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Interference Characterization in Unlicensed National Information Infrastructure (U-NII) band

by
Zafar Masood

*A thesis submitted to the
Faculty of Graduate Studies and Research
in partial fulfillment of the requirements
for the degree of*

Master of Engineering

**Ottawa-Carleton Institute for Electrical and Computer Engineering
Faculty of Engineering
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December 2000**

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Graduate Studies and Research acceptance of the thesis

**Interference Characterization in Unlicensed
National Information Infrastructure (U-NII) band**

submitted by

Zafar Masood

in partial fulfillment of the requirements
for the degree of

Master of Engineering

Professor David Falconer
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Abstract

Recently FCC has allocated 300 MHz of spectrum for unlicensed use at 5 GHz frequency. These bands referred to as the unlicensed national information infrastructure bands (U-NII) are subdivided into three sub-bands of 100 MHz each, with minimal rules. The only restrictions of U-NII bands imposed by FCC are on the maximum transmitted power and the power spectral density. Due to the large available bandwidth it is expected that U-NII will support new wireless data applications with a high data rate (>10 Mb).

To utilize the full potential of U-NII bands, a few technical challenges need to be overcome, the foremost being the interference among the users in an uncoordinated environment. This interference can be reduced substantially by using directional antennas and power control techniques. In this study we will present simulation results for an indoor wireless peer to peer ad hoc network and demonstrate the impact of directional antenna and power control on the system performance. In order to understand the behavior of such a system different propagation environments are studied. Signal to interference plus noise (SINR) and probability of outage are used to evaluate the system performance. We show that the power control has a greater impact on the system performance as compared to the directional antenna. Nevertheless, directional antennas must be used to get a minimum level of performance.

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List of Acronyms

U-NII	Unlicensed National Information Infrastructure Band
LAN	Local Area Network
WLAN	Wireless LAN
MAN	Metropolitan Area Network
HiperLAN	High Performance LAN
FCC	Federal Communications Commission
SINR	Signal to Interference plus Noise ratio
SNR	Signal to Noise ratio
SIR	Signal to Interference ratio
ISM	Industrial Scientific and Medicine Band
UPCS	Unlicensed Personal Communication Band
LMCS	Local Multipoint Communication System
CDMA	Code Division Multiple Access
MSS	Mobile Satellite Services
LOS	Line of sight
NLOS	Non line of sight
FER	Frame Error Rate
GR	Gain Ratio

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Chapter 1

Introduction

1.1 Thesis Objectives

The newly allocated Unlicensed National Information Infrastructure (U-NII) band for unlicensed use at 5 GHz has potential to support high data rates and has been allocated to provide a wireless infrastructure to connect schools and communities through wireless LANs and MANs. The U-NII band is designed to attract a large number of smaller diverse vendors and service providers, to rapidly bring into existence a great variety of novel wireless systems and services. In contrast, licensed spectrum is acquired by the large telecommunication companies after expensive bidding. As a consequence, services offered within licensed bands are fairly expensive. It is anticipated that competition among U-NII services will result in inexpensive, short range, high speed wireless data communication services.

The U-NII band is allocated at 5 GHz to facilitate American industry to develop products for both the U-NII and HiperLAN (High performance local area network) in Europe. Europe has already developed wireless LANs under the name of HiperLAN at 5 GHz. The U-NII band has 300 MHz of total allocated spectrum, which is divided in 3 sub-bands of 100 MHz each [17]. Restrictions in this band imposed by FCC are on maximum transmitted power and power spectral density. The first band 5.15-5.25 GHz has the shortest range, generally within a building. It has the highest chance of facing interference with Mobile Satellite services which also operate in the

same band [22]. This still allows U-NII devices operating in this range to communicate indoors, usually within a room. Nevertheless, the first sub-band is limited to indoor applications, with the maximum power spectral density of 2.5 mW/MHz and a maximum power of 50 mW. The mid-range band 5.25-5.35 GHz has a power spectral density of 12.5 mW/MHz, with the allowance of using a directional antenna of 6dBi gain and it can be used outdoors. The third band at 5.725-5.825 GHz has the highest power spectral density of 50 mW/MHz and a maximum power of 1W. This band is capable of providing networks of several kilometers and could provide school to school links. All these rules are summarized in table 2.1 in chapter 2. All of these bands are limited to a secondary non-interfering basis, with priority given to other co-channel users such as industrial scientific and medicine (ISM) band and mobile satellite services.

Like other unlicensed bands, U-NII also offers serious technical challenges which are not experienced in licensed bands. Since there may be no control on bandwidth, modulation scheme, multi access methods and traffic characteristic of different users, the interference experienced by each user can be severe. Furthermore, each autonomous system can compete independently for resources paying no attention to interference it creates in other nearby systems apart from the aforementioned restrictions on power and power spectral density, and can suffer from interference created by others; without being able to communicate directly and coordinate its activity with nearby systems.

The main objective of this study is to understand the behavior of interference in a highly uncoordinated environment. Since most of the applications are likely to be indoor, only an indoor ad hoc peer to peer wireless model is considered. Ad hoc models are an example of wireless LANs (Local Area Network), where the topology of the network is not fixed. An example of such a network could be a laptop computer talking to another computer. Computer simulations are performed to estimate the outage probability and average signal-to-interference plus noise ratio (SINR). Different propagation environments are considered to observe the interference behavior. They include the propagation exponent and standard deviation of log normal shadowing. Also, the effect of distance between the transmitter and receiver is studied. This factor has the most significant impact to determine the system performance in terms of system availability. Other

factors which are studied include antenna beamwidth, antenna gain ratio and maximum number of users in the simulation area.

The use of directional antennas and power control has already been proven to be very effective to reduce the interference, resulting in an increased system capacity. [21] have already shown the effectiveness of directional antenna for LMCS (local multipoint communication services) which is a fixed broadband wireless application. Similarly, use of power control is well known for cellular systems especially for CDMA, to increase the system capacity. We also use these two techniques to show the performance improvement in terms of outage and average SINR.

1.2 Thesis Organization

This thesis is divided into 5 chapters organized as follows:

Chapter 2 gives the literature survey and essential background information. Different approaches for spectrum management are described. A complete overview of the U-NII band along with the rules is presented. This is followed by some of the wireless communications concepts.

In Chapter 3 the problems associated with the implementation of U-NII band are presented. System capacity is defined as the maximum number of users per unit area. The use of directional antenna and power control is suggested to improve the system capacity.

Chapter 4 describes the detailed simulation model with analytical work. The model presented in this study is an indoor ad hoc network with peer to peer communication. Two different scenarios are considered: single interferer and multiple interferers. We derive the average SIR and outage for a single interferer model. This analysis is verified by simulations. The single interferer model is only used to identify system parameters e.g. antenna beamwidth, and their effect on performance. Computer simulations are carried out to study the system behavior for the multiple users case. We only consider the case where all the users are transmitting signals all the time. To make the model a worst case scenario, it is assumed that all the users are transmitting all the time using the maximum allowable power at the same frequency. Therefore no modulation or multiple access is considered and all the users were assigned the same carrier frequency during the simulation

for single interferer case. Whereas for one of the multiple users simulation scenarios users were assigned random carrier frequencies.

Finally, Chapter 5 concludes the thesis with summary of results and recommendations for future research.

1.3 Thesis Contributions

This thesis proposes a system model which helps in analyzing system performance for indoor wireless applications. The performance has been evaluated for a system which includes directional antennas together with power control. This model can provide a base for further study of other parameters e.g. packet transmission under similar conditions.

Analytical results for the single interferer case have been derived for average SIR and outage with the consideration of directional antennas in section 4.4.2. The impact of different parameters such as antenna beamwidth, propagation exponent, and standard deviation of lognormal shadowing can be studied using this analysis. This analysis is verified by computer simulations in figures 4.5 to 4.10.

Computer simulations are carried out to study the impact of different parameters on system performance. Figure 4.11 to 4.19 give the system performance for different parameters which include antenna beamwidth, antenna gain ratio, desired transmitter separation, propagation exponent and standard deviation of lognormal shadowing.

System capacity is defined in terms of maximum number of users per unit area. Multiple interferers are introduced in section 4.4.3. It is verified that the use of directional antenna and power control can improve the system capacity significantly. This can be observed through figures 4.20 to 4.24. For a power control scenario the power is found to be log normally distributed (figure 4.29, figure 4.30). This is verified by the Kolmogorov-Smirnov test, which is shown in figure 4.31. It has also been observed that for such a system the transmitter-receiver separation between the desired pair is a very important parameter. This essentially refers to the effective range which can be achieved under different user densities.

Chapter 2

Literature Survey and Background

This chapter will cover the necessary information on the spectrum management policies and some basic wireless communication principles. The first section describes the two major ways to manage spectrum; licensed and unlicensed approaches. We will also describe the newly allocated Unlicensed National Information Infrastructure (U-NII) band. In the next section we will review the fundamentals of wireless communications which includes the different path loss models, shadowing and fading phenomena, outage and signal-to-noise-plus-interference ratio (SINR). We will also discuss the fundamentals of directional antennas and power control techniques to mitigate interference.

2.1 Spectrum Management Policy Options

Historically, radio communication has been dominated by narrow beam high power analog transmission. Those radios are very sensitive to interference from other signals using nearby frequencies within the same geographical area. Should two transmitters operate on the same frequencies, there would be continual interference with the highest power signal being the clearest. So, the FCC (Federal Communications Commission) in the USA was formed to keep electromagnetic peace. They assign licenses to a particular user for a particular frequency. The licenses were assigned on the basis of first come first serve, lottery system or by auctioning off the bandwidth

to the highest bidder [22]. In another approach FCC allocates spectrum on an unlicensed basis. The first spectrum released for unlicensed use was Industrial Scientific and Medicine (ISM) band in 1981, which was part 15 of FCC rules. Examples of other unlicensed bands include unlicensed PCS and U-NII bands. In another approach spectrum can be managed in an open access fashion, as discussed by [33]. In this option a license holder would allow many devices to use its spectrum without a prior licensing agreement in return for some compensation.

2.1.1 Licensed Bands

This is the oldest and simplest approach. In this approach the government divides spectrum into non-overlapping blocks. Licenses are then distributed or auctioned, where a license gives its recipient the exclusive right to transmit in one such block of spectrum in a given geographic region. It is obvious that this exclusive access approach solves the problem of mutual interference [33]. Hence, there is little co-ordination required between services. Most spectrum is managed in this way all over the world. However, some of the bands allow limited sharing in the form of “primary” licenses and “secondary” licenses. In this case, a secondary license holder can use the same spectrum provided they do not cause interference with the primary users. Examples of these bands include Personal Communication Systems (PCS), Cellular, Land Mobile etc.

2.1.2 Unlicensed Bands

As opposed to the licensed approach, unlicensed bands do not require any license for their operation in any geographic region. Devices are in principle allowed to transmit at any time and anywhere. This approach has several *advantages*, as it can support many devices that may not be suitable for licensed bands. For instance, if we want to move a wireless LAN to some other place, it would be difficult with the licensed approach. However, it is easy to move such an application in the unlicensed band as there is no permission required to do so. Another benefit of this approach is spectrum sharing. In case of the traditional licensed approach, the spectrum is idle when not in use by the license holder, which is obviously inefficient. On the other hand with the unlicensed band, many devices can share the same spectrum, so that when one is not transmitting another

may do so. This can lead to a great potential for efficient use of spectrum, i.e. more traffic can be carried when spectrum is shared. Especially applications that require intermittent access can use the spectrum more efficiently. Since licenses are not required, services in unlicensed bands can be fairly cheap. Finally, the use of unlicensed band eliminates the potentially lengthy and expensive process of distributing licenses, thereby promoting experimentation and innovation. Though there are several advantages of the unlicensed approach, there are few problems associated with it. The foremost is the behavior of interference. Before taking full advantage of unlicensed approach, the interference need to be characterized.

Unlicensed Bands in North America

In North America examples of unlicensed bands include:

- 1) ISM (Industrial Scientific and Medicine) band
- 2) UPCS (Unlicensed Personal Communications Systems) band
- 3) UNII band

The frequency allocation of these bands is illustrated in figure 2.1. IEEE has already developed a standard for wireless LAN which is known as 802.11, for use in ISM band at 2.4 GHz. This standard can be compared to the 802.3 standard for Ethernet wired LANs. The supported data rates are 1 and 2 Mbps [25]. Another application which is developed for use in 2.4 GHz band is Blue tooth technology [1]. This is an open specification for wireless communication of data and voice and is intended for short range indoor communications. The supported data rate is 1 Mbps. The 20 MHz UPCS is already in use by fixed point microwave users. This band is split into voice and data, to avoid different interference behavior for two types of applications [22]. In the next section an overview of UNII band is present.

2.1.3 UNII Band

On January 9, 1997 the FCC released 300 MHz of electromagnetic spectrum called UNII band. The UNII is composed of three 100 MHz bands of unlicensed spectrum. The frequency

Figure 2.1: Spectrum allocation for unlicensed bands in North America

range for band 1 is 5.15-5.25, band 2 is 5.25-5.35 and band 3 is 5.725-5.825 GHz.

The intended purpose is for schools, businesses and individuals to be able to create local computer networks and wide ranging community networks without having to wire their buildings or pay for air time.

As a result of efforts by industry for allocation of a big piece of spectrum the FCC decided on 300 MHz to be used without the requirement of any license. The FCC decided not to adopt any modulation efficiency and channeling plan because they want U-NII to remain as flexible as possible. It should be noted, however, that there is a power-density limit that calls for signals with a bandwidth less than 20 MHz to have a proportional decrease in transmit power. So although a manufacturer could still design a low bandwidth U-NII device it would not be able to transmit at full power.

As mentioned earlier, the UNII band is divided into 3 sub-bands of 100 MHz each. The first one is typically for the indoor environment and termed as short range. The second one is intended for greater coverage, i.e. for use in campus or small neighborhoods. This band has exactly the same power limits as HiperLAN in Europe [15]. The last sub-band has the largest coverage area and is intended for the community networks of several kilometers and even farther. This band could provide school to school connection for example.

General Technical Requirements

The peak transmit power over the frequency band of operation shall not exceed 50 mW, 250 mW and 1 W for the bands 1,2 and 3 respectively. The maximum peak power spectral density is

	Band 1	Band 2	Band 3
Frequency (GHz)	5.15-5.25	5.25-5.35	5.725-5.825
Peak Radiated Power	50mW	250mW	1W
EIRP With 6dB Antenna Gain	200mW	1W	4W
Power Spectral Density	2.5mW/MHz	12.5mW/MHz	50mW/MHz
Applications	Indoor	College campus and small neighborhood	Typically 6 miles of radius

Table 2.1: Summary of UNII rules

2.5 mW/MHz, 12.5 mW/MHz and 50 mW/MHz for bands 1, 2 and 3 respectively. If transmitting antennas of directional gain greater than 6 dBi are used, both the peak transmit power and the peak power spectral density shall be reduced by the amount in dB that the directional gain of the antenna exceeds 6 dBi [17]. The effect of these rules are depicted in figure 2.2.

Peak power spectral density measurements are made using a resolution bandwidth of 1 MHz. The peak transmit power must be measured over any interval of continuous transmission using instrumentation calibrated in terms of an RMS-equivalent voltage. Within the 5.15-5.25 GHz band, UNII devices will be restricted to indoor operations, to reduce any potential for harmful interference to co-channel MSS (Mobile Satellite Services) operations. The peak levels of emissions outside of the frequency band of operation shall be attenuated below the maximum peak power spectral density contained within the band of operation. For example, for band 1 all emissions within the frequency range 5.14-5.15 and 5.35-5.36 GHz must be attenuated by a factor of at least 27 dB; within the frequency range outside these bands by a factor of at least 37 dB.

Any device that operates in band 1 shall use a transmitting antenna that is an integral part of the device. Moreover, all equipments shall be considered to operate in general population/uncontrolled environment. Table 2.1 summarizes the UNII rules.

Figure 2.2: Maximum Power and Power Spectral Density Resulting from U-NII Rules

2.2 Wireless Networks

Wireless LANs

With a wireless LAN, a mobile user can connect to a local area network (LAN) through a radio connection. Wireless technologies for LAN connection include spread spectrum, microwave and infrared light. One of the potential applications for U-NII band is for wireless LANs. IEEE has already developed a standard 802.11 for wireless LANs which operate in the ISM band at 2.4 GHz. Wireless LAN topologies can consist of purely peer-peer communication and/or include an “access point”.

Ad hoc Networking

An ad hoc network is a local area network or other small network, especially one with wireless or temporary plug-in connections, in which some of the network devices are part of the network only for the duration of a communication session. Such a network can be deployed rapidly because it needs no infrastructure, making it useful in many applications such as home networking, search-and-rescue in remote areas, disaster response, law enforcement and military operations. In mobile ad hoc networks, different hosts communicate over wireless links, and messages may traverse multiple wireless links before reaching their destination. The term has been applied to future office or home networks in which new devices can be quickly added; for example, the proposed Bluetooth technology in which devices communicate with the computer and perhaps other devices using wireless transmission. Each user has a unique network address that is immediately recognized as part of the network. It could be with centralized control or peer to peer communication.

2.3 Fundamentals of Wireless Communications

2.3.1 Path Loss Models

The path loss in a radio channel is the difference between received and transmitted signal power in dB. If the propagating characteristics are not specified, generally the path loss is assumed

to occur in free space. The model of free space treats the region between the transmit and receive antennas as being free of all objects that might absorb or reflect radio frequency (RF) energy. It also assumes that, within this region, the atmosphere behaves as a perfectly uniform and non-absorbing medium. In this idealized free-space model, the attenuation of RF energy between the transmitter and receiver behaves according to an inverse-square law. The received power expressed in terms of transmitted power is attenuated by a factor $L(d)$ [18] and is referred to as free space loss. For the isotropic antenna at receiver, this factor is given by

$$L(d) = (4 \times \pi \times d/\lambda)^2 \quad (2.1)$$

where d is the distance between the transmitter and receiver, and λ is the wavelength of the propagating signal. It can be observed that for this idealized propagation model, the received signal power is very predictable. However, for most of the channels, signal propagation takes place in the atmosphere and near the ground. Therefore, the free space model is insufficient to describe the path loss for such cases. Several models are presented in the literature based upon the propagation environment. These models can be divided based on the cell size. Further for small cells these can be subdivided into outdoor or indoor models. All these different models are depicted in Figure 2.3 [24]. Since our model is an indoor model, indoor path loss models are more important for this study. Outdoor models are necessary to describe the complete list for different path loss models.

Outdoor Models

Different models which are presented in the literature for the outdoor environment include Longley-Rice, Durkin, Okumara, Hata and PCS extension to Hata models [36]. Among these, Okumara's model is the most widely used for signal prediction in urban areas. This is mainly based on measured results and is not as good in rural areas. The Hata model is an empirical formulation of the graphical path loss data provided by Okumura. It gives path losses for the frequency range of 150-1500 MHz. Another model which is also an extension of Hata model is COST-231. This model was developed for a frequency range around 2 GHz by the European

Figure 2.3: Different Pathloss Models

Co-operative for Scientific and Technical research (COST).

Indoor Models

For indoor models the distance covered by the signal is less as compared to the outdoor. However, indoor environment has more variations. AT&T Bell Laboratories [11] and British Telecom [4] were the first to study the indoor propagation models. In general channels can be classified as line-of-sight (LOS) or obstructed (OBS) [36]. For most of the indoor models, signal strength is predicted by actual measurements from the site. These models are site specific and ray tracing is used as a mean of deterministically modeling any indoor or outdoor propagation environment. For the cases, where such information is not available, log distance path loss model is used. It should be noted that these two models can also be used for an outdoor environment.

Since many of the applications of UNII band are for indoor wireless LANs, we can use the log distance model for this study. However, for the third sub band which is intended for the outdoor purposes a different model has to be assumed, such as the COST model.

2.3.2 Large Scale Fading:Shadowing

Large-scale fading represents the average signal power attenuation or the path loss due to motion over large areas. This phenomenon is affected by prominent terrain contours (e.g., hills, forests, clumps of buildings, etc.) between the transmitter and receiver. The receiver is often represented as being *shadowed* by such obstacles. The statistics of large-scale fading provide a way of computing an estimate of path loss as a function of distance. This is described in terms of a mean-path loss (nth power law) and log-normally distributed variations about the mean [18]. Mathematically it can be expressed as

$$Pr[P_L(d) \leq \gamma] = \frac{1}{\sqrt{2\pi}\sigma} \left[\int_{-\infty}^{\gamma} \exp[-(P_L(d) - \overline{P_L(d)})^2/2\sigma^2] \right]$$

where $P_L(d)$ is the pathloss at distance d

2.3.3 Small Scale Fading and Multipath

Radio waves between a transmitter and a receiver can propagate in three different ways: line of sight (LOS), non-LOS (NLOS) or a combination of two. The NLOS component is due to the reflection and scattering from the surfaces of the obstructions such as buildings and by diffraction from them. Therefore, various incoming microwave components arrive from different directions with different time delays. These multiple copies of the same signal are termed as “multipath”. Any signal amplitude variations due to the movement of transmitter, receiver or reflectors are called “multipath fading” or simply “fading”. The small scale fluctuations caused by the local multipath follows a Rayleigh distribution for NLOS situation and typically has a Ricean distribution for LOS [36].

The behavior of small-scale fading is different for different bandwidths in a given multipath channel. The fading could be flat or frequency selective. If the channel bandwidth is greater than the transmitted signal's bandwidth, the fading is termed as flat. If the transmitted signal has a bandwidth greater than the channel bandwidth, the signal undergoes frequency selective fading.

In this study we assumed that the use of directional antennas can reduce the fading effect, therefore it is not included in the model. Although for single interferer case we have used isotropic and wide beam width antennas, we can still neglect the effect of fading because it can be assumed that coding and interleaving can compensate its effect.

2.4 Power Control

Power control is an interference management technique which results in an increased channel capacity. For instance, the channel capacity of a cellular system is significantly influenced by the co-channel interference. By minimizing the transmitted power, co-channel interference can be reduced. Other techniques such as frequency reuse patterns, orthogonality etc also contribute to reducing interference. Similarly the “near far” phenomenon is a well known problem in CDMA systems, where the received power at the base station from mobiles near it is higher than the mobiles farther from it. In order to ensure the same received power level for mobiles, power

control is applied.

Power control has to compensate not only for signal strength variations due to the varying distance between base station and the mobile but it also attempts to compensate for signal strength fluctuations typical for a wireless channel [18]. These fluctuations are due to the changing propagation environment between the transmitter and receiver. As was explained in the previous sections these movements or obstructions which result in shadowing and fading can cause signal variations.

Power control can be divided into two types: open loop and closed loop. The open loop power control estimates the channel and adjusts the transmitted power accordingly but does not attempt to obtain feedback information on its effectiveness. Obviously, the open loop power control is not very accurate, but it is relatively fast. The closed loop power control may base its decision on an actual communication link performance metric, e.g. received signal power level, received signal-to-noise ratio, received bit error rate or received frame error rate or a combination of them. The two types of power control schemes can be explained by considering a CDMA system. In a CDMA system all the mobile users receive a pilot signal transmitted by base station. According to the power level of the pilot signal measured at the mobile, the mobile adjusts its transmitted power. When the measured power at a mobile is large, the mobile needs to transmit at a small power and vice versa. Since the received power at a mobile is proportional to the inverse of the n th (propagation exponent) power of the distance from a base station, the received power is larger for a smaller transmission distance and smaller for a larger transmission distance. Therefore, a mobile near a cell boundary needs to transmit at a higher power level than a mobile close to the base station. This is called open loop power control. On the other hand for a closed loop power control base station measures the power of the signal from a mobile and controls the transmitted power of the mobile by sending a command over a command channel. A closed loop can have outer and inner loop. Outer loop sets the targeted value of power or SINR based on frame error rate, whereas inner loop controls the actual power by sending the commands over the command channel.

In the ideal case, power control compensates for the propagation loss, shadowing and fast

fading. However, several factors which include fast fading rate, infinite delay of the power control system, non ideal channel estimation, error in the power control command transmission, limited dynamic range etc. all contribute to degrade the performance of power control. In this study, power control command errors, loop delay is neglected and an ideal closed loop SINR based power control system is assumed. Only inner loop is considered, which means that our targeted SINR is fixed for all the cases.

2.5 Directional Antennas

Generally antennas may be classified as omnidirectional, directional, phased array, adaptive and optimal [19], [20]. An omnidirectional antenna radiates equally in all directions and is also known as an isotropic antenna. Directional antennas on the other hand, have more power in certain directions and less in others. The direction in which the power of these antennas is maximum is referred to as the main lobe of the antenna. Whereas, all the other directions where the antenna power is smaller are termed side lobes. The gain of the antenna is defined as the ratio of the maximum power density from the antenna and the power density from an isotropic antenna.

$$G = \frac{P_{\max}}{P_t/(4\pi r^2)}$$

where $P_{\max}$ is the maximum power density from a directional antenna and P_t is the power radiated from an isotropic antenna which has an area of $4\pi r^2$.

The ratio of main and maximum side lobe gain is called the gain ratio. The directiveness of a directional antenna can be determined by its beam width. The beam width is defined as the angle between two half power (-3 dB) points on either side of the main lobe of the radiation.. The gain of directional antennas in the main lobe is more than that of omnidirectional antennas and is measured with respect to the gain of the omnidirectional antennas. For example, a gain of 10 dBi (sometimes indicated by dBic or simply dB) means the power radiated by this antenna is 10 dB more than that radiated by an isotropic one. The gain of the antenna is inversely proportional to the beamwidth, thus a highly directional antenna could have quite high antenna gain in its main lobe.

In theory an array of antennas is able to null interference from different directions, and the beamwidth of the antenna can be extremely sharp if the number of the antenna elements is large enough and the elements are properly adjusted [30].

Delay spread is the impairment which occurs due to the phenomenon of multipath. This is the difference in propagation delays among the multiple paths. When the delay spread exceeds about 10 percent of the symbol duration, significant intersymbol interference can occur, which limits the maximum data rate [36]. With delay spread, the array treats delayed versions of the signals as separate signals. Specifically, an adaptive array with M antennas can eliminate delay spread over $(M-1)/2$ symbols [16] or cancel $M-1$ delayed signals over any delay. Therefore, in a multipath environment, an adaptive array can separate signals from closely spaced antennas.

Thus directional antennas can increase the system capacity and supported data rate for the applications in U-NII band by reducing the interference. In practical situations the alignment of antenna beamwidths is an important issue. When the beamwidth is very narrow, even a slight misalignment may not give the desired performance. In later sections we will explain our model for the antenna and its impact on system performance.

2.6 Performance Parameters

There are a number of specific metrics that are used to evaluate the performance of mobile communication systems. Link metrics provide an objective measure of performance for a particular user within a system and are directly dependent on the radio channel characteristics, as well as the specific transmitter and receiver implementations. Such metrics include average and instantaneous bit error rate (BER), average frame error rate (FER), average signal-to-interference-plus-noise ratio and outage. The instantaneous bit error pattern is important for evaluating the performance of voice coding algorithms and error correction techniques. In packet radio systems, the average and worst case transmission delays are important link metrics.

Signal-to-Interference-plus-Noise ratio

The signal-to-interference-plus-noise ratio (SINR) is a convenient measure of performance at various points in the link. It is defined as

$$SINR = \frac{\text{signal power}}{\text{noise power} + \text{interference power}}$$

The term SINR and SNR are used interchangeably in the literature for interference limited environments such as CDMA systems. All of the powers used in the formula are average powers. The SINR can degrade by either a reduced desired signal power or a high interference-plus-noise power. The desired signal can be reduced due to absorption, diversion, scattering or reflection along its route to the intended receiver. Thus, a portion of the transmitted energy does not arrive at the receiver. The sources of noise could be the devices' nonlinearities or thermal noise. In this study only thermal noise is considered. Interference is obviously the signals from other users which may be due to the imperfect orthogonality between codes, frequency or time.

Outage

Outage may be defined as the percentage of time/location where the specified criteria are not satisfied. Usually it is the probability of SINR being lower than some threshold for a continuous transmission, i.e.

$$Pr[S/I < Threshold]$$

For packet or data transmission outage may be defined as the condition when a received frame contains more than a specific number of bit errors. It can be defined as

$$Pr[(FER_{inst} > FER_{max})] \leq x$$

where x is the percentage of time for which this criteria is not satisfied, FER_{inst} is the instantaneous frame error rate, FER_{max} is the maximum frame error rate. Frame error rate is defined as the number of received frames that contain an error in the frame payload divided by the total number of transmitted frames.

Chapter 3

Issues in U-NII Band

In this chapter we will address the challenges associated with the use of unlicensed bands in general and the U-NII band in particular, the foremost being the behavior of interference in this band. It can be expected that the interference behavior is quite unpredictable in the unlicensed approach as compared to other approaches because of no or few rules. The U-NII scenario offers a unique set of technical challenges not experienced in other wireless communication systems where access is controlled by the license holder [2]. In a licensed band a user experiences only controlled interference from other users of that system. But for the unlicensed band, the situation is quite different. Each system can use distinct modulation schemes and multiaccess methods and carry traffic characteristics according to its market. Another important aspect of this approach is that an autonomous system can in principle compete independently for resources paying no attention to interference it creates in other nearby systems, and can suffer from interference created by others, without being able to communicate directly and coordinate its activity with nearby systems.

A given pair of terminals communicating in a U-NII system will likely have an initial procedure at the start to select (perhaps at random) a frequency channel on which to communicate. The outage event thus corresponds to a bad choice of this channel due to interference or low SINR.

Normal operation could include pseudo-random periodic frequency-hopping, in which case Pr_{outage} would be the error or erasure probability seen by a suitable forward error correction code. Another alternative would be frequency-hopping only when necessary (after an outage

event occurs). In this case Pr_{outage} is the probability that such a hop is necessary.

In this study, we will develop a model which characterizes the interference behavior of U-NII band under different propagation conditions. This model will also help in determining the capacity of the system and establish a possible rule/etiquette. The UPCS band has a rule of “Listen Before Talk” [35], which simply means that devices are required to sense the channel for a specific period before acquiring it. However, for the U-NII band there is no such rule/etiquette at this time. In the absence of any sharing rules, there might be possibilities that the benefits of unlicensed approach are not fully utilized. Interference cancellation techniques, power control and directional antennas are used to mitigate the interference. In the following pages we will describe the capacity of the U-NII band, capacity improvement using directional antenna and power control. This will follow a possible etiquette for devices operating in U-NII band.

3.1 Capacity of U-NII Band

The capacity of a system can be defined in different ways. [5] investigated the system capacity in terms of Area Spectral Efficiency for variable rate cellular systems. It is defined as the sum of the maximum bit rates/Hz/unit area supported by a cell's BS, for a cellular data system, for a specified BER. This definition is an extension of the previously defined system spectral efficiency for constant data rate cellular systems, which was defined as the ratio of the carried traffic per cell (in Erlangs) to the product of the total system bandwidth and area supported by a base station.

In a recent publication [23], the capacity of adhoc networks has been studied. [23] expressed capacity in terms of throughput, which is defined as bits per second. Two different topologies are considered: arbitrary and random. For arbitrary networks, node locations, destinations of sources and traffic demands are arbitrarily chosen, whereas random networks choose the nodes and destinations randomly. The maximum possible throughput is calculated under a condition of no interference. This essentially means that the capacity is calculated under optimum conditions.

For our case, capacity can be defined as the maximum number of users per unit area for a given outage. The outage as was explained in the earlier chapter was defined as SINR being

lower than some threshold. This definition is generic and can be extended for any modulation scheme and multiple access method. Therefore, if we consider a circular area of radius r , and the maximum number of users are denoted by N , then the capacity is given by

$$C = N/(\pi * r^2) \text{users/m}^2$$

The capacity of the system is considered for a worst case scenario. This means that all the users are using the same bandwidth and same carrier. However, we also study the case when users might have different random carrier frequencies. Also, it is assumed that the users are transmitting all the time i.e. continuous transmission. Although the use of wireless LAN essentially refers to the packet transmission, we restrict ourselves to continuous transmission. Therefore, when packet transmission is considered an increase in the capacity is expected.

3.1.1 Interference Management Techniques

Several techniques have been proposed to mitigate the interference in a wireless environment, which in turn increases the capacity of the system. Recently a task group on Coexistence of Broadband Wireless Systems in working group IEEE 802.16, suggested some mitigation techniques in a fixed broad band wireless access [9]. They include the sectorized, adaptive array or directional antennas. Other techniques include the cross polarization isolation, frequency plan, more robust modulation and encoding schemes. Additionally, it suggests increasing the distance between the interfering transmitter and the victim receiver. Although the last factor was found to be the most difficult one for implementation, this could be a crucial factor for the uncoordinated environment. In our study, we will look into the effect of the distance between the interfering transmitter and desired receiver. Additionally, two of the interference mitigation techniques, namely directional antenna and power control are also studied.

Directional Antennas

The use of directional antennas was found to be effective for different wireless systems. For fixed wireless LMCS, [21] found a performance improvement of 3 times when the subscriber antenna

beam width reduces from 10° to 2° , with a 3 sectored base station antenna. [21] also studied the effect of antenna gain ratio and found the improvement in outage from 0.22 to 0.13, when the gain ratio is increased from 0 to 30 dB.

In another study [28] showed a significant improvement in a CDMA system when a directional antenna is employed at a base station. Rappaport compared five different antenna patterns at the base station, which are omnidirectional, sectorized, flat topped, adaptive and adaptive sectorized. Their simulations show an improvement of an order of magnitude in BER when the antenna pattern is changed from omni to a three element linear array. Similarly, for the flat topped, the performance in improvement is better than two orders of magnitude when compared with the omni directional antenna. They also observed that for a given bit error rate, two to four times as many users may be supported using directional antennas as for omnidirectional antennas.

We have seen that the use of directional antennas results in an improved capacity of different wireless systems. Therefore, an improved performance is expected in the U-NII band after the implementation of directional antennas. We will show this improved performance in our simulation results.

Power control

Power control is a well known technique to reduce the outage due to high power interference. Also, it ensures the smallest transmitting power which is still necessary to maintain a good quality link. For example in CDMA cellular system, the signals from the mobiles near the base station are strong as compared to the mobiles which are farther. This causes interference for the mobile far from the base stations. The use of power control eliminates this problem and mobiles near the base stations are required to transmit at a lower power, while mobiles far away from the base station can transmit at a higher power. This effectively reduces the interference, which in turn causes an increase in capacity of the system. Although it is more critical for the performance of CDMA systems, it could be used with CDMA or TDMA systems. It could be based on the received power or SIR. In our simulations SIR based power control is implemented.

3.2 Possible Etiquette

As was discussed in the previous chapter the problem of interference needs to be resolved before we can take the advantage of the unlicensed approach. Additionally there is a need of some etiquette, which can help the coexistence of devices in an uncoordinated environment. These etiquettes or rules could be helpful in reducing the mutual interference. Moreover, the spectrum can be shared fairly by adopting some etiquettes.

Currently, the unlicensed PCS band has an etiquette which is known as *Listen before Talk*. It requires devices to monitor the channel and transmit only if the signal energy is below a threshold throughout a specified monitoring time. This wait time is randomly distributed between 50 and 750 μ sec. [38], [37] suggest some modification in the etiquette *Listen before Talk*, which is basically an imposition of a time penalty for the devices which do not release the spectrum after the use.

Another example of etiquette could be the maximum size of packet. Recently a coexistence study group is developing recommendations for coexistence of short distance WLAN in 2.4 GHz. [14],[42],[13] have studied the interference behavior in a mixed bluetooth and WLAN 802.11 environment. [42] has shown the impact of packet size when Bluetooth devices and 802.11 wireless LAN are operating together. This packet size is dependent upon the utilization and density of the blue tooth devices. [42] also showed that the number of interferers is affected by the distance of an 802.11 AP (access point) from the Bluetooth devices. This means that by increasing the distance, the number of interferers can be reduced.

So far the U-NII band has no rules apart from some power, spectral density and antenna gain restrictions. One possible rule could be the minimum distance between interfering subscriber terminals. By applying this rule interferer can be placed at a distance which gives enough SINR for our desired receiver. However, the implementation of this rule is not very clear at this point, since at a later stage an interferer can be a desired signal source. Another rule could be the maximum size of packet that can be transmitted for such applications.

We have seen the problems associated with the U-NII band, the foremost being the interference between the devices and absence of any rule/etiquette. In the following chapter we will study the interference behavior and look at the performance improvement by using directional antenna

and power control techniques.

Chapter 4

Simulations for U-NII Band

In this chapter the simulation model is described. Simulation is carried out for two different scenarios: (1) with one interferer and (2) with multiple interferers. The system performance is quantified by the signal to noise plus interference ratio and the outage. It is well known that directional antennas and power control can improve the performance of a system significantly. System capacity is defined as the number of users in a unit area. Using these techniques system capacity is investigated under different propagation environments. The parameters which are used in the simulation include beamwidth and gain ratio of directional antennas, separation between transmitter and receiver and the total number of interferers. The last parameter will eventually be translated into the user density per unit area.

4.1 System Methodology

A major application of the U-NII band is for wireless LANs. In a wireless LAN operating in peer-to-peer mode, there is no centralized control and devices communicate with each other in an ad hoc manner. The standard for wireless LANs has already been developed for 802.11 at 900 MHz and 2.4 GHz. In Europe, HIPERLAN (High performance LAN) has already been implemented at 5 GHz. Therefore, we have developed a wireless peer-peer model in two different scenarios: single interferer and multiple interferer.

4.1.1 Single interferer model

A simple model is considered first. This model consists of a single transmitter/receiver pair, communicating without any centralized control. This type of communication is referred to as an ad hoc network. Another transmitter is assumed transmitting in a random direction. This is considered as an interferer to the receiver of our desired pair. The simulated area is considered to be 200 m diameter. An indoor environment is considered. The interferer is placed randomly in the area. The signal to noise plus interference ratio (SINR) is determined at these random locations. The worst case is assumed; this simply means all the users are transmitting all the time. Moreover, all the users are transmitting with their maximum power permitted by the FCC rules. Everyone is using the same carrier frequency and using the same band of 20 MHz, which is followed by the maximum power and power spectral density rule. The maximum EIRP (Effective Isotropic Radiated Power) allowed by FCC is -7 dB, which means with the maximum transmitted power of -13 dBW the antenna gain can not exceed 6 dBi. If we want to increase the antenna gain more than 6 dBi maximum transmitted power has to be reduced in proportion in order to maintain the maximum EIRP. Our model assumes maximum transmitted power of -13 dBW and maximum antenna gain of 25 dBi. This makes our maximum EIRP 19 dB higher than the specified maximum EIRP. Our simulation results are equivalent where EIRP is lowered by 20 dB and for a lower power noise with a bandwidth of 200 kHz.

The separation between desired transmitter and receiver is assumed to be 10 m. The receiver is assumed to be located at (0,0), and the desired transmitter is at (10,0). A log normal shadowing with 6 dB of standard deviation is considered. The shadowing is assumed to be correlated as will be subsequently described.

The impact of directional and omnidirectional antennas is observed. For simplicity, it is assumed that all the users have the same beamwidth and gain ratio. The desired receiver and transmitter antennas are always pointing towards each other. Hence both of them receive the maximum antenna gain from each other. However, the interferer's antenna is assumed to be transmitting in a random direction, which is uniformly distributed from 0 to 360 degrees. This direction determines whether the desired receiver falls in the main or side lobe of the interferer.

Simulation Parameters	Values
Maximum Transmitted Power	50 (mW)
Beam width (θ)	6°, 15°, 30°, 45°, 90°, 360°
Gain Ratio	25, 30, 35 (dB)
Propagation Exponent	2, 3, 4, 5, 6
Total Standard Shadowing deviation (σ_t)	6, 8 10, 12 (dB)
Noise Bandwidth	20 MHz
Outage Threshold (SINR)	10 dB
Separation between desired pair	10, 25, 40, 75, 95 m
Interference Location (Random)	0–100 m
Simulating Area	Circular 100m radius

Table 4.1: Simulation Assumptions for single interferer case

Similarly, based on the interferer random position, it is decided if it falls in the main or side lobe of desired receiver.

The different beam width values chosen for the simulation are 90, 45, 30, 15 and 6 degrees. Three different gain ratios are chosen for the calculation of main and side lobe gain. They are 25, 30 and 35 dB. Different propagation environments have also been investigated. The different values for the propagation exponent are 2, 3, 4, 5 and 6. Different standard deviations for log normal shadowing have also been assumed. Then the impact of separation of transmitter and receiver has been observed on the system performance. Simulations are run for 10^{-5} trials.

All these simulation assumptions are summarized in Table 4.1

4.1.2 Multiple interferers

After investigating the model for a single interferer, more interferers are added in steps. Initially no power control was assumed. Therefore, all transmitters are transmitting at the maximum allowable power with a random antenna orientation, in the same simulating area. However based on the observations from the single interferer case, we can discard parameter combinations that are not expected to lead to interesting performance levels. For example it has been observed that

Figure 4.1: Simulation model for single interferer

the use of an isotropic antenna does not give the desired performance, therefore we do not consider it for the multiple interferer case. Outage is plotted against the number of interferers.

Two different power control schemes are considered. In the first scheme power is adjusted based on the distance dependent path loss and noise power only. Therefore it is limited in the sense that we do not consider interferer's power. In the other scheme interference is also considered i.e. it is based on received SINR. Since the power adjustment is based on the SINR at an individual receiver, the receiver for each transmitter is also added. It is assumed that all the pairs are separated by the same distance, and the antennas of each pair of transmitters and receivers, are pointing towards each other. Later the distance between the interfering pairs is also made random, which is uniformly distributed between 3 and 40 m. Depending upon the received SINR and whether it is lower or greater than the set threshold for power control, transmitters are asked to increase or decrease their power. To reduce the boundary effect the simulation area is increased to a circular area of 300 m radius in this case.

For the multiple interferers case, the worst case is assumed initially. This means that all the users are using the same band at the same time. But later, the model is modified and bands are assigned randomly, which is uniformly distributed between 5 and 100 Mhz. This represents the effect of smaller or larger interferer bandwidth relative to the desired user bandwidth. The summary for the simulation assumptions for multiple interferers case is given in table 4.2.

4.2 Propagation Model

As was explained earlier that the signal strength in a wireless channel is affected by the propagation environment/exponent, shadowing, multipath fading, distance between the transmitter and receiver and motion of the mobile. However, we only consider networks, with no mobility, in an indoor environment. Moreover, the multipath fading is ignored in this model. Therefore, we are left with the distance-dependent path loss and shadowing effect.

Simulation Parameters	Values
Beam width (θ)	6°
Gain Ratio	25 (dB)
Propagation Exponent	2, 3, 4, 5, 6
Total Standard Shadowing deviation (σ_t)	6, 8, 10, 12 (dB)
Noise BandWidth	20 MHz
Outage Threshold (SINR based PC)	10, 15, 17 dB
Outage Threshold (SNR based PC)	10, 15, 20, 25 dB
Power Control Threshold (δ)	15, 20 dB
Power Control Step size (Δp)	0.5 dB
Separation between desired pair	8, 10, 25, 40 m
Simulating Area	Circular 300m radius

Table 4.2: Simulation Assumptions for multiple interferer case

4.2.1 Path loss model

Usually path loss models are obtained from observed data with curve fitting techniques. Different models are developed for different propagation environments. For example, Hata, Okumara and ray tracing models are used for outdoor environments [36]. Other log distance and ray tracing models are used for indoor environments. However, these two models can also be used for outdoor environments. If the complete structure is available for the indoor environment, ray tracing is used, otherwise the log distance model is used. In our case, making no assumption on the structure of environment the log distance path loss model is assumed.

Free Space Path Loss Model

This model is used when there is an unobstructed and clear line of sight between transmitter and receiver. It predicts the path loss as the function of transmitter-receiver separation distance raised to the power of two.

$$\overline{PL}(dB) = 20\log(d/4\pi\lambda) \quad (4.1)$$

where λ is the wavelength given by c/f , c is the speed of light, f is the frequency of the radio wave in Hz. In this model f is chosen as 5 GHz, therefore $\lambda = 0.06m$.

Log-distance Path Loss Model

It has been found that for most indoor environments the average received power decreases logarithmically with distance [36]. The average large scale path loss for an arbitrary transmitter receiver separation is expressed as a function of distance

$$L(d) \propto (d/d_o)^n \quad (4.2)$$

where d_o is the minimum distance between transmitter and receiver, and d is the distance between transmitter and receiver ($d \geq d_o$), and n is the propagation exponent, indicating the rate of path loss.

Alternatively, we can write

$$\overline{PL}(dB) = \overline{PL}(d_o) + 10n \log(d/d_o) \quad (4.3)$$

where $\overline{PL}(d_o)$ is the free space path loss

The value of reference distance d_o is usually obtained from the field measurements, and typically it is between 1m and 100m for microcellular systems. This value should be greater than the far field distance. In our model this value is set to 1m which is less than the calculated one, which makes our results conservative. The value of n is a function of the propagation environment. For instance, in free space propagation environment, n is 2. For other environments, its value depends upon the obstructions and is usually determined by field measurements.

4.2.2 Log Normal Shadowing

It has been noted [36] that for the same transmitter receiver separation, the measured signal is different from the predicted value given by equation (4.3). This is due to the different surrounding environment and paths along which the signal arrives. This phenomenon is termed shadowing and the received signal power is found to fit a Gaussian distribution in dB domain. Therefore this phenomenon is also referred to as log-normal shadowing. The mean of the lognormal random variable is distance dependent and has a certain standard deviation σ which describes the shadowing effect.

In a multi-user environment, shadowing for different users can be correlated [8], [41]. The shadowing effect on the signal received from a channel can be modeled as the sum of two components. One is specific to the location of receiver and the other to the path between the receiver and transmitter. The location specific contributions are identical for all paths to a given location; the path-specific contributions are independent of one another and of the location-specific contribution [8]. If $\mathbf{X}_l$ is the location dependent component, and $\mathbf{X}_p$ is the path dependent component, then total shadowing will be given by

$$\mathbf{X}_t = \mathbf{X}_l + \mathbf{X}_p$$

$\mathbf{X}_l$ and $\mathbf{X}_p$ are also modeled as gaussian random variable in dB with σ_l and σ_p standard deviation respectively. Let σ_t be the total standard deviation for the lognormal random variable. Then the total variance can be calculated by

$$\sigma_t^2 = \sigma_l^2 + \sigma_p^2 \quad (4.4)$$

In our simulation we have chosen σ_t to be 6, 8, 10 and 12 dB. For outdoor environments the typical values for σ_p and σ_l are taken as 8 and 8.3 dB [8], which give σ_t equal to 11.5 dB. Since no information is available on the statistics of σ_p and σ_l for indoor environments, they are assumed to be equal. This gives

$$\sigma_t = \sqrt{\sigma_l^2 + \sigma_p^2}$$

Therefore

$$\sigma_t = \sqrt{2} \times \sigma \quad (4.5)$$

4.2.3 Thermal Noise

Finally, in our model thermal noise has also been added, which is assumed to be additive white Gaussian noise (AWGN). The noise power is given by [39]

$$N = 10\log_{10}(KTF) + 10\log_{10}(BW_{IF}) \quad (4.6)$$

where N is the noise power, K is the Boltzman's constant ($1.374 \times 10^{-23} \text{ joule/k}$), T is the ambient temperature (290°K), F is the noise figure and the $BW_{(IF)}$ is the receiver IF bandwidth. In this

study F is assumed to be 8 dB. Noise bandwidth is taken as 20 Mhz, which is the maximum bandwidth that a user can acquire if he is transmitting at the maximum allowable power with the maximum power spectral density. Therefore the total noise power is -123 dBW. However, for the multiple interferer case when we use random bandwidth for all the users, the noise bandwidth depends upon the randomly assigned bandwidth for the desired user. Therefore, in that situation the noise power is random too.

4.2.4 Link Budget

Using the above parameters, we can calculate the link budget. The value of S/N ratio at the edge of simulation area is calculated. This is the minimum required S/N ratio, which the system should have for satisfactory performance. The farthest point in the simulation area is 100m. Using equation 4.3 path losses at 100m are calculated. The path losses are found to be -126 dB. The received signal power in dBW is given by

$$P_{desired} = P_t + G_t + G_r + PL_{100m} \quad (4.7)$$

The antenna gains are selected to be maximum, as the desired transmitter and receiver are pointing to each other all the time. The value of the main lobe gain is 17 dB, with the beamwidth of 6° and a gain ratio of 25 dB. The transmitted power is set to the maximum limit which is -13 dBW. Therefore the power received from the desired transmitter is -105 dBW. The noise power is calculated in section 4.2.3, using equation 4.6 which is -123 dBW. Therefore, signal to noise ratio is given by

$$S/N = P_{desired} - N \quad (4.8)$$

Parameters	Units	Values
Band width	MHz	20
Power Control		no
Transmitted power	dBW	-13
Transmitter Antenna Gain	dB	17
EIRP	dBW	4
Receiver Antenna Gain	dB	17
Simulating Area (circular)	m(radius)	100
Path losses at the edge of simulating area	dB	-126
Received power at the edge of area	dBW	-105
Noise Figure	dB	8
Noise Power	dB	-131
S/N	dB	18

Table 4.3: Link Budget

4.3 System parameters

4.3.1 Signal to interference plus noise ratio

The signal to interference plus noise ratio is a performance parameter for a given bit error rate. For example under AWGN (Additive White Gaussian Noise) channel conditions for a QPSK modulation for a bit error rate of 10^{-3} , with coherent detection, the required SINR is 10 dB [39]. In this study 10^{-3} is taken as the target BER. Therefore, an SINR of 10 dB is set as the minimum tolerable value. Hence any point falling below the SINR threshold (10 dB) is counted as outage. This outage threshold is chosen for single interferer case and multiple interferer without power control. Later the effect of outage threshold is also studied for the case of power control. Different values that are used can be found in table 4.2. It is important to note that this targeted SINR can be reduced when proper error control coding is incorporated.

4.3.2 Directional Antenna

As mentioned earlier, a directional antenna can significantly improve the system performance. The beamwidth and gain ratios are varied to observe the effect of directional antennas. A directional antenna emphasizes the signal received from certain desirable directions and de-emphasizes signals received from other directions [29]. The direction of maximum power is called the primary beam, or the major lobe, whereas secondary beams are referred to as the minor lobes. Since the major lobe propagates and receives the most energy, this lobe is called the *main* lobe. Lobes adjacent to the major lobe are called the *side* lobes and the lobe in a direction exactly opposite to the front lobe is called the *back* lobe. In this model we assume that the energy of the back lobe is higher than the side lobes and therefore only main and back lobes are considered. The main lobe gain is calculated by [29]

$$G_m = 101.2/\theta \quad (4.9)$$

where G_m is the main lobe gain of the transmitter/receiver in linear scale, and θ is the half of the beamwidth in degrees

The gain ratio (GR) in dB is given by

$$GR = G_m - G_b \quad (4.10)$$

Therefore the value of the back lobe gain can be calculated by

$$G_b = GR - G_m \quad (4.11)$$

The gain ratio is chosen to be 25, 30 and 35 dB according to the commercially available products from most antenna manufacturers [34]. For multiple interferers case the value of the GR is set to 25 dB. From equation 4.11, it can be seen that by choosing highest value of gain ratio, we can reduce the value of back lobe gain. Therefore, higher gain ratio will give the better performance. But as shown by [6], there is a minimum required side lobe level depending upon the required S/I. This is due to the effect of scatterer and reflections from the surroundings. This phenomenon is also reported by a recent research done by [26]. Therefore, we may not be getting the specified value of the GR, and the actual GR value may be lower than the specified one. For this reason the value of 25 dB is chosen for the rest of the simulation scenarios.

4.3.3 Power Control

As discussed earlier, power control could be based on the received power or received SINR. Since SINR is directly related to the BER, [7] suggests SINR based power control is more appropriate. Therefore SINR based power control has been chosen for this model. However, a limited power control scheme has also been studied which is based on the distance dependent path loss and noise power.

For the single interferer case the power control is not applied, particularly since the single interferer model is only used to establish the parameters for the multiple interferers. However, for the multiple interferers case the use of power control proved to be significant. Simulation is performed for a large number of random trials. For each trial, the initial power is randomly assigned to all the transmitters. The minimum value of power is set such that target SINR (10 dB) can be achieved in an interference-free environment i.e -123 dB of noise power is overcome. The maximum power is set according to the FCC limit. Therefore the initial random power for a transmitter is uniformly distributed between -113 dBW and -13 dBW. In each trial, power is adjusted iteratively for each individual pair. For each iteration desired pair is created at a fixed known location and power received at desired transmitter is calculated. All other interfering transmitter receiver pairs are created randomly in the simulation area and power received at the desired receiver from interfering transmitters is calculated. SINR is measured at the receiver and compared to the predefined SINR threshold. This process is repeated until the system reaches a steady state. If the measured SINR is above the threshold transmitted power is reduced by a fixed step size (dB), otherwise it is increased by the same step size. This process of power control is done at every pair in the system. Let P_{ti} be the transmitted power, in dBm, in the i^{th} run, ∇ be the fixed step size in dB and SIR_i be the received signal-to-interference-plus-noise ratio, then in the absence of power command errors the transmit power in the next iteration is given by [7]

$$P_{t(i+1)} = P_{ti} - \nabla \text{sgn}(SIR_i - \delta) \quad (4.12)$$

where

$$\text{sgn}(x) = \begin{cases} 1 & \text{if } x \geq 0 \\ -1 & \text{if } x < 0 \end{cases}$$

where δ is the set SINR threshold.

In this study the step size ∇ is chosen as 0.5 dB, and δ is chosen as 15 and 20dB. The change in transmitted power over time (iteration) is observed through simulation (figure 4.2). It is found that the system becomes stable after 150 iterations. This observation is made for a couple of scenarios where the transmitter receiver separation was at maximum i.e 40m under different propagation environments. To be conservative, we therefore select the number of iterations to be 300.

Figure 4.2: Determination of number of iterations for power control

4.4 Performance Evaluation

In this section the system performance is evaluated for various scenarios. The significant effect of a directional antenna on the performance improvement is discussed. Also, we will discuss the performance improvement by using power control. The effect of different propagation environments are also discussed, which mainly include the propagation exponent and the standard deviation of the shadowing component.

4.4.1 Performance Parameters

The performance of the system is evaluated using the mean signal-to-interference-plus-noise ratio (SINR) and the outage probability.

The outage probability is defined as the probability that the SINR is smaller than some threshold. As explained in the beginning of the chapter, this threshold is chosen to be 10 dB for the single interferer and multiple interferer cases without power control. Different values are assumed for the power control cases.

The mean SINR is the averaged SINR over all the possible combinations of device locations, shadowing variations and antenna orientations. In this study, we choose to average the SINR over the decibel domain rather than over the linear domain, since this seems to be a more appropriate measure of performance. Our reasoning is as follows:

- 1) Compared with the absolute-valued SINR, the decibel-valued SINR is of more practical interest. Therefore, the mean of SINR in decibel domain is more indicative.
- 2) For all the physical channels, the bit error rate (BER) is the ultimate measure of performance. Further, the order of BER, or the logarithm of BER, is more of engineering interest. Notice, in most communication channel (with or without coding), the logarithm of BER appears to be approximately linear in decibel valued SINR for the error rate of practical interest, i.e. below 10^{-3} . Thus the decibel-valued SINR is a more appropriate measure of performance in reality.
- 3) Averaging SINR in decibel domain is equivalent to taking the geometric average of SINR in linear domain. Since the geometric average is always less than or equal to the arithmetic average,

the averaging SINR in decibel domain is more conservative than the average in linear domain.

Therefore, for the above stated reasons, the mean SINR is chosen to be the mean of the dB-valued SINR.

4.4.2 Single interferer

Theoretical Analysis

Effect of Interferer

In this section, the system performance is derived analytically. Average SINR and outage probability has already been studied by several researchers [10], [40], [31]. However, all the analysis has been done for cellular structure with isotropic antennas for both mobile and base stations. [3] studied different methods of computing outages and correlated lognormal sum distributions for digital wireless applications. In all of the abovementioned work, the effect of shadowing is considered. Early research suggests shadowing to be statistically independent [10],[40], while later research [3], [31] found it to be correlated.

Our model differs from the previous work in terms of antenna directivity and topology. In our model all of the devices have directional antennas and they are deployed in an ad hoc way without any centralized control. However, we will be following a similar approach, as was used in the abovementioned references, in deriving the statistics of SIR and outage. To be more precise, we will consider the effect of correlated shadowing and outage will be defined in a similar way. The outage was defined as SIR being lower than some threshold. In the following analysis background thermal noise is neglected.

Assume that the receiver is located at $(0,0)$ and the desired transmitter is at $(d,0)$. The interferer is located at $(r\cos\psi, r\sin\psi)$, where r is the distance between the interferer and the receiver. The interferer has its antenna pointing towards $\psi-\theta+\pi$. This topology is shown in figure 4.3.

Assume the transmitter antenna and receiver antenna have the same beam pattern as shown in figure 4.4. Notice in figure 4.4 all the quantities are in dB. A worst case for side lobe is assumed.

It is straight forward that the antenna gain ratio $GR=P_{main}-P_{side}$. Further it is assumed that the interferer and the transmitter transmit at the same power level. With all these assumptions, the signal power S (dB) and the interferer power X (dB) can be determined directly from the log distance path loss model.

$$S = 2P_{main} + K - 10n\log d + \xi_1 \quad (4.13)$$

$$X = P(\psi) + P(\theta) + K - 10n\log r + \xi_2 \quad (4.14)$$

where K is a constant including the transmitted power and the residual parts in the path-loss model, and ξ_1 and ξ_2 are the random variables for the shadowing components along the signal path and the interference path respectively. Since the shadowing on the interference and signal paths are correlated in our model, we can write

$$\xi_1 = m_1 + c$$

$$\xi_2 = m_2 + c$$

where m_1 and m_2 are the path-specific component and c is the location specific component and as assumed in the system model $\sigma_{m_1}^2 = \sigma_{m_2}^2 = \sigma_c^2$. Then the SINR given that r , θ and ψ can be derived as

$$SIR|r, \theta, \psi = 2P_{main} - P(\psi) - P(\theta) + 10n\log(r/d) + z \quad (4.15)$$

where $z = \xi_1 - \xi_2$ is a zero mean Gaussian random variable with $\sigma_z^2 = 2\sigma_c^2$ (due to the independence between random variable m_1 and m_2).

It follows immediately that the expected SINR given r , θ and ψ is

$$E[SIR|r, \theta, \psi] = 2P_{main} - P(\psi) - P(\theta) + 10n\log(r/d) \quad (4.16)$$

Notice from the antenna model, equation 4.15 can readily be rewritten as

Figure 4.3: Model for theoretical analysis

Figure 4.4: Antenna pattern for system model

$$E[SIR|r, \theta, \psi] = \begin{cases} 10n\log(r/d) & |\theta| \leq \Delta/2 \& |\psi| \leq \Delta/2 \\ 10n\log(r/d) + GR & |\theta| \leq \Delta/2 \& |\psi| > \Delta/2 \\ & or \& |\theta| > \Delta/2 \& |\psi| \leq \Delta/2 \\ 10n\log(r/d) + 2GR & |\theta| > \Delta/2 \& |\psi| > \Delta/2 \end{cases} \quad (4.17)$$

The overall expected SIR or the mean SIR is thus given by

$$E[SIR] = \int_{r=0}^R \int_{\theta=0}^{2\pi} \int_{\psi=0}^{2\pi} E[SINR|r, \theta, \psi] f_r(r) f_\theta(\theta) f_\psi(\psi) d\psi d\theta dr \quad (4.18)$$

where $f_r(r)$, $f_\theta(\theta)$ and $f_\psi(\psi)$ are the pdf of r , θ and ψ respectively, and given by

$$f_r(r) = 2r/R^2 \quad 0 \leq r \leq R$$

$$f_\theta(\theta) = 1/2\pi \quad 0 \leq \theta \leq \pi$$

$$f_\psi(\psi) = 1/2\pi \quad 0 \leq \psi \leq \pi$$

Equation 4.18 can then be further expressed as

$$E[SIR] = \int_0^R \frac{2r}{R} \left[\left(\frac{\Delta}{2\pi} \right)^2 \left(10n\log \frac{r}{d} \right) + 2 \left(\frac{\Delta}{2\pi} \right) \left(\frac{2\pi - \Delta}{2\pi} \right) \left(10n\log \frac{r}{d} + GR \right) + \left(\frac{2\pi - \Delta}{2\pi} \right)^2 \left(10n\log \frac{r}{d} + 2GR \right) \right] dr \quad (4.20)$$

Equation 4.20 gives an analytical expression for the mean SIR. In a similar way the probability of outage can be derived as follows:

From equation 4.15 and 4.16, we have

$$SIR|r, \theta, \psi = E[SIR|r, \theta, \psi] + z \quad (4.21)$$

The outage probability is given by

$$Pr_{outage} = Pr[SIR < T]$$

where T is the SIR threshold for outage. It can be rewritten as

$$\begin{aligned} Pr_{outage} &= \int_{\psi=0}^{2\pi} \int_{\theta=0}^{2\pi} \int_{r=0}^R Pr[SIR|r, \theta, \psi < T] f_r(r) f_\theta(\theta) f_\psi(\psi) dr d\psi \\ &= \int_{r=0}^R \frac{2r}{R^2} \left[\left(\frac{\Delta}{2\pi} \right)^2 Q \left(\frac{10n \log(r/d) - T}{\sigma_z} \right) \right. \\ &\quad \left. + 2 \left(\frac{\Delta}{2\pi} \right) \left(\frac{2\pi - \Delta}{2\pi} \right) Q \left(\frac{10n \log(r/d) + GR - T}{\sigma_z} \right) \right. \\ &\quad \left. + \left(\frac{2\pi - \Delta}{2\pi} \right)^2 Q \left(\frac{10n \log(r/d) + 2GR - T}{\sigma_z} \right) \right] dr \end{aligned} \quad (4.23)$$

where $\sigma_z = \sqrt{2}\sigma_c$. In our model, this standard deviation equals that of the total shadowing along a path.

Effect Of Noise

The effect of noise is considered separately. Equation 4.13 for desired signal power can be rewritten as,

$$S = P_t + G_t + G_r + 20 \log \frac{\lambda}{4\pi d_0} + 10n \log \frac{d_0}{d} + \xi_1 \quad (4.24)$$

where P_t is the maximum transmitted power by the desired transmitter, G_t and G_r are the antenna gain of the desired transmitter and receiver respectively, d_0 is the reference distance which is chosen

as 1m for our model, ξ_l is the shadowing component with 0 dB mean and σ_{ξ_l} is the standard deviation and d is the distance between desired transmitter and receiver. The gain values can be calculated by using equation 4.9.

The value of thermal noise was calculated in section 4.2.3 using equation 4.6 and found to be -123 dBW.

Using equations 4.24 and 4.6, signal to noise ratio can easily be found. Since we are interested in the mean/expected value, S/N can be expressed as

$$E[S - N] = \mu - N \quad (4.25)$$

where

$$\mu = P_t + G_t + G_r + 20 \log \frac{\lambda}{4\pi d_0} + 10n \log \frac{d_0}{d}$$

Similarly outage probability can be expressed as

$$Pr[SNR = S - N < T] = Q\left(\frac{\mu - N - T}{\sigma_{\xi_l}}\right) \quad (4.26)$$

Thus, in this section, the system performance for single interferer case has been derived analytically, which is given by equations 4.20, 4.23, 4.25 and 4.26. These results will be compared with the simulation results in the next section.

Comparison of Analytical and Simulation Results

In this section we will present some of the analytical results using equations 4.20, 4.23, 4.25 and 4.26. Average SINR and outage is plotted as a function of interferer's distance from the desired receiver. These results are also compared with the simulations. We will use different parameters to study their impact on the system performance. They include antenna beamwidth, distance of the desired transmitter and propagation exponent.

Figures 4.5 and 4.6 show the results for different antenna beamwidth with all the other parameters fixed. Comparison of figure 4.5 and 4.6 clearly shows a performance improvement as we narrow down the antenna beamwidth from 90° to 30°. For instance with antenna beamwidth

Figure 4.5: System performance with 90° antenna beamwidth, when desired transmitter separation = 10 m, antenna gain ratio = 25 dB, propagation exponent = 4 and shadowing SD = 6 dB

Figure 4.6: System performance with 30° antenna beamwidth, when desired transmitter separation = 10 m, antenna gain ratio = 25 dB, propagation exponent = 4 and shadowing SD = 6 dB

of 30° interferer can be as close as 32m as compared to 45m with 90° beamwidth for an outage of 10^{-3} . This means that the interferer's effect can be mitigated for the closer distances as we narrow down the beamwidth. It can also be seen that a narrow beamwidth can reduce the outage due to noise, because of the increased gain due to narrow beamwidth as can be noted from equation 4.9. Figures 4.5 and 4.6 also show that simulation results are in close agreement with the analytical results. However, since we calculate SIR and SNR separately, we can notice the difference between the simulated and calculated results in Figure 4.5 and 4.6. After a certain distance noise gets dominated and both simulation and analysis match exactly. However, at closer distances simulation has joint effect of noise and interference, whereas analytical results only have the effect of interference which cause the difference between the two. The same effect can be observed in the following results.

The effect of the desired transmitter separation is also studied in figure 4.7 and 4.8. Initially we placed our desired transmitter at 10m from the desired receiver. Later the desired transmitter is moved to 40m and 95m, as shown in figure 4.7 and 4.8 respectively. At 95m separation the outage is fairly high for all the different interferer placements. No matter how narrow the antenna beamwidth and how far the interferer is from the desired receiver, outage remains high. Hence, desired transmitter can not be placed that far from the receiver. However, for 40m of separation an outage of 10^{-3} can be achieved if the interferer is 42m away from the desired receiver. Again inspection of figure 4.7 and 4.8 confirms simulation by analysis.

Finally, figure 4.9 and 4.10 represent the cases with two different propagation exponents of 2 and 3 respectively. It can be noted from the figures 4.9 and 4.10 that the effect of the n depends upon the location of interferer relative to the desired transmitter. When interferer is closer than the desired transmitter a higher n gives a higher outage and vice versa. This is explained in more detail in a later section, where we describe our simulation results under different propagation environments.

In this section we briefly showed the impact of some of the parameters on the system outage and SINR. Also, we showed that simulations are in close agreement with analytical results. The following sections present more detailed simulation results for different parameters.

Figure 4.7: System performance with 95m of desired transmitter separation, when antenna beamwidth = 6° , antenna gain ratio = 25 dB, propagation exponent = 4 and shadowing SD = 6 dB

Figure 4.8: System performance with 40m of desired transmitter separation, when antenna beamwidth = 6° , antenna gain ratio = 25 dB, propagation exponent = 4 and shadowing SD = 6 dB

Figure 4.9: System performance with a propagation exponent of 2, when antenna beamwidth = 6° , antenna gain ratio = 25 dB, desired transmitter separation = 10m, and shadowing SD = 6 dB

Figure 4.10: System performance with a propagation exponent of 3, when antenna beamwidth = 6° , antenna gain ratio = 25 dB, desired transmitter separation = 10m, and shadowing SD = 6 dB

Effect of Antenna Beamwidth

The simulation result shown in figure 4.11 indicates the effect of antenna beamwidth with a fixed gain ratio of 25 dB. It can be seen that at a given desired transmitter receiver separation there is a significant improvement in the system performance as we decrease the antenna beamwidth. Highly directional antennas are not only helpful to avoid most interference, but also can provide very high gain for the reception of the desired signal. Also, it can be observed from the figure 4.11 that noise becomes dominant as the interferer distance increases. Moreover, average SINR saturates at 10-20m, while outage probability (which is more indicative of performance) continues to decrease up to 60m.

Figure 4.11: Effect of antenna beamwidth on the system performance, when desired transmitter separation = 10 m, antenna gain ratio = 25 dB, propagation exponent = 4 and shadowing SD = 6 dB

The outage probability can be estimated by the instances when interferer and desired receiver, both are pointing to each other. Let $Pr(inf.in.rx)$ be the probability of interferer in the beamwidth of receiver and $Pr(rx.in.inf)$ be the probability of receiver in interferer's beamwidth.

Inf_bw and Rx_bw are the interferer's and receiver's beamwidth. The two probabilities are equal and given by

$$Pr(inf_in_rx) = \frac{Rx_bw}{360}$$

$$Pr(rx_in_inf) = \frac{Inf_bw}{360}$$

Therefore, outage probability can be approximated by

$$Pr(outage) \approx Pr(inf_in_rx) \times Pr(rx_in_inf) \quad (4.27)$$

Using equation 4.27 the outage probabilities for 90° and 30° are calculated. For 90° it is found to be $(90/360)^2 = 0.0625$, and for 30° it is equal to 0.00694. These results are in close agreement with figure 4.11, where average SINR and outage are plotted as a function of interferer's distance from the receiver. Let's consider the point at 10m, where interferer and desired transmitter, both have equal separation from the receiver. For isotropic antenna i.e. antenna beamwidth equal to 360°, we have an outage of 100%. For 90° and for 30° it is around 10% and 1% respectively. Therefore performance improves by 10 times by using 90° beamwidth and 100 times by 30° beamwidth. Moreover, for many applications an outage of 10^{-3} or less is required. This outage can be achieved for most of the interference distances by using a 6° beamwidth. Therefore an isotropic antenna may not be suitable for the U-NII band applications, and a directional antenna with smaller beamwidth can give a much better performance.

Another important observation can be made from figure 4.11, for average SINR. After a certain interferer distance the average SINR becomes almost constant. Strictly speaking beyond an interferer distance which is greater than the desired transmitter distance the average SINR remains constant. This is mainly due to the fact that noise becomes the main source of interference as the interferer moves farther and farther. Therefore, if the desired transmitter is quite far, then the directivity of antenna has very little effect on the average SINR. However, antenna gain (and therefore received power) goes up as beamwidth decreases. So, the outage due to noise should go down as beamwidth decreases. This effect is more clear in figure 4.12, where outage is plotted against the antenna beamwidth for different desired transmitter separations.

Figure 4.12: Effect of antenna beamwidth on the system performance, when desired transmitter separation = 25 m, antenna gain ratio = 25 dB, propagation exponent = 4, shadowing SD = 6 dB and interferer is at 10 and 50 m

Effect of Gain Ratio

The gain ratio between the main and side lobe is a crucial parameter in antenna design. From equation 4.10, it can be seen that for a given mainlobe gain, the value of sidelobe can be varied by choosing different gain ratios. The value of main lobe gain is dependent upon the beamwidth, as given by equation 4.9. Therefore by choosing a higher gain ratio we essentially reduce the side lobe value. The simulation results shown in figure 4.13 show the system performance with different antenna gain ratios. The performance improvement can be noted before the desired transmitter separation, which is 25 m in this case. Beyond this point all the gain ratios give the same performance, which is because of the dominant noise effect. This effect can be seen more clearly, when the desired transmitter and receiver are separated by a larger distance. Therefore, if the interferer is closer than the desired transmitter, a higher gain ratio will give a better performance.

In figure 4.14 this effect can be observed more clearly. The effect of gain ratio is observed

Figure 4.13: Effect of antenna gain ratio on the system performance when desired transmitter separation = 25 m, propagation exponent = 4, shadowing SD = 6 dB

Figure 4.14: Effect of antenna gain ratio on the system performance when antenna beamwidth = 6 degrees, propagation exponent = 4, shadowing SD = 6 dB

for two fixed interferer positions, which are 10 and 18 m. Two different transmitter separations at 10 and 95 m have been chosen. The simulation results show less sensitivity to the gain ratio when the interferer is far enough. This is mainly because of the noise effect. However for a desired transmitter distance of 10 m the gain ratio plays important role to mitigate the interference, when the interferer distance is near the transmitter-receiver separation. The value of 25 dB is chosen for the later cases, as was explained in the simulation model.

Effect of desired transmitter-receiver separation

Another important parameter that needs to be investigated is the separation of the desired transmitter from the receiver. This parameter will help to establish the effective range of such systems in the U-NII band. For instance, if we are looking at an outage of 10^{-3} , we can decide how far our interferer should be from the desired receiver for a specific separation. Figure 4.15 gives the result with a beamwidth of 6 degrees, 25 dB antenna gain ratio and a propagation exponent of 4.

Figure 4.15: Effect of desired transmitter separation on the system performance, when antenna beamwidth = 6 degrees, propagation exponent = 4, shadowing SD = 6 dB, gain ratio = 25dB

The simulation result shows that for an outage of 10^{-3} , interferer at distances greater than 9m and 26m respectively can be tolerated when the desired transmitter is at 10 and 25 m. Moreover, it can also be noted that the desired transmitter can not be placed beyond 40m, since otherwise the outage would be very high, even if the interferer is placed at the farthest point. It should be noted that this performance is observed with the smallest value of beamwidth. The performance would be worse if we use larger antenna beamwidth. We can see that beyond 40m, we can not operate the system. Although at this stage, i.e. with single interferer without any power control, we may not conclude accurately about the range of the system. However, we can roughly say that 40m is the maximum range that can be provided in this band for such type (WLAN) of applications. It should be noted that the range of HIPERLAN is also 50 m [15].

Effect of propagation exponent

The sensitivity of propagation exponent has also been studied in this simulation. In our model we have assumed that all the users have same antenna gain. For the single interferer case when no power control is employed and if the shadowing effect and thermal noise are ignored, the SIR will only depend upon the distance between the receiver and transmitter. Let d_{des} be the distance between desired transmitter and receiver, and d_{inf} be the distance between interferer and receiver. Then the SIR is given by

$$S/I = (d_{inf}/d_{des})^n \quad (4.28)$$

As can be seen from equation 4.28, the effect of propagation exponent n depends upon the interference distance from the receiver, since the distance between desired pair is assumed to be fixed. For the case when $d_{inf} > d_{des}$, if n increases from n to $n + \delta$ equation 4.28 will increase for higher δ . Similarly if the interferer is closer then the desired transmitter, i.e $d_{inf} < d_{des}$ an increase in n will reduce the value of SIR. Therefore, we can infer that for a LOS environment i.e with propagation exponent of 2 a non-LOS interferer can be tolerated closer than the desired transmitter.

These results are shown in figure 4.16 where outage is plotted as a function of propagation

exponent for two cases: when interferer is at a distance smaller than the desired transmitter separation and when the interferer is at a distance greater than the desired transmitter separation. It can be noted from the figure 4.16, that when the interferer is closer than the desired transmitter, a higher propagation exponent gives poor results. Whereas, when the interferer is located at a distance greater than the desired transmitter, performance gets improved as the propagation exponent is increased. However, beyond a propagation exponent of 4, the performance starts degrading. This is mainly due to the fact that as the interferer moves farther, the effect of noise dominates the interferer power.

Figure 4.16: Effect of propagation exponent on the system performance, when shadowing SD = 6 dB, gain ratio = 25 dB, transmitter separation = 25 m

[21] found that higher propagation exponent always gives a better performance. The reason for different results here is due to the difference in topology. In [21], the model is a cellular structure, where the interfering and desired mobile, both are communicating with a fixed location base station. The interferers are at a distance greater than the desired subscriber. Whereas, in our

case the location of interferer is variable with respect to the receiver, while the desired transmitter is at a fixed distance. So, depending upon the interference location different propagation exponents give different results. Hence, the impact of propagation exponent in two models is different.

Effect of shadowing standard deviation

The effect of the lognormal shadowing standard deviation is shown in figure 4.17. Although the simulation is done for all the different parameters i.e different transmitter separation, antenna beamwidth, antenna gain ratio and propagation environment, here only one of such case is shown.

It can be noted from the figure 4.17 that as the standard deviation of the lognormal shadowing is increased the system performance starts getting poor. However, the effect on the mean SINR is negligible, because the mean of the shadowing does not change. Another observation is that as the interferer moves farther from the receiver relative to the desired transmitter separation, we can notice a significant variation in the performance. So there is more sensitivity to the standard deviation when the interferer moves farther.

The first parameter of our simulation indicates that the system performance can be improved by using highly directional antennas. Nevertheless, the narrower the beam of the antenna, the more sensitive it is to the lognormal standard deviation. This can be observed in figure 4.18 and 4.19. It can also be seen that when the interferer is farther than the desired transmitter, then different antenna beamwidths show more sensitivity to the lognormal standard deviation.

4.4.3 Multiple interferers without power control

Effect of number of interferers

Figure 4.20 shows the SINR and outage as a function of the number of interferers in the system. As was explained earlier the simulated area for power control case is increased to 300m from 100m to include the boundary effect. Eventually we will be comparing numbers of users in the single interferer case to the multiple interferer case by user density instead. User density may be defined as number of users per unit area. Based on the single interferer's results we choose

Figure 4.17: Effect of lognormal standard deviation on the system performance: antenna beamwidth = 6 degrees, gain ratio = 25 dB, propagation exponent = 4, transmitter separation = 25m

Figure 4.18: Effect of lognormal standard deviation on the system performance: antenna gain ratio = 25 dB, propagation exponent = 4, transmitter separation = 50, interferer location = 25m

our antenna beamwidth and gain ratio to be 6 degrees and 25 dB respectively. These results are plotted under different propagation environments. Although there is a very little impact on the SINR, outage is different for different user densities. The main factor which contributes to outage is the shadowing component.

The result in figure 4.20 shows that an increase in number of interferers degrades outage. For a threshold outage of 10^{-3} , the number of users are different for different propagation environment. For instance, under a propagation environment of 4, we can have maximum of 4 interferers if the acceptable outage probability is 10^{-3} .

Effect of propagation exponent

As can be seen from figure 4.20, different propagation exponents give different results. Propagation exponents of 2 and 3 give similar performance. For an outage of 10^{-3} , we could have a maximum of 6 interferers that can be placed in the system with a propagation exponent of 2 and 3. However, for many applications a propagation exponent of 4 is realistic, and there can be a maximum of 4 users with this propagation exponent. Therefore for a LOS environment we could have 1.5 times more users as compared to the propagation environment with an exponent of 4.

Another observation made from figure 4.20 is that as the propagation exponent increases, the effect of noise becomes dominant. So, no matter how many interferers we add, it is going to give us the same SINR. However, due to the effect of lognormal shadowing the outage is different for different propagation environments. The results for multiple interferers case is different than single interferer case under different propagation exponents, which can be observed by comparing figure 4.16 and 4.20. For single interferer case we observed the outage as a function of distance which gives different results for different interferer locations. Whereas for multiple interferer case this effect is averaged over the all distances and outage is plotted as the function of number of interferers.

Figure 4.19: Effect of lognormal standard deviation on the system performance: antenna gain ratio = 25, propagation exponent = 4, transmitter separation = 25m, interferer location = 10m

Figure 4.20: Effect of number of users on the system performance without power control, when $d=10m$, $SD=6dB$, $bw=6degrees$, $GR=25dB$

Effect of desired transmitter separation

As was seen before, in the case of single interferer case, the desired transmitter separation has the most significant effect on the system performance. This is also true for the multiple interferers case. After looking at the number of users that a system can accommodate with a 10 m desired transmitter-receiver separation, we moved our desired transmitter to 25 and 40 m away from the receiver. Figure 4.21 and 4.22 represent the two cases.

Figure 4.21: Effect of desired transmitter separation on the system performance without power control, when $d=25\text{m}$, $SD=6\text{dB}$, $bw=6\text{degrees}$, $GR=25\text{dB}$

From figure 4.21, we can observe that the number of acceptable interferers drops to 2 from 6 for a propagation exponent of 2. Furthermore, only a single interferer can be accommodated for a propagation exponent of 3. All other propagation exponents give a high outage even for one interferer, although a better outage can be achieved by moving a single interferer far from the desired receiver, as was observed in the single interferer case.

Since all of these results supports a very low number of interferers, we move our desired transmitter a little bit closer than our original model. The simulation was run for a desired

Figure 4.22: Effect of desired transmitter separation on the system performance without power control, when $d=40\text{m}$, $SD=6\text{dB}$, $bw=6\text{degrees}$, $GR=25\text{dB}$

Figure 4.23: Effect of desired transmitter separation on the system performance without power control, when $d=8\text{m}$, $SD=6\text{dB}$, $bw=6\text{degrees}$, $GR=25\text{dB}$

transmitter separation of 8 m. The results are shown in figure 4.23. It can be observed that for a very high propagation exponent, there can be few interferers accommodated for the threshold outage. We can tolerate only two interferers with a propagation exponent of 6. For all the previous cases we could not have any interferers in such a propagation environment. If we compare the number of users when the propagation exponent is 4, with 10 m desired transmitter separation, we can find that by just shifting 2 m we can tolerate 7 interferers as opposed to 4. Hence we can almost tolerate twice the number of interferers in this case. This picture is not completed yet, as we do not consider receivers for the interfering transmitters. They are included in the model with the power control scenario.

4.4.4 Multiple interferers with power control

Limited Power Control with different outage thresholds

The system performance has been observed with a limited power control scenario. In this scenario users are transmitting at a power which is enough to overcome distance dependent path loss and noise power. The simulation has been run for different outage thresholds.

Figure 4.24 gives the results for a limited power control scenario with different outage thresholds. By comparing Figure 4.20 and 4.24, it can be noted that the number of users supported for a given outage remains the same with and without limited power control. For example 4.20 shows that 4 users can be supported for an outage of 10^{-3} for the case of propagation exponent of 4. By inspecting Figure 4.24 we found exactly the same number of users for this outage. This clearly indicates that the limited power control does not have a performance improvement over the case of no power control. These results are observed only for the case when transmitter receiver separation is 10 m. For a larger separation we might have some improvement in the performance even with the limited power control scheme. However in order to get a better performance a more comprehensive power control scheme is required. Therefore power control scheme based on SINR rather than SNR is implemented.

Another observation that can be made from Figure 4.24 is the effect of outage threshold.

Figure 4.24: System performance with limited power control with different outage thresholds when, beamwidth = 6 degrees, SD = 6 dB, propagation exponent = 4, transmitter-receiver separation=10m

The outage threshold in our previous simulation was chosen as 10 dB for all different sets of parameters. After choosing the parameters which give the desired performance we look at the impact of different outage thresholds which directly relates to the modulation schemes. Four different outage thresholds of 10,15,20 and 25 dB are observed. It can be noted that a very high threshold can not give the desired performance. Outage thresholds of 15 and 20 dB can only support up to 1 user. Whereas when outage threshold is reduced to 10 dB we can tolerate up to 4 interferers.

Since we do not assume any modulation scheme, the performance gets worse with an increase in outage threshold. However, as explained in [39], the same bit/symbol error rate can be achieved for different SINR thresholds by employing higher order modulation schemes. For instance a symbol error rate of 10^{-6} can be achieved with a set SINR threshold of 10 dB with BPSK modulation and the same symbol error rate can be achieved by 16-QAM if the SINR threshold is increased to 16 dB.

Different Outage and Power Control Threshold

After observing the impact of SNR based power control, the rest of the simulations are carried out with SINR based power control. Two different Power Control thresholds of 15 and 20 dB, and three outage thresholds of 10, 15 and 17 dB have been studied. As was explained in section 4.3.3 power control threshold is the minimum SINR which each user should have and power is adjusted until that SINR value is achieved. Figure 4.25 gives the result for two different Power Control (PC) thresholds of 15 and 20 dB. Inspection of figure 4.25 shows that if this threshold is increased there is a high outage for the same number of users. This is so because we want to allocate more power to all the users and hence there is more chance to have more users not getting that threshold.

Figure 4.25: Effect of different Power Control thresholds when, beamwidth = 6 degrees, SD = 6 dB, propagation exponent = 4, transmitter-receiver separation=25m

Figure 4.26 shows the results for different outage thresholds with fixed PC threshold of 20 dB. The higher value of PC is chosen so as the higher values of outage threshold can be studied. The system behaves in a similar manner as the case with limited power control case. This means

Figure 4.26: Effect of different outage thresholds with SINR based Power Control when, beamwidth = 6 degrees, SD = 6 dB, propagation exponent = 4, transmitter-receiver separation=25m

that higher outage values should give a poor performance which can be seen in Figure 4.26. It is evident from Figure 4.25 and 4.26 that whenever the either threshold i.e PC or outage goes high the performance gets poor.

Effect of desired transmitter separation

We have observed from the single interferer's results that the desired transmitter separation has the most significant impact on the system performance. Figure 4.27 gives the result for the multiple interferer case with power control for different desired transmitter-receiver separations. The simulation was run with two different assumptions: with the same fixed transmitter receiver separation for all pairs, and with the fixed separation for the desired pair and random separation for the rest of the interfering pairs.

Comparing figure 4.20 and 4.27, we can observe the improvement in terms of number of users that can be supported in the simulated area. However, as explained in the simulation model the radius of the simulation area for power control is increased to 300m from 100m to reduce

Figure 4.27: System performance with different desired transmitter separations with power control when, beamwidth = 6 degrees, SD = 6 dB, propagation exponent = 4

the boundary effect. Therefore, it is more appropriate to look at the user density, which can be defined as number of users per unit area, instead of number of users in an area for fair comparison. From Figure 4.20 we can see that at most 4 users can be allowed for an outage of 10^{-3} , for 100 m radius of area. This translates 127 users at a particular frequency channel used by the desired transmitter-receiver pair in an area of 1km^2 . On the other hand Figure 4.27 gives 707 users per 1km^2 . Therefore, by employing power control capacity is increased 5.5 times. Similar results can be obtained by comparing figure 4.21 and 4.22 with 4.27. Comparison of 4.21 and 4.27 gives an improvement of 4.3 times and 4.22 and 4.27 shows an improvement of 10.6 times. It is important to note that we could not accommodate any interferers when the transmitter's separation was 40m without power control. However, the use of power control allows us to have 3 interferers in the new simulating area. It is interesting to note in figure 4.27 that the impact of power control starts reducing as we move the desired transmitter away from the receiver.

Figure 4.28 shows the case of different separations between the interfering transmitters with their respective receivers. The separation between the interfering transmitters with their respective

Figure 4.28: System performance with fixed and variable separation between the interfering pairs
beamwidth = 6 degrees, SD = 6 dB, propagation exponent = 4

receivers was uniformly distributed between 3 and 40m. This models a more realistic situation. For random separation between the interfering pairs, the performance is improved. However, this effect can be observed for a higher number of users. To make our model more realistic, we then assign the bandwidths randomly which are distributed uniformly between 5 to 100 MHz to the users. As expected the performance gets improved as all the users are assigned random bandwidths. For 200 users, the outage probability drops to 20% from fixed bandwidth to variable bandwidth case. It is important to note that for a lower user density the impact of change in simulation set up is minor.

Distribution of Power

Power statistics have been collected for all the users. Figure 4.29 shows the histogram and cdf for the transmitted power for desired transmitter. It is evident from the figure that this distribution is Gaussian. One interesting point to note is the mean value of the power. It has been found that the mean power does not change very significantly by increasing the number of users. For example

the mean transmitted power with 2 users in the system is -62 dBW, and with 100 users it stays the same. Similarly, standard deviation of the power also has a very little impact as it stays 6 dB for 2 and 100 users respectively. All these values are noted for the 10 m of desired transmitter separation, with 6 degrees of antenna beamwidth and a propagation exponent of 3.

Figure 4.29: CDF of transmitted power when transmitter separation = 10m, beamwidth = 6 degrees, SD = 6 dB, propagation exponent = 3, number of pairs=2

The mean value of the transmitted power changes significantly by varying the desired transmitter distance. Once again it is observed that the most important parameter in our simulations is the separation between transmitter and receiver. Under similar conditions, but with a separation of 25 m, the mean transmitted power for 2 users is found to be -50 dBW. For 100 users, it is -49 dBW. Comparing these values with their respective number of users for 10 m separation, we found that roughly 12 dB more power is required for 25 m separation. However the standard deviation of the power does not change very much for any separation and/or number of users. For 25 m separation, it is 6 dB for 2 and 100 users respectively. It can be noted that the required mean power does change by increasing the number of users in the system, for a larger separation. This change however is very small i.e. 0.5 dB for 25 m separation. Similar results were found for a separation

Figure 4.30: CDF of transmitted power when transmitter separation = 25m, beamwidth = 6 degrees, SD = 6 dB, propagation exponent = 3, number of pairs=2

of 40m, where the required transmitted power has a 3 dB change from 2 to 100 interferers. It has also been observed that the mean transmitted power depends on the propagation environment. The power controlled scenario was simulated under 3 different propagation exponents, which were 2,3 and 4. For a LOS system, the propagation exponent is 2. The average required transmitted power for LOS environment is found to be -72 dBW, whereas for a propagation exponent of 3 and 4 the average transmitted power is -62 and -52 dBW respectively. Therefore, for a perfect LOS environment the average required transmitted power is lower than for the other propagation environments.

Moreover, the observation of minor change in standard deviation of transmitted power under different conditions come from the fact that it is mainly due to the standard deviation of lognormal shadowing. This has been verified by excluding shadowing component from our simulation model and running it with the same parameters. All of these statistics are collected with the same transmitter receiver separation for all the users including desired pair. We have also run the simulations with the variable separation between the interfering pairs and fixed separation between

Number of pairs	separation of transmitter (m)		
	10	25	40
2	-62	-50	-44
50	-62	-49	-43
100	-62	-49	-42

Table 4.4: Average transmitted power (dBW) for different transmitter separations

Number of pairs	Propagation exponent		
	2	3	4
2	-72	-62	-52
50	-72	-62	-52
100	-72	-62	-52

Table 4.5: Average Transmitted Power (dBW) for different propagation exponents and fixed separation of 10m

the desired pair. The CDF of the transmitted power is most likely to be Gaussian with the variable separation case for the desired transmitter, since only shadowing contributes to the distribution of Power.

These results are tabulated in table 4.4 and 4.5. Table 4.4 gives the transmitted power under a propagation exponent of 3, with a beamwidth of 6 degrees for different transmitter receiver separations. Table 4.5 gives the mean value of transmitted power under different propagation environment for a fixed separation of 10 m for different number of pairs. From table 4.5 it is evident that different propagation environment requires different average transmitted powers, which is independent of the number of pairs in the system.

The Kolmogorov-Smirnov Tests

As discussed in [27], there are four steps in the development of a useful model of input data. The first one being the collection of data from the real system of interest. Second to identify a probability distribution, which represent the input process. This identification is made by plotting

histogram of the data. Based on the shape of the distribution and structural knowledge of process, a known distribution is chosen. Third step is to choose the parameters that determine a specific instance of the distribution family. Finally, the chosen distribution is evaluated for goodness-of-fit test. Goodness-of-fit may be evaluated via graphical methods or via statistical tests. The chi-square and Kolmogorov-Smirnov tests are standard goodness-of-fit tests. If the chosen distribution does not pass the test, we have to go back to step 2 and choose a different distribution and repeat the process.

The data is required to be placed in class intervals for chi-square test. By changing the width of interval and grouping data in a different way might give different results. Therefore the power of the test is low. The Kolmogorov-Smirnov test is generally more efficient than the chi square test. There are two different types of Kolmogorov-Smirnov tests : one sample and two samples [32]. One sample test is the goodness-of-fit test and it concerns the agreement between an observed CDF of sample values and a specified continuous distribution. Whereas, the two sample test applies, where agreement between two different distribution has to be made i.e if both distributions are identical.

The one sample/goodness-of-fit test is based on the maximum absolute difference D between the values of the cumulative distribution of a random sample of size n and a specified theoretical distribution. First the observed distribution is plotted. Then the theoretical distribution is plotted above and below $1 - \alpha$. Where α is defined as the chance that the maximum deviation between the cumulative distributions of the population and of the sample exceeds the value d [12]. The value of d can be determined from table A-21 (ref) for a specific number of samples n and the value of $1 - \alpha$.

In our simulation the sample size n is 10^5 . By observing histogram, figure 4.30, the assumption of a lognormal distribution seems to be fair. To perform the KS test, we choose the value of $1 - \alpha$ to be 0.99 i.e. with a confidence of 99% we can say that our distribution is lognormal. The value of d is calculated using table A-21 from [12], which is given by

$$d = 1.63/\sqrt{N}$$

Figure 4.31: Kolmogorov-Smirnov test for the distribution of transmitted power
beamwidth = 6 degrees, SD = 6 dB, propagation exponent = 3, number of pairs=2

The value of d is found to be 0.0052. Figure 4.31 shows the result of KS test for the same parameters which are used to plot figure 4.18. As can be seen that the observed distribution has passed the test and hence the power is distributed lognormally in the system.

Effect of propagation exponent

The effect of propagation exponent is similar for both cases i.e. with and without power control. As before, the performance is more or less same for a propagation exponent of 2 and 3. However, as can be noted by the figure 4.21 that performance degrades roughly by 1.5 times as the propagation exponent is changed to 4. For instance, at an outage of 4×10^{-4} 100 interferers can be accommodated for a propagation exponent of 4, whereas 160 interferers can be allowed for the same outage when the propagation exponent is 2 or 3. This result is also in agreement with the observations for the case of without power control.

The effect of power control can also be observed under different propagation environment. Comparing figures 4.20 and 4.32, we can find a performance improvement of 4 to 5 times. For an

Effect of propagation exponent (n) on the system performance with power control
transmitter separation = 10 m, beamwidth = 6 degrees, SD = 6 dB

Figure 4.32: Effect of propagation exponent

SINR of 10dB there could be 6 and 250 interferers for without and with power control scenarios respectively, for a propagation exponent of 2 and 3. After converting these numbers into the number of *users/km²*, we get 191 and 884 *users/km²* for without and with power control cases respectively. This gives a performance improvement of 4.6 times. Similarly, for propagation exponent of 4, we could have 127 and 707 *users/km²* for without and with power control case respectively. This shows a performance improvement of 5.5 times.

4.4.5 Summary

In this chapter we have derived analytical results and developed simulation models to study the system performance. We have chosen average SINR and outage as our performance parameters. Outage was defined as the probability of SINR being lower than some threshold. We have chosen 10 dB as threshold for this study. The single interferer model was used to choose the parameters

which give results of interest. A Multiple interferer model is finally used to study the impact of directional antenna and power control under different propagation environments.

Some important observations from simulations can be summarized as follows: The use of directional antenna can reduce the interference in the system. We have chosen 6° of beamwidth in the rest of the simulations, after we found it to give the lowest outage probability. The gain ratio of the antenna is also directly related to the system performance. The higher the gain ratio, the more power is concentrated in the main lobe and hence a lower outage. However, we noted that due to the scattering and reflecting effect the actual gain might be lower than the specified gain. So, we choose the lowest value of gain ratio for our simulations, which was 25 dB.

The effect of desired transmitter separation is also studied. We have found 40 m to be the distance beyond which we can not achieve our desired outage. This is also in close agreement with the HIPERLAN range which is 50m as was stated in the previous section. The propagation exponent has a different effect for different interferer's distance relative to the desired user's distance. If it is closer than the desired user, a higher propagation exponent will give higher outage. On the other hand outage would be lower for higher propagation exponents, when the interferer is farther than the desired transmitter. The standard deviation of lognormal correlated shadowing has almost no impact on average SINR, because of its zero mean. However, due to different variance, outage is different and higher for the high values of standard deviation.

For the multiple interferers we observed that power control has improved the system capacity very significantly. SINR based power control scheme is employed in this study. System Capacity is defined as number of users per unit area. We observed 5 to 10 times improvement in system capacity with power control. Also, we found the randomly assigned power to the users follow a normal distribution. It was interesting to note that the average power does not change too much when we increase number of users in the system. However, as we increase the separation between the pairs or change the propagation environment average transmitted power does change.

Therefore, we can conclude that directional antenna and power control are very effective techniques to realize U-NII band applications. All of these results are concluded for a worst case scenario.

Chapter 5

Conclusions and Future Work

5.1 Conclusions

Unlicensed bands can be an inexpensive way of providing wireless services at home, schools and communities. U-NII band is one of such unlicensed bands at 5 GHz. The idea behind its allocation is to build an infrastructure to connect schools and communities through wireless MANs (Metropolitan area networks).

In this thesis we have studied the characteristics of interference in U-NII band by modeling an ad hoc network. Our results applies to a narrow bandwidth system (4.1.1). For a wider bandwidth we would have to scale down the distances. We have found that directional antennas and power control techniques can significantly improve the system performance. The simulation results showed that the outage probability can be reduced significantly by decreasing the beamwidth (4.4.2). The outage can be reduced from 100% to 0.1% by reducing the beamwidth from 360° to 6°. The gain ratio can improve the performance only when interferer is closer than the desired transmitter. Nevertheless, the scattering and reflecting effect of the environment may prevent to realize the specified gain ratio. Therefore, the lowest value of gain ratio was selected which was 25 dB.

We also observed that the desired transmitter separation has most significant effect on the system performance. This effect can be seen for single and multiple interferers case (4.4.3) both.

Also, when we implemented the power control, the required transmitted power changes between 8 to 10 dB for every 15 m of increase in the separation between each pair (4.4.4).

The system is also sensitive to the propagation exponent. However, it depends upon the distance of the interferer relative to the desired transmitter's distance from the receiver for the single interferer case. Our result is different than [21], who found a higher propagation exponent gives always a better result. This difference is due to topology, as in [21] model, the interferer is always at a distance greater than the desired user. Therefore, for our model in a LOS environment i.e. a propagation exponent of 2, interferers can be closer than the desired user. The impact of propagation exponent was different in our multiple interferer model. Inspection of figures 4.22 and 4.32 shows that a higher propagation exponent always give a poor performance. This is because we have assumed the same propagation exponent for all the users. So, when the propagation exponent goes up, signals (of the desired and interferers both) get weaker and the outage is due to the noise. Similarly for small propagation exponents signals become higher and the interference effect dominates over the noise. This causes a higher SINR, which in turn causes a lower outage. We have seen that the system capacity is decreased roughly by 1.5 times when propagation exponent is increased to 4 from 2 or 3 (4.4.4). Therefore, a small propagation exponent is desirable for U-NII applications.

We also incorporated log-normal shadowing in our model. Shadowing was assumed to be correlated with a path specific and a location specific component. We found that for narrow beamwidths and larger desired transmitter separation, the performance is more sensitive to log-normal standard deviation (4.4.2).

System capacity was defined as the number of users per unit area. A SINR based power control technique was used to increase the system capacity. It was found that the capacity can be increased up to 10 times by using power control (4.4.4). Without power control we could have 127 *users/km*². Whereas the number of users can be increased to 707 *users/km*², when power control is applied. This improves the system capacity more than 5 times. Once again the separation between the desired pair is found to be an important parameter as average transmitted power varies significantly with the different separation between the transmitter and receiver pairs

in the multiple interferers model.

Finally, we assigned random bandwidths to all the pairs in system which further improves the capacity by 20% (figure 4.28), when the user density is high enough, in our case it is $200\text{user}/200\text{m}^2$. However, the random bandwidth assignment has very little impact on the system performance for lower user densities.

At this point it is appropriate to mention that our results are conservative because of all users are assumed to transmit all the time. We could have a better performance after we incorporate adaptive modulation and error correction codes and some possible etiquettes, and if bursty packet transmission predominates.

5.2 Future Work Recommendations

In this study we have done some preliminary modeling to see the behavior of interference behavior in an uncoordinated way. Our study is limited by the fact that we did not assume any modulation scheme, coding and multiple access. As a next step various factors need to be included in studying the behavior of such systems. They include the effect of the modulation scheme and adaptive antennas instead of directional antennas. This could be some random frequency hopping scheme, which implies that devices can search for the frequencies that are not being used and have ability to switch to another frequency in case of high interference. Also, coding can provide an increased capacity for such systems. Interference behavior need to be studied for a broad band system, as our results applies to a narrow band system.

We also did not include effect of multipath due to applications of directional antenna with sharp beamwidths. However, there might be still some multipath and neglected delay spread in some critical areas even though highly directional antennas are employed. Furthermore, the effect of scattering and reflection in the environment may also need to be studied in detail, which will determine the exact impact on the gain ratio of the directional antenna.

We have assumed in our case the continuous transmission for all the users. However, this is a worst case scenario. So, future study for the packet transmission is recommended at this

point. This will increase the system capacity and the model would be more practical and real. This model could also be used in determining the packet size, for instance, which could be one of the possible etiquettes. Also gaps can be introduced during the transmission. This will allow receiver to distinguish between desired signal and interfering signal. Also, this might be helpful in implementing power control scheme for such a system.

Besides those above mentioned model specific recommendations, some more general future work recommendations for the U-NII band are as follows: Before deploying the networks or producing the devices, we need to predict the market and products/services to be offered. The demand of these products and/or services need to be forecast for the economical deployment and development of the products. For each of the prominent products and services, we must characterize their potential access protocols, modulation schemes, power levels and coverage areas, likely locations and their usage frequency.

Finally, there is a need to develop new etiquettes and design access protocols for important applications when operating under new etiquettes.

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