access point and the IWS antenna decreases. At some point the curves that represent the power control case and no-power control case become the same, and no improvement is seen with the power control. Notice that the point at which the improvement is not significant any more is different for different AP antenna directions.

It is interesting to point out that in the case without power control, the worst area coverage was noticeable when the distance between the access point and the IWS antenna was shortest. However, in the power control case the worst case is no longer the shortest distance, but somewhere in the middle. This is important because one of the problems in cellular systems is finding an adequate place for the access point antenna in an urban area. So, if the provider is "stuck" in some location, it can be determined whether, in that particular case, a power control should be used or not.

A good thing about the power control is that its usefulness is most visible in the worst cases. In the following figure, Fig 4.6.4, the power control actually has the greatest improvement for $\Theta_{AP}$=180°, which, in Section 4.3, was the worst case. The improvement in this case is represented as:

$$\mathrm{Im}\,provement = \frac{forbidden\ \ zone\ \ without\ \ power\ \ control}{forbidden\ \ zone\ \ with\ \ power\ \ control} \qquad (64)$$

As shown in the figure, after $d_a$=2500 m, the improvement is not significant in any of the cases, and it is close to 1.

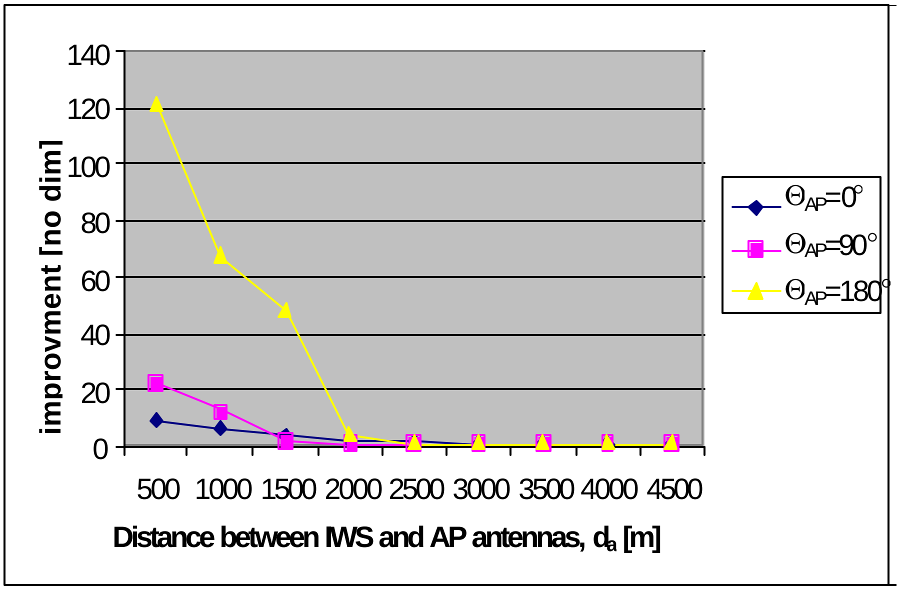



Fig 4.6.4 Comparison of the improvement in the area coverage for different $\Theta_{AP}$. The improvement is defined as a measure of how much the power control improved the area coverage.

In Section 4.4 it was shown that the increase of the access point antenna height did not affect the area coverage when a no-power control is used. Just to confirm that the same conclusion holds when the power control is used as well, the following, Table 4.6.5 and Fig 4.6.5, represent the improvement of the area coverage when the power control is used and the access point antenna is raised from 30m to 70m.

$\Theta_{AP}$=180° power control used.

| | Forbidden Area Ratio, FAR [%] | |
|---|---|---|
| $d_a$ | $h_{AP\_antenna}$=30m | $h_{AP\_antenna}$=70m |
| 500m | 0.2463 | 0.2055 |
| 1000m | 0.2726 | 0.2632 |
| 1500m | 0.29 | 0.2824 |
| 2000m | 2.6559 | 2.4845 |
| 2500m | 7.8407 | 6.6994 |
| 3000m | 5.7417 | 5.7325 |
| 3500m | 3.0627 | 2.9643 |
| 4000m | 1.5558 | 1.5126 |
| 4500m | 0.681 | 0.6776 |

Table 4.6.5

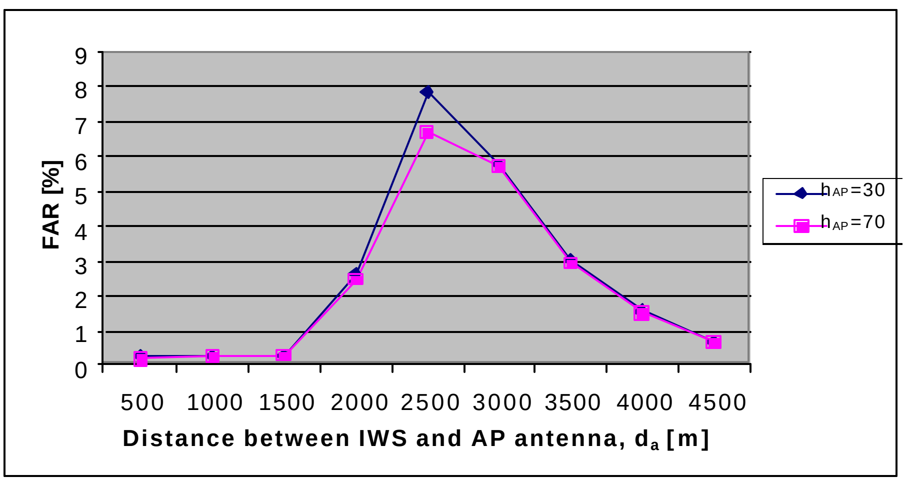



Fig 4.6.5 Effects of the AP antenna height on the coverage area when a power control is used. The measurements are taken for $h_{AP\_antenna}$=30m and $h_{AP\_antenna}$=70m

Just as in Section 4.4, it is obvious that the access point antenna height does not play a major role in the area coverage.

## 4.7 Effects of IS Antenna Gain Increase on the Coverage Area

The next thing to be analyzed is the trade-off between the power level of the IS antenna and the gain of the IS antenna. The question is: is it better to make the IS antenna more directional, and reduce the power level, or it is better to have a higher power level but less directional antenna? The adjustments in the gain and the transmit power is done based on Eqn. (30) in SEction 2.4. The Table 4.7.1 shows the results when the gain of the IS antenna has been increased for 2 dB for each measurement. The antenna pattern is adjusted by resizing the dimensions of the antenna. Thus, the antenna is made more directional. This causes a change in the whole pattern. As a result of improving the gain, the main lobe (null-to-null beam width) shrinks. Since the gain of the antenna is improved for 2dB, the transmit power at the IS antenna site is lowered for 2dbm. Thus, the EIRP remains the same and the performance of the AP-IS antennas' link is not being affected. Table 4.6.1 shows the results for a case where no-power control has been used:

| | Forbidden Area Ratio, FAR [%] | | | |
|---|---|---|---|---|
| $\Theta_{AP}$ | Gain=18dbi | Gain=20dbi | Gain=22dbi | Gain=24dbi |
| 0 | 0.9586 | 0.7736 | 0.6528 | 0.5099 |
| 5 | 0.9584 | 0.7707 | 0.6409 | 0.516 |
| 10 | 0.8705 | 0.7319 | 0.6127 | 0.4902 |
| 15 | 0.7257 | 0.6104 | 0.5129 | 0.4058 |
| 20 | 0.7478 | 0.4675 | 0.2657 | 0.24 |
| 25 | 0.7407 | 0.6385 | 0.5496 | 0.4752 |
| 30 | 1.2474 | 1.1953 | 0.9109 | 0.8456 |
| 35 | 1.0441 | 0.7213 | 0.5749 | 0.4538 |
| 40 | 0.9355 | 0.7107 | 0.515 | 0.4232 |
| 45 | 1.5092 | 1.275 | 1.146 | 1.0519 |
| 50 | 1.3931 | 0.9475 | 0.5709 | 0.4864 |
| 55 | 0.9359 | 0.7154 | 0.4956 | 0.3977 |
| 60 | 0.8648 | 0.7363 | 0.6368 | 0.5343 |
| 65 | 0.9006 | 0.7088 | 0.5783 | 0.4557 |
| 70 | 1.0313 | 0.7493 | 0.4848 | 0.353 |
| 75 | 2.9672 | 2.1023 | 1.2269 | 0.6015 |
| 80 | 5.6293 | 4.614 | 3.5644 | 2.7273 |
| 85 | 6.9513 | 5.7481 | 4.5913 | 3.8457 |
| 90 | 7.4202 | 6.1988 | 5.0216 | 4.0157 |
| 95 | 7.1633 | 6.1239 | 4.9546 | 3.9858 |
| 100 | 6.1677 | 5.0421 | 4.1516 | 3.4311 |
| 105 | 4.3196 | 3.1936 | 2.182 | 1.416 |
| 110 | 2.9083 | 1.575 | 0.7209 | 0.4732 |
| 115 | 3.6543 | 3.4799 | 2.8944 | 2.3943 |
| 120 | 4.7146 | 3.4957 | 3.04 | 2.7607 |
| 125 | 5.9003 | 4.5597 | 3.001 | 1.0862 |
| 130 | 4.5597 | 4.0924 | 3.8029 | 3.1846 |
| 135 | 6.3682 | 4.2307 | 3.7125 | 3.3762 |
| 140 | 7.4852 | 5.9813 | 4.7295 | 3.4497 |
| 145 | 6.5018 | 4.7255 | 4.1705 | 3.4318 |
| 150 | 5.1502 | 4.9142 | 4.314 | 3.5397 |
| 155 | 7.8306 | 5.5569 | 4.1024 | 2.3924 |
| 160 | 7.5249 | 4.9664 | 3.9784 | 3.4105 |
| 165 | 6.5495 | 5.7076 | 5.014 | 4.1415 |
| 170 | 6.2935 | 5.9287 | 5.0014 | 4.3798 |
| 175 | 6.8478 | 5.6348 | 4.4569 | 3.2123 |
| 180 | 8.8896 | 5.4306 | 3.1243 | 2.0852 |

Table 4.7.1.

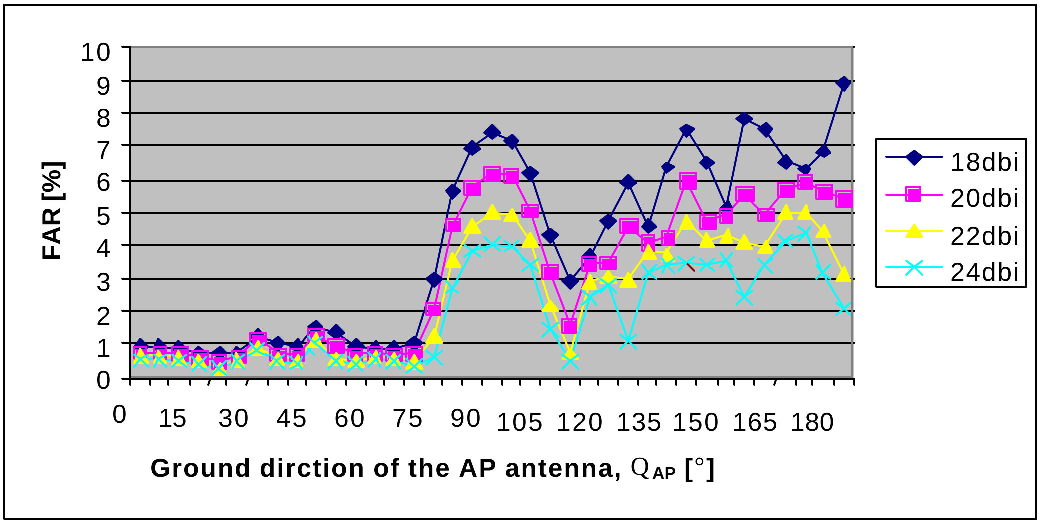



Fig 4.7.1 Dependence of the area coverage on the IS antenna gain. As the IS antenna becomes more directional, the forbidden zone decreases.

According to the results presented in Fig 4.7.1, the increase of the antenna gain reduces the forbidden area. This is true for all directions of the access point. However, the negative aspect of increasing the gain of the antenna is the increase of the antenna dimensions. This may not be practical for antenna installation at the user site.

Fig 4.7.2 shows the dependence of the area coverage on the IS antenna gain in three different directions:

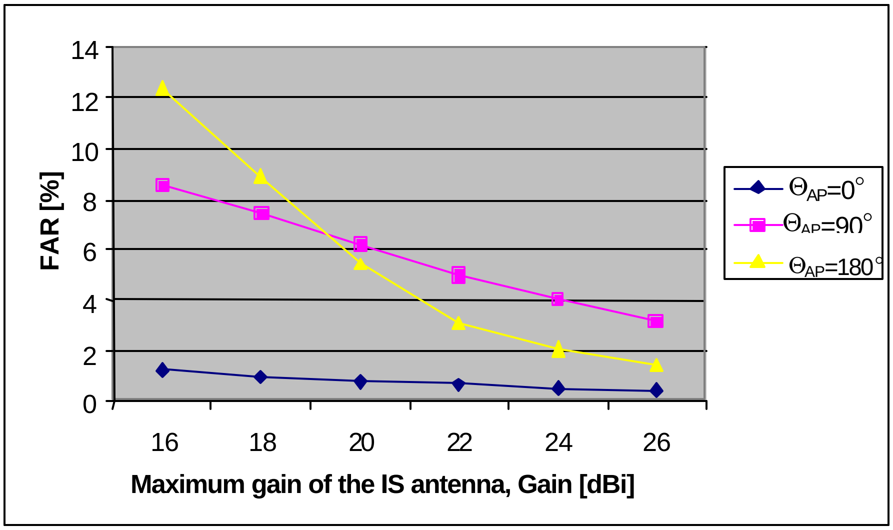



Fig 4.6.2 Trade-off between more directional antenna and power level. For this particular antenna the maximum gain is in the direction of $\theta_{IS\_AP}$=0°.

Notice, as in the power control case, that the gain-power trade-off is most useful for 180°. The slope of the curve for 180° is steepest; conversely, for 0° it is smallest.

The following tables (4.7.3, 4.7.4, 4.7.5) and figures (4.7.3, 4.7.4 and 4.7.5) show the area coverage improvement in terms of the distance between the access point and the receiver. It shows the improvement due to a higher gain antenna for three different angle position of the access point antenna.

$\Theta_{AP}$=0 °

| | Forbidden Area Ratio, FAR [%] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Gain | $d_a$=500 m | 1000 m | 1500m | 2000m | 2500m | 3000m | 3500m | 4000m | 4500m |
| 18 dBi | 1.4764 | 1.2018 | 1.0592 | 1.0002 | 0.9586 | 0.9489 | 0.9753 | 0.8951 | 0.4525 |
| 20 dBi | 1.1858 | 0.9402 | 0.8539 | 0.8087 | 0.7736 | 0.7693 | 0.766 | 0.7599 | 0.4 |
| 24 dBi | 0.7746 | 0.601 | 0.5593 | 0.514 | 0.5099 | 0.5054 | 0.4785 | 0.4776 | 0.2808 |

Table 4.7.3.

$\Theta_{AP}$=90 °

| | Forbidden Area Ratio, FAR [%] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Gain | $d_a$=500 m | 1000 m | 1500m | 2000m | 2500m | 3000m | 3500m | 4000m | 4500m |
| 18 dBi | 12.873 | 11.4266 | 10.0959 | 9.3852 | 7.4202 | 4.9982 | 2.8022 | 1.3428 | 0.5527 |
| 20 dBi | 12.0509 | 9.981 | 8.711 | 7.7844 | 6.1988 | 3.9856 | 2.3076 | 1.1333 | 0.5033 |
| 24 dBi | 9.8654 | 7.3777 | 5.9443 | 5.2708 | 4.0157 | 2.5872 | 1.5954 | 0.7957 | 0.3963 |

Table 4.7.4.

$\Theta_{AP}$=180 °

| | Forbidden Area Ratio, FAR [%] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Gain | $d_a$=500 m | 1000 m | 1500m | 2000m | 2500m | 3000m | 3500m | 4000m | 4500m |
| 18 dbi | 29.8923 | 18.5038 | 13.9867 | 11.101 | 8.8896 | 6.2122 | 3.3482 | 1.6023 | 0.6801 |
| 20 dbi | 20.9896 | 15.1001 | 9.8938 | 6.8924 | 5.4306 | 4.03 | 2.1689 | 1.2161 | 0.5703 |
| 24 dbi | 15.3471 | 5.7054 | 2.7979 | 2.1531 | 2.0852 | 1.4152 | 0.7397 | 0.455 | 0.3183 |

Table 4.7.5.

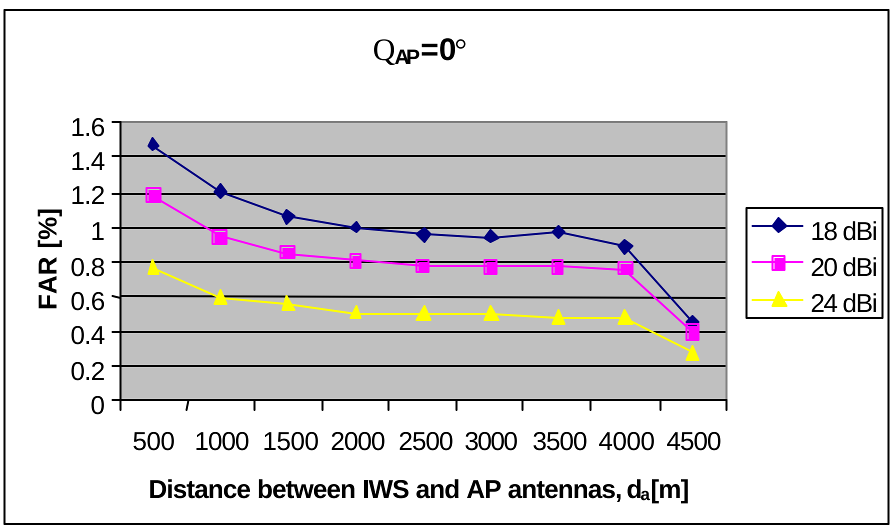



Fig 4.7.3 Improvement in the area coverage for different IS antenna gains. Higher gain improves the area coverage. The ground direction of the AP antenna is $\Theta_{AP}$=0°.

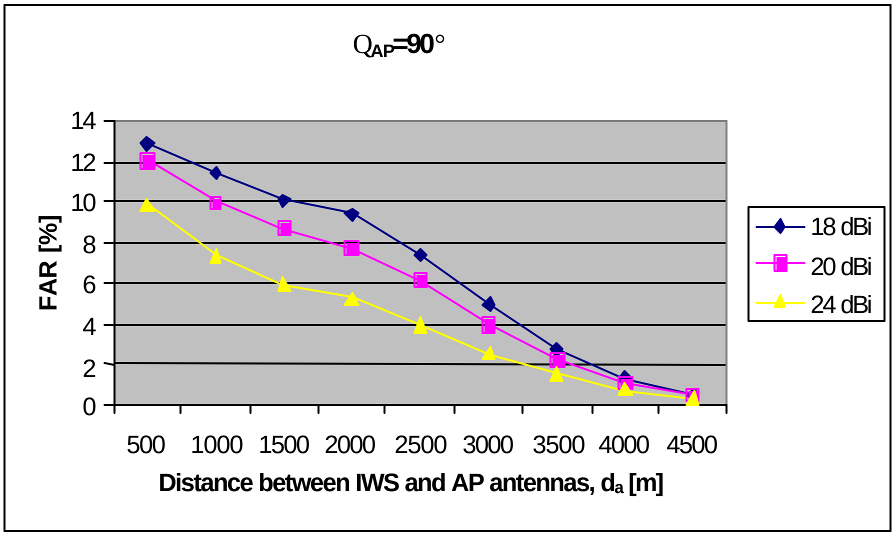



Fig 4.7.4 Improvement in the area coverage for different IS antenna gains. Higher gain improves the area coverage. The ground direction of the AP antenna is $\Theta_{AP}$=90°.

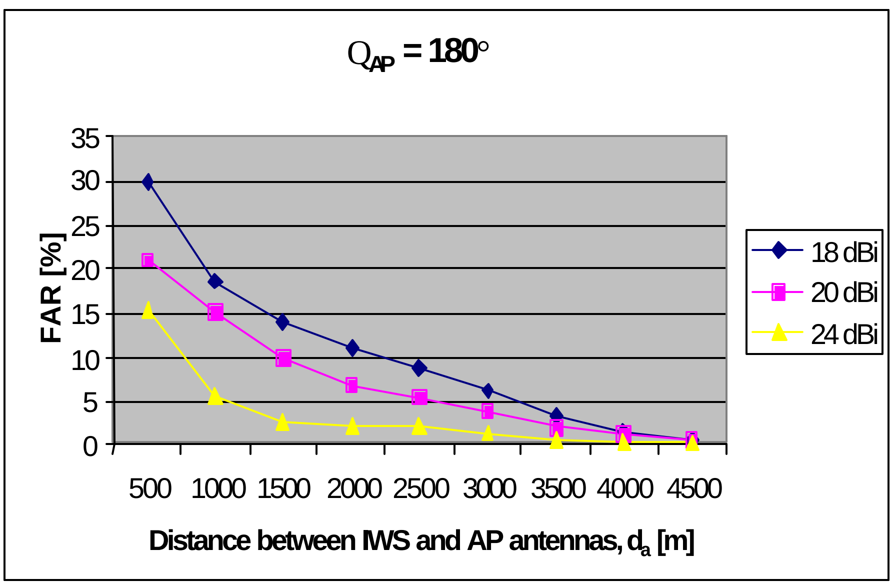



Fig 4.7.5 Improvement in the area coverage for different IS antenna gains. Higher gain improves the area coverage. The ground direction of the AP antenna is $\Theta_{AP}$=180°.

Notice that for all three different ground directions of the AP antenna, increasing the antenna size decreases the forbidden zone ratio and, thus, improves the area coverage. Contrary to the power control case, the improvement is more or less equal for all distances between the access point and the receiver. If the same definition for improvement is used, as in formula (64) in Section 4.6, the following, Fig 4.7.6, shows the improvement of the area coverage depending on the distance between the AP antenna and the IWS antenna, $d_a$. In this case the improvement is the ratio between the forbidden zones when the IS antenna gain is 18 dBi and 24 dBi.

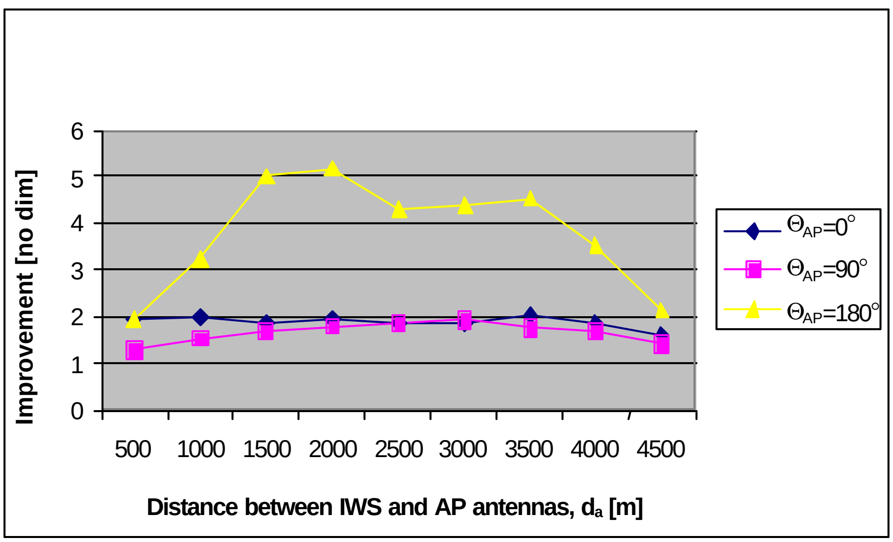



Fig 4.7.6 Dependence of the improvement of the area coverage on the distance between the IWS and the AP antennas. The improvement in this case is the FAR for 24 dBi IS antenna gain divided by FAR for 18 dBi IS antenna gain.

If a comparison is made between the power control case and this case, it is obvious that the improvement in this case is not as much, but what is characteristic is that it is, for the most part, the same for all distances. This was not the case in the power control case, where the improvement after 2000m did not play a major role. So an obvious conclusion would be that if the access point is located at a distance of more than 2000 meters from the IWS antenna, then the increase of the IS antenna gain would be a more useful solution than the power control.

This conclusion can be easily seen in the following Fig 4.7.7:

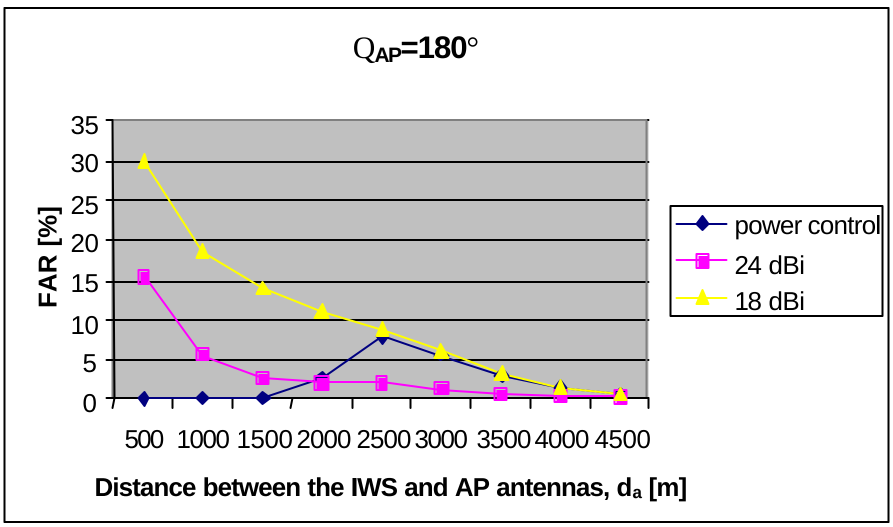



Fig 4.7.7 Comparison between the power control case and the case when directional IS antenna is used.

## 4.8 Interference from the Access Point Antenna

In all the results presented so far, the assumption was that the AP antenna did not cause interference to the IWS antenna. The justification for this assumption is presented in the results that follow. When examining the results, two things need to be kept in mind. The AP antenna and the IS antennas always transmit one at a time. Therefore, either an IS antenna or the AP antenna can cause interference at a certain point in time. Also, as it was shown in Section 4.4 the AP antenna height variation did not have much of an effect on the interference caused by the IS antenna. In this Section the height of the AP antenna is varied in order to see what kind of effect it will have on the interference caused by the AP antenna. For each change in AP antenna height it was calculated how far the AP antenna should be positioned from the IWS antenna in order not to cause interference. This was done for a circle around the IWS antenna with a radius of 5 km. When completing the calculations the AP antenna in the elevation plane looks straight ahead (90 º), as in previous chapters. In the azimuth plane, it looks straight at the IWS antenna, which represents the worst case for the interference in terms of the azimuth plane. Fig 4.8.1, Fig 4.8.2, Fig 4.8.3 and Fig 4.8.4 show the shape of the area where the AP antenna can be located for different AP antenna heights. Table 4.8.1 and Fig 4.8.5 show the graphical presentation of the area allowed, depending on the AP antenna height.

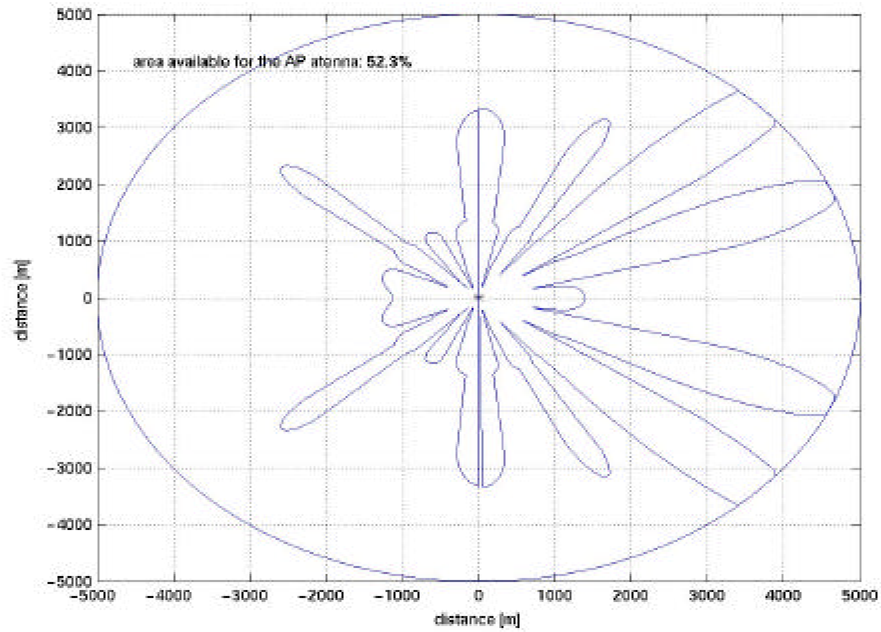



Fig 4.8.1 Area around the IWS antenna where the AP antenna can be located and not cause interference. The AP antenna height is 20m.

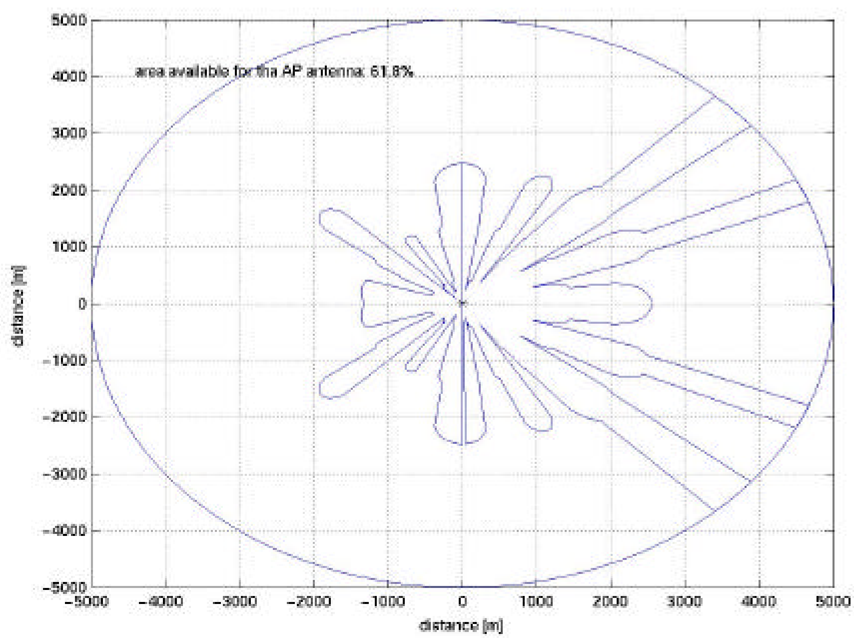



Fig 4.8.2 Area around the IWS antenna where the AP antenna can be located and not cause interference. The AP antenna height is 40m.

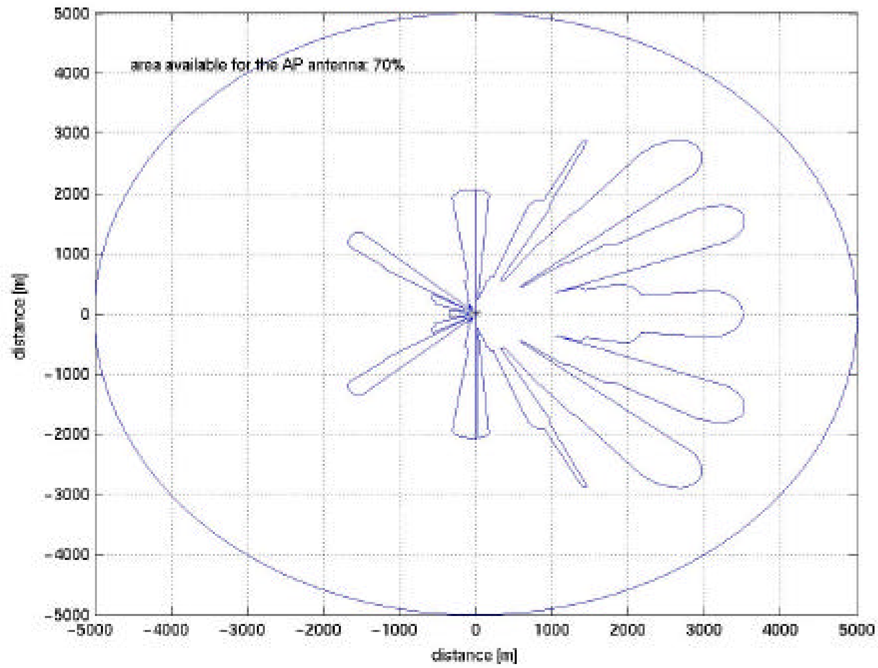



Fig 4.8.3 Area around the IWS antenna where the AP antenna can be located and not cause interference. The AP antenna height is 60m.

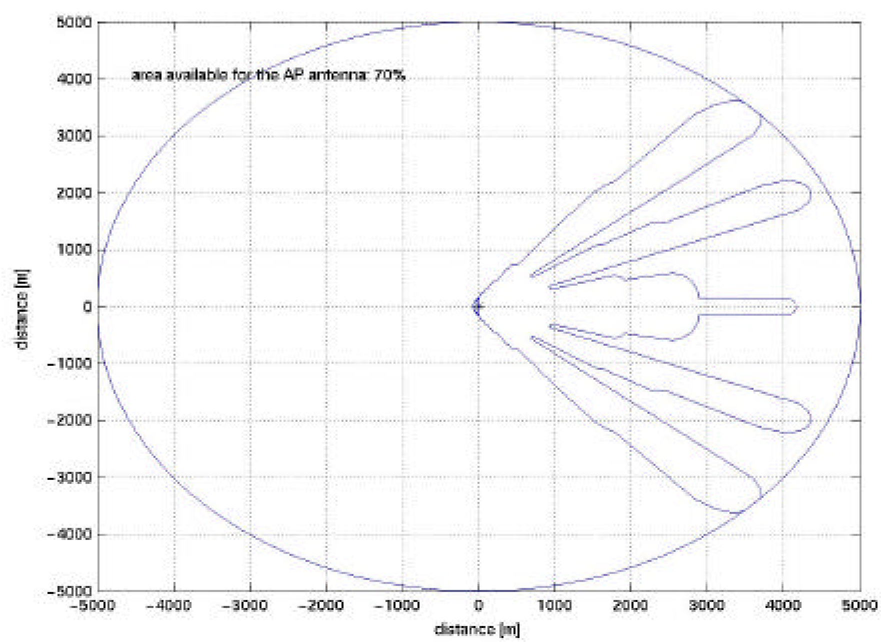



Fig 4.8.4 Area around the IWS antenna where the AP antenna can be located and not cause interference. The AP antenna height is 80m.

| AP antenna height [m] | 20 | 30 | 40 | 50 | 60 | 70 | 80 |
|---|---|---|---|---|---|---|---|
| Area Available for the AP antenna [%] | 51.22 | 58.6 | 61.76 | 68.5 | 70.12 | 68.74 | 70.72 |

Table 4.8.1

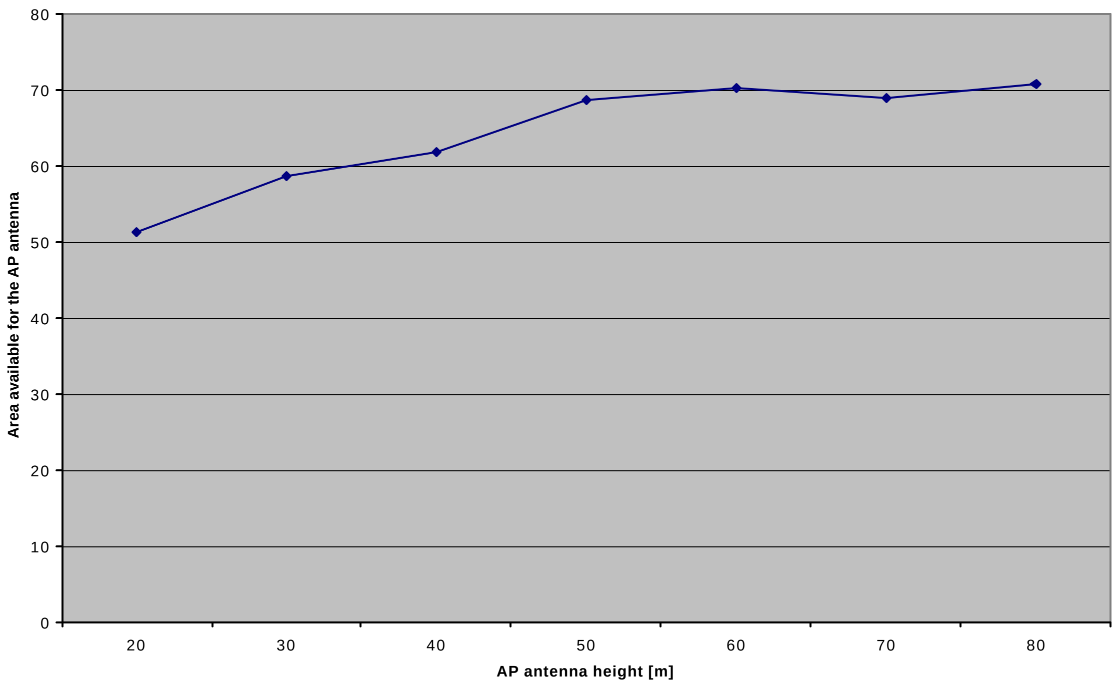



Fig 4.8.5 Area percentage around the IWS antenna available for positioning the AP antenna as a function of the AP antenna height.

Based on the results presented above, the available area around the IWS antenna is relatively large. The increase of the AP antenna height, up to 60m, increases the area available for the AP antenna. What is more important, however, is the fact that the increase of the antenna height also affects the shape of the allowed area. For example, if the provider is going to put the AP antenna right in front of the IWS antenna, a 20m height will be a better choice, despite the fact that the total area is lowest from all other heights. According to the results, the provider will have a relatively large area to locate the AP antenna in a position that will not cause interference to the IWS antenna. Furthermore, just by adjusting the antenna height, the provider can to some extent shape the allowable area and ensures that the AP antenna does not cause interference. Therefore, the assumption that the AP antenna will not cause interference to the IWS antenna is reasonable.

# CHAPTER 5

## 5. CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

### 5.1 Summary of Results

This chapter summarizes the individual results presented in Chapter 4, and gives an overall conclusion in terms of the possibility of employing such a system. According to the results, with proper planning, it is possible to position such a system without interfering with the existing one. In such employment the provider will be able to service between 90%-99% of the area in the sector. If the provider estimates that covering 90% of the area is economically justifiable, then using the non-allocated frequencies for a wireless connection may be a good idea. Based on the results, such coverage can be established only by adjusting the physical parameters of the system, antenna positions, antenna heights, antenna dimensions, etc. The only exception was the power control case, where the provider will have to install additional equipment in order to control the power level of each customer. However, since the system is not mobile, this should not be a problem. Once the power level of a certain customer is determined, it will remain at the same level for future use. Also, when calculating the results, a relatively conservative assumption was made about using the available margin of the existing system. Only 20% of the margin (1db out of 5db) was used to implement this system. This leaves room for any other unexpected signal fading. In fact, since this is a non-allocated frequency, some other provider may have the same idea and decide to use it for its own system. The conservative margin assumption potentially leaves that option open as well.

In order to establish the best area coverage and not to cause any harmful interference to the existing system, the following steps should be followed:

1. Pick the direction from the IWS antenna that minimizes the forbidden zone. This is accomplished by examining the forbidden area ratio as the AP antenna is being rotated around the IWS antenna. As presented in Section 4.3, there may be several directions that are acceptable. Since the variations in the area coverage when rotating the AP antenna is due to the pattern of the IS antenna, the provider, in this step, can also try different IS antennas. For instance, in Section 4.7, it was shown that more directional IS antennas will produce better results.
2. Once the desired direction is determined, the distance between the access point and the receiver should be maximized. As explained in Section 4.5, in order to maximize the area coverage, the distance between the AP antenna and the IWS antenna should be maximized as well.

3. Adjust the access point antenna height such that it does not cause interference to the receiver. Adjusting the antenna height will ensure that the AP antenna will not cause interference, as explained in Section 4.8. At the same time, it will not cause any major change in the interference caused by the IS antenna, as presented in Section 4.4. Also, in this step the provider can rotate the AP antenna in the azimuth plane in order to decrease the interference from the AP antenna. As presented in Section 4.2 this will not have an affect on the interference by the IS antenna.
4. After the first three steps are completed, the position of the AP antenna will be determined. At this point the provider needs to determine whether power control is necessary or not. As presented in Section 4.6, the power control will be useful if the provider had to pick a place for the AP antenna that was close to the IWS antenna.

Following the above steps is a general guideline for minimizing the forbidden area. However, often the provider will have problems finding the best place for the AP antenna due to property issues. In such cases it may be necessary to go back and forth through the above steps until the position of the AP antenna satisfies all criteria. Each of the steps is independent of each other. So, if the provider has some limitations in choosing a location for the access point, it can look at every step and determine which one of the steps is applicable for its case. For example, if the location is already determined, the provider can go straight to step four and determine whether power control is necessary or not. Or, if the distance is already predetermined due to some property rights limitations but several directions are possible, step two can be skipped.

The analysis performed in this report has some limitations. The area close to the IWS antenna was considered for the forbidden zone, without calculating the interference. The far-field formulas were used for the antenna patterns, and they do not necessary apply for very close distances. However, this can be justified by the fact that in most cases the near environment of the IWS antenna will not be available for users anyway, due to the property rights limitations. As presented in Section 2.3, the far-field starts at distance of 80m from the IWS antenna.

In closing, the era of Internet and Cellular phones has change the whole telecommunication world. On one side, the customers are experiencing more convenient ways of being connected. On the other side, the service providers are researching new ways of providing cheaper and better quality service. Broadband wireless connection is one of the many new technologies that are looking for cheaper ways to reach to the end user and still be able to deliver high bit rate connection. Being able to use the wireless environment as a medium for bit transfer can cut the installation costs, however, it also has some limitations due to the limited number of frequency bands available for use. This report is only a small contribution towards researching an idea of using the same frequency bands by different systems. It looks at a certain scenario that may occur in practice and gives an idea of what can be done to maximize the area coverage without causing interference to the other system. As presented by the result, with proper planning, the coverage area can be increased to a level that may be economically justifiable. Of course, there are number of issues and scenarios that are not examined in the report, some of which are suggested as future work in the following section. However, it can be used as one point of view for further research in the area of interference between two different systems.

## 5.2 Suggestions for Future Work

In all the calculations only one IWS antenna was considered to be in the area. The research can be extended for a case with two or more IWS antennas. Furthermore, the IWS antenna used was assumed to be part of a satellite system. However, if another provider comes in the area, it may cause a different scenario with another AP antenna and its own users in the area.

In this report, the antenna patterns were predetermined. Experimenting with some other antenna types and patterns may result in widening or narrowing the area coverage.

Finally, all the results presented were theoretically computed. Proving the results by measurements taken in practice will be an excellent opportunity for some future work.

# APPENDIX A

Section 3.1 shows the derivation of the formulas of the following angles: $\theta_{IS\_IWS}$, $\phi_{IS\_IWS}$, and $\theta_{IWS\_IS}$. However, if some other model is used, for instance, when the AP antenna also causes interference, the remaining angles may also be of interest, too. Therefore, for the purpose of future work, this appendix lists the relationships for all other angles. Since the derivation procedures remain the same as in Section 3.1, only the final equations will be presented.

In a case where the IWS antenna is not circular, the azimuth angle of the IWS antenna towards the IS antenna will also be important when calculating the gain of the IWS antenna in the direction of the IS antenna. The formula between the desired azimuth angle and the parameters listed in Section 3.1 is as follows:

$$f_{IWS\_IS} = \arctan\left(\frac{-d\sin(p - \Theta_{IS})}{A_1}\right) \qquad (65)$$

where $A_1$ is defined as,

$$A_1 = -(h_{IS\_antenna} - h_{IWS\_antenna})\cos(ElevAngle_{IWS}) + d\cos\Theta_{IS}\sin(ElevAngle_{IWS}) \qquad (66)$$

In a case where the access point antenna also causes interference, it is necessary to find the azimuth and elevation angels that determine the direction of the IWS and the AP antennas towards each other. The elevation angle that determines the direction of the IWS antenna in relation to the AP antenna is given by the following equation:

$$q_{IWS\_AP} = \arccos\left( \frac{A_2 \cos(ElevAngle_{IWS})}{2d_a \sqrt{(h_{AP\_antenna} - h_{IWS\_antenna}) + d_a{}^2}} \right) \tag{67}$$

where $A_2$ is defined as

$$\begin{aligned} A_2 = {} & (h_{AP\_antenna} - h_{IWS\_antenna})^2 + d_a{}^2 \left( 1 + \frac{1}{\cos^2(ElevationAngle_{IWS})} \right) - \\ & - (h_{IWS\_anteenna} + d_a \tan(ElevAngle_{IWS}) - h_{AP\_antenna}) - 2d_a{}^2 (1 - \cos\Theta_{AP}) \end{aligned} \tag{68}$$

If the IWS antenna is not circular, the elevation angle alone will not be enough to determine the gain of the IWS antenna towards the AP antenna. Therefore, the following formula gives the azimuth angle of the IWS antenna in relation to the AP antenna:

$$f_{IWS\_AP} = \arccos\left( \frac{A_3 \cos\Theta_{AP} \cos a_1 \sin(ElevAngle_{IWS}) - A_3 \sin a_1 \cos(ElevAngle_{IWS})}{-A_3 \cos a_1 \sin\Theta_{AP}} \right) \tag{69}$$

where $A_3$ and $a_1$ are defined as

$$a_1 = \arctan\left( \frac{h_{AP\_antenna} - h_{IWS\_antenna}}{d_a} \right)$$

$$A_3 = \sqrt{d_a{}^2 + (h_{AP\_antenna} - h_{IWS\_antenna})^2} \qquad (70)$$

The elevation and azimuth angles of the AP antenna relative to the IWS antenna are given in the next set of equations:

$$q_{AP\_IWS} = \arccos(d_a \cos(AziAngle_{AP} - p + \Theta_{AP}) / \sqrt{(h_{AP\_antenna} - h_{IWS\_antenna})^2 + d_a{}^2})$$

$$f_{AP\_IWS} = \arctan\left( \frac{h_{AP\_antenna} - h_{IWS\_antenna}}{-d_a \cos(3p - \Theta_{AP} - AziAngle_{AP})} \right) \qquad (71)$$

where $AziAngle_{AP}$ is the azimuth angle of the AP antenna.

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