INTERFERENCE AWARE WIRELESS NETWORKS WITH POINT TO POINT BEAM FORMING

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MASTER OF SCIENCE

BY

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University of Missouri - Kansas City, 2012

ABSTRACT

Recent dramatic changes in the end-user devices and applications demand the idea of peer-peer packet transmissions without the help of base stations or wire-line backbone networks. This concept of distributed communication systems has quite a few areas of interest, whether it is gaming, emergency response, or for surveying purposes. Network scientists now are more interested in this de-centralized Ad-Hoc Network than the conventional centralized base-station or wire line based communication system. Very little research has been done in simulating the beamforming procedure and actually studying the effects of change in beam width of the antenna pattern and some other antenna parameters. In our work we investigate and build a model that could possibly overcome interference by changing such physical layer parameters and using them to exploit the benefits not only in the physical layer but also in network and medium access layers. In particular we delve into the physical antenna parameters like beamwidth, main lobe gain, and we see how it affects the network capacity. We intend to investigate power calculations around a transceiver and build a model that will provide an estimate of interference severity for medium access purposes. We then use this model to show the enhancement in network efficiency from conventional omnidirectional and directional cases for different main lobe gains. The interference model presented in this study has been simulated in MATLAB and studied extensively for the efficiency and capacity of the network with varying parameters namely beam width, network area, and number of users. With the help of simulations and analysis of the results we conclude that the beamwidth and power calculations play a major role in enhancing the network capacity. The results for our beamforming model show the enhancement in network efficiency from conventional omni-directional and directional cases.

APPROVAL PAGE

The faculty listed below, appointed by the Dean of the School of Computing and Engineering have examined a thesis titled "Interference Aware Wireless Networks with Point to Point Beamforming" presented by Madhav Ram Nusetty, candidate for the Master of Science degree, and certify that in their opinion it is worthy of acceptance.

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CHAPTER 1

1. INTRODUCTION

1.1 Purpose

Recent dramatic changes in end-user devices and applications demand the idea of peer-peer packet transmissions without the help of base stations or wire-line backbone networks. This concept of distributed communication systems has quite a few areas of interest, whether it is gaming, emergency response, or for surveying purposes. Network scientists now are more interested in this de-centralized Ad-Hoc Network than the conventional centralized base-station or wire line based communication system. The applications for such a technology are also increasing; a few such applications can be mentioned here.

Some researchers have the idea of multi-player games that would directly communicate with other mobile devices. Several sensors can be thrown on to the walls of an active volcano to monitor its activity and then each one of them could collectively piece together the information needed to successfully perform their task. The complete failure of the communication infrastructure during Hurricane Katrina in New Orleans, USA could also have been a perfect use for a fly-by (ad-hoc) network, which does not need any infrastructure to set up communication. Every victim of the hurricane had devices, but could not use them to communicate, as everything came down including the cellular network. The devices they had could communicate with other nearby devices to convey information across a wireless ad hoc network. They could not do that either because there was no ad hoc network setup, or there was no software to set up such a fly-by network; no application on their smart phones could call for help or just send their current location. Another example for an ad-hoc environment can be a group of emergency responders sweeping through a burning building for survivors [1].

1.2 Feasibility

Applications of Ad-Hoc networks are more prevalent in the military environment as of now, but as the operating frequency continues to increase in the future; Ad-Hoc networks with beamforming antennas will play a vital role in wireless world. The reason operating frequency plays a vital role is, at the usual 2.4 GHz and a nominal half wavelength spacing, an 8 element cylindrical array will be of a radius which is nearly 8cm, which is too big for current day smart phones and tablets. So as the operating frequency increases like the current 802.11a Wireless LAN’s 5 GHz frequency, the antenna sizes shrink. At 5.8 GHz ISM band the radius of the same cylindrical array comes down to 3.3cm, and at 24 GHz ISM band it will be a tiny 0.8cm. Ad-Hoc networks have always been very feasible to military applications mainly because of the significantly large nodes (such as war-tanks, aircrafts or heavy road vehicles). Each of these nodes is by themselves very expensive so that the cost of even the most complex and efficient antenna is dwarfed. [4]

1.3 Ad-Hoc Networks and Beamforming

The study of Ad-Hoc networks has been going on for quite some time now, and there are different ways and schemes in which they are setup and run. One such distinction in the way they are setup is the antenna type that is used, that is; either an Omni-directional antenna being used or instead a directional antenna being used. While each kind of antenna has its own advantages and disadvantages, directional antennas enjoy some important merits of increased signal quality (beamforming), reduced interference (null steering), spectral re-use (spatial multiple reuse) and robustness to multipath fading (spatial diversity) [2]. Using directional antennas, interference to other communicating pairs can be significantly reduced thus efficiently using the wireless medium and as a result we have better network performance. Also the basic concept of focusing all the energy in the required direction helps in increased communication ranges for the same amount of power, and also decreasing the interference because of the non-spread out beams. [3]

We consider the applicability of such directional beamforming antennas, which can steer or point one or multiple beams towards an intended direction. Such an intelligent or smart antenna should possess enough sophistication to have more control on the elements of the antenna to provide increased gain, more beams and beam agility. There are two ways in which this can be achieved. The first approach is to shift the phase of each element's signal by a set amount so that multiple stationary beams can be formed. The transceiver can then choose to select the beam which has the qualities that it desires. This is known as a switched beam system. These systems show an increase in spatial re-use; tracking moving nodes will be difficult which will result in periods of lower gain when the transceiver moves between beams.

The second way the control over antenna elements is obtained is known as a steered beam system. The main beam in these systems can be pointed in any desired direction, which is usually found automatically by latest sophisticated signal processing algorithms by estimating the "direction of arrival". The steering in steered beam systems is automatically and adaptively done. For this reason these systems are known as smart antennas. Smart antennas are composed of a collection of more than two antennas working in unison to radiate energy in a unique pattern. The synchronous group of antenna elements is known as an array of antennas. We can further classify steered beam systems into dynamic phased arrays and adaptive arrays. Dynamic arrays maximize the main lobe gain, while adaptive arrays go a step further and minimize the gain in unintended or interference prone directions i.e., basically creating nulls towards interfering sources. In this paper we use the terms beamforming antenna or smart antenna in a loose way to refer to steered beam antenna systems or in particular adaptive antenna arrays.

1.4 Scope and Outline

Usually the benefits of beamforming antennas are relevant to the physical layer, where the beamforming parameters and information can be exploited. However, we do not intend to study just the physical layer benefits but also investigate the benefits of beamforming for the network and medium access layer. In particular we delve into the physical antenna parameters like beamwidth, main lobe gain and see how they affect bandwidth efficiency. We intend to investigate the power calculations around a transceiver and build a model that will provide an estimate of interference severity for medium access purposes. We then use this model to show the enhancement in network efficiency from conventional omnidirectional cases for different main lobe gains.

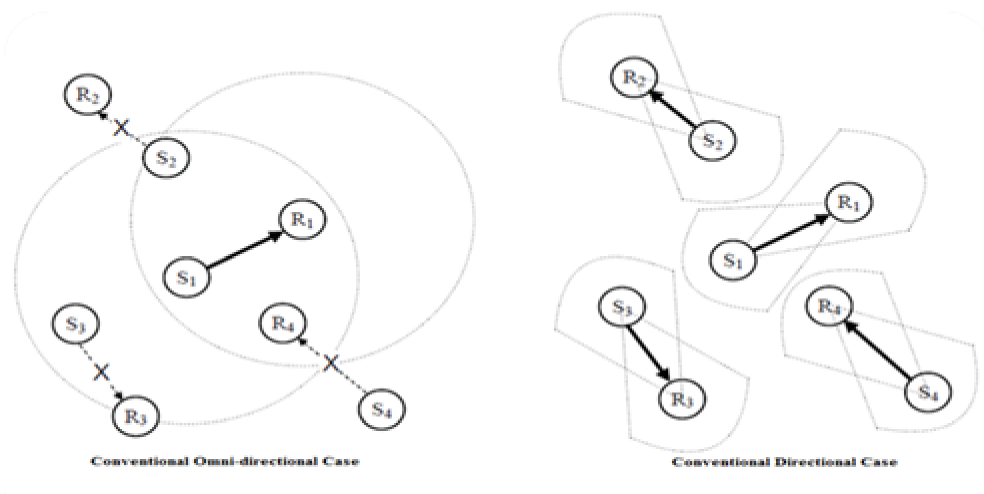


Figure 1.1 Conventional models based on directionality of antennas

Figure 1.2 Our proposed directional model

CHAPTER 2
2. BEAMFORMING

2.1 Antenna Basics, Types and Patterns

An antenna is basically used to couple electromagnetic energy from one medium to another. Traditionally a simple dipole antenna is used to couple the electromagnetic energy into the space surround it in all directions, so they are known as omni directional antennas. So the area into which the electromagnetic energy is spread will be represented as a plot or a function and called an antenna pattern. Thus this pattern describes the directional aspects of that antenna and has two different names depending upon which function it depends on. If the pattern depends upon the function that describes the electrical and magnetic fields, then it is known as field pattern. If it is based upon the radiation intensity function (which can be viewed as a distance normalized power density), then it is called a power pattern. If the pattern is not a result of functional description, but of antenna measurements then the measured pattern may be called as a field pattern or as a power pattern. In Figure 2.1 the field pattern plot is shown in both rectangular and polar co-ordinates. Beamwidth is that area of an antenna pattern where most of the energy is concentrated. Beamwidth of an antenna is defined as the angle between the half power points of an antenna power pattern. The half power points are the same as 3-dB points for a power pattern. Irrespective of whether an antenna pattern is based upon the fields or on the power, the beamwidth is defined as the angle between the points where the value of energy is 3-dB less than the maximum. The ability of an antenna to radiate energy in a preferred direction is known as directivity and this directivity does not account for the various losses in an antenna. So the term used to describe directivity which accounts for various antenna inefficiencies is the antenna gain.

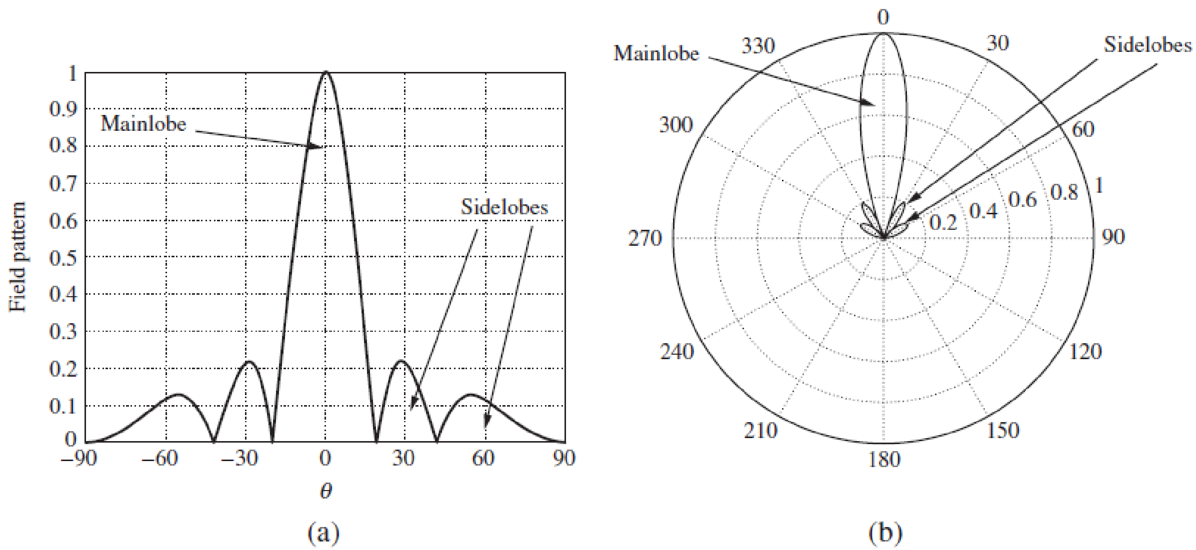


Figure 2.1: (a) Field pattern plot in Rectangular coordinates. (b) Field Pattern plot in Polar coordinates [13]

An antenna can not only radiate/transmit energy in various preferred directions but also receive energy from the same preferred directions. The principle which makes this possible is reciprocity. If an antenna radiates a power with density P_t then a corresponding receiving antenna will receive a portion of the radiated power, which is P_r. Harald Friis devised a formula relating P_t and P_r which is known as the Friis Transmission Formula. It is given as follows

$$P_r = \frac{P_t\, G_t G_r}{L_p}$$

Where G_t is the gain of the transmit antenna, G_r is the gain of the receive antenna and L_p is the loss of energy between the transmitting and receiving antennas, which is termed as Path Loss. We use this Friis Transmission Formula to calculate the transmit power and the interference area caused by the side lobe. Now we turn to how these antenna terminologies and principles can be used to Ad-Hoc networks.

In Section 1.3 we have defined the antenna arrays, now continuing further, an array of antennas can take any geometric form like a linear array or a circular array. The simplest is a linear array. All elements are arranged in a straight line fashion and usually have a uniform inter-element spacing. There are a few modes of operation for linear arrays.

2.2 Related Work

There has been an increasing interest in the study and development of ad-hoc networks with beamforming and smart antennas. This recent interest has also driven research into modeling the interference between individual connections; thus creating systems that are self-aware and can function with minimal network resources and infrastructure [6]. There has been significant research into the several network functions in ad-hoc networks like medium access control [7], routing [8], [9] and topology control [10]. There are a few systems and algorithms designed to meet the severe restrictions on computational capability and energy consumption in mobile ad hoc networks. In [6] the authors present a comprehensive survey of interference models for wireless ad hoc networks which focus on the study of the effects of interference on the physical layer and also the higher layers. In [11] authors design a bi-directional beamforming system that improves the capacity performance in pair wise two-way communication through bi-directional use of spatial resources. Then they compare it with non- bidirectional beamforming systems and successfully show that the achievable sum rate scales twice as fast as that when conventional beamforming is employed. Very little research has been done in simulating the beamforming procedure, calculating the power around a transceiver to determine the interference severity and actually studying the effects of change in beamwidth of the antenna pattern. The work in [4] goes as far as using beamforming antennas for ad-hoc networks to investigate the improvement in network throughput and delay by varying main lobe gain (and as a result beamwidth and side lobe gain) and network density. In our work we intend to investigate the power calculations around a transceiver and build a model that will provide an estimate of interference severity to help decision making for medium access. We then use this model to show the enhancement in network efficiency from conventional omnidirectional and directional cases.

CHAPTER 3
3. NETWORK MODEL

3.1 Assumptions

Our simulation considers a network over an area where the maximum distance between any two points is 3km., and the nodes (starting from 20 in number to 100) are randomly placed. Each node is equipped with a beamforming antenna which can communicate with any of the other nodes in the network. So the model is basically a single hop point to point communication. Figure 3.2 shows a sample network with 40 nodes in the network.

We assume that one central node is constantly aware of the instantaneous position of all other nodes in the network and it periodically updates all nodes. We assume each node is always greedy for channel access, i.e. it always has information to send. A few values that are essential in link budget and antenna pattern approximation have been assumed negligible irrespective of the RF propagation medium. Along with these assumptions there is one other assumption that is made regarding the pattern of the antenna which will be discussed in the next section. These assumptions are quite feasible to be achieved with the current day advances in the fields of antenna design and signal processing.

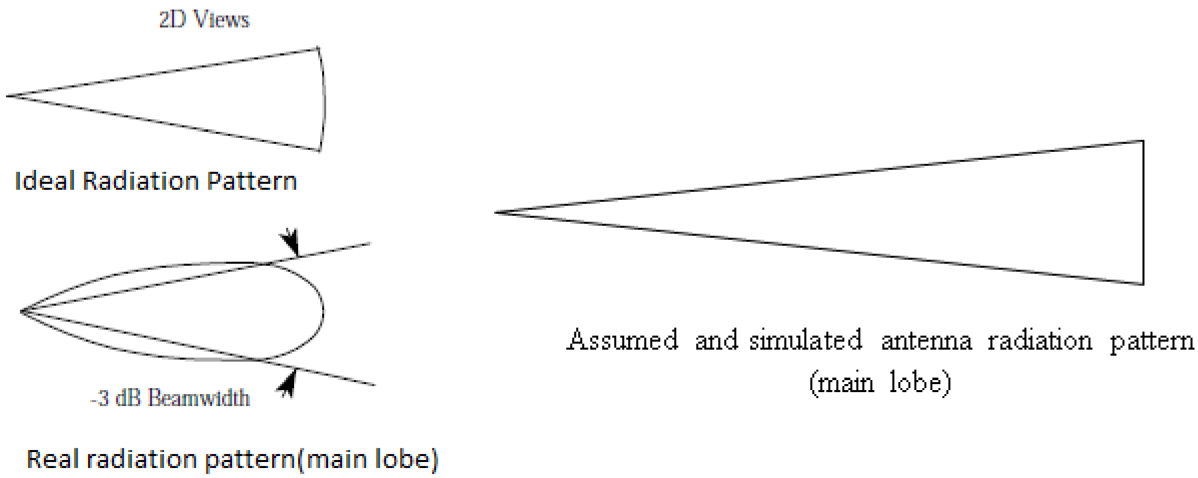


Figure 3.1 Antenna Patterns (in 2-D) along with simulated and assumed patterns

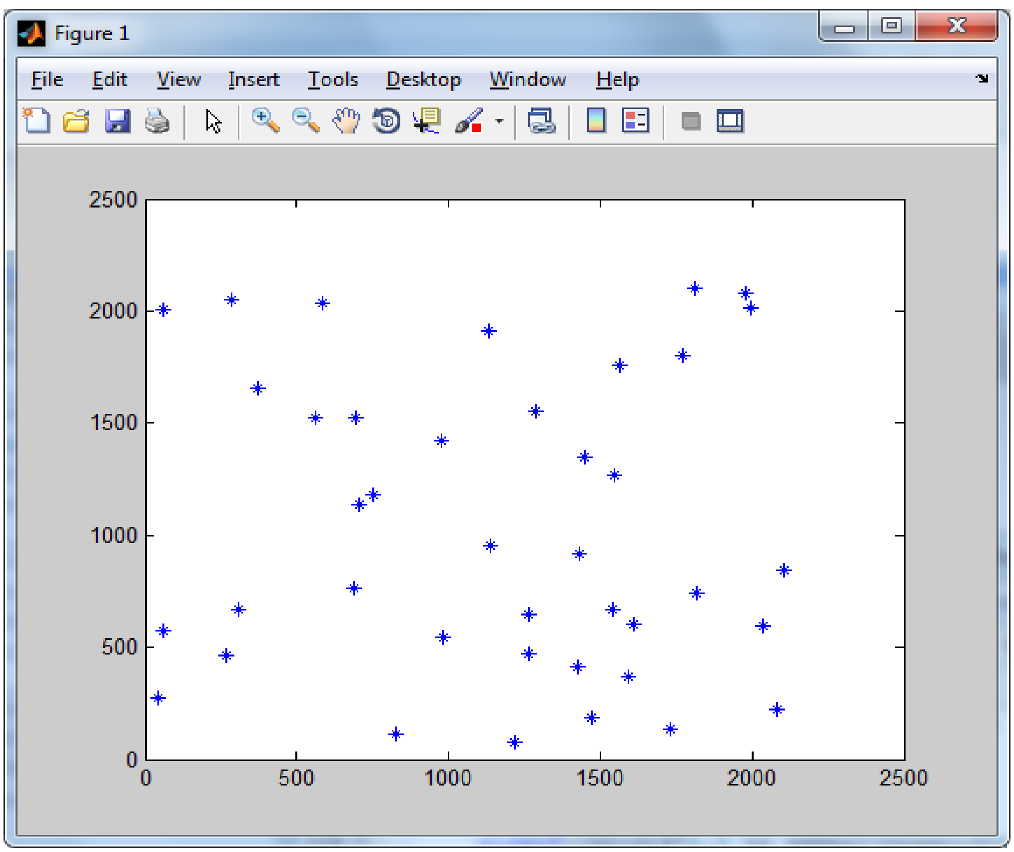


Figure 3.2: Showing randomly placed 40 nodes in the network

3.2 Pattern Simulation

The energy radiated from an antenna is characterized by the antenna's radiation pattern. This pattern shows how energy is radiated in to space. Any antenna pattern has some portions of it known as lobes. So main lobe, side lobe and back lobe are the terms used to refer to a particular part of the antenna pattern. For example, in the main lobe shown in Figure 3.1, locations inside the beam have a power greater than ½ of the maximum and locations outside do not. A lobe can also be treated as a part of the pattern that meets certain conditions based on our requirements. For example, a main lobe is the one where most of the energy radiates from. Side lobes and back lobes are the parts of an antenna pattern through which energy leakage occurs.

Figure 3.1 shows how we have approximated the shape of the main lobe as a wedge. Our simulation also approximates the side and back lobe regions to be a circle around the transmitting and receiving antennas. This circle, i.e. its radius is calculated using mathematical analysis based on the required Signal to Interference Ratio (SIR) levels and the Friis transmission equation. This assumption can be justified further; the region around the transceiver where the nulls (or zero interference areas) can be found is very negligible, so we consider those areas to be interference prone areas. Figure 3.3 shows radiation patterns of some practical antennas, and how we can generalize the patterns to the one that is being simulated in this work.

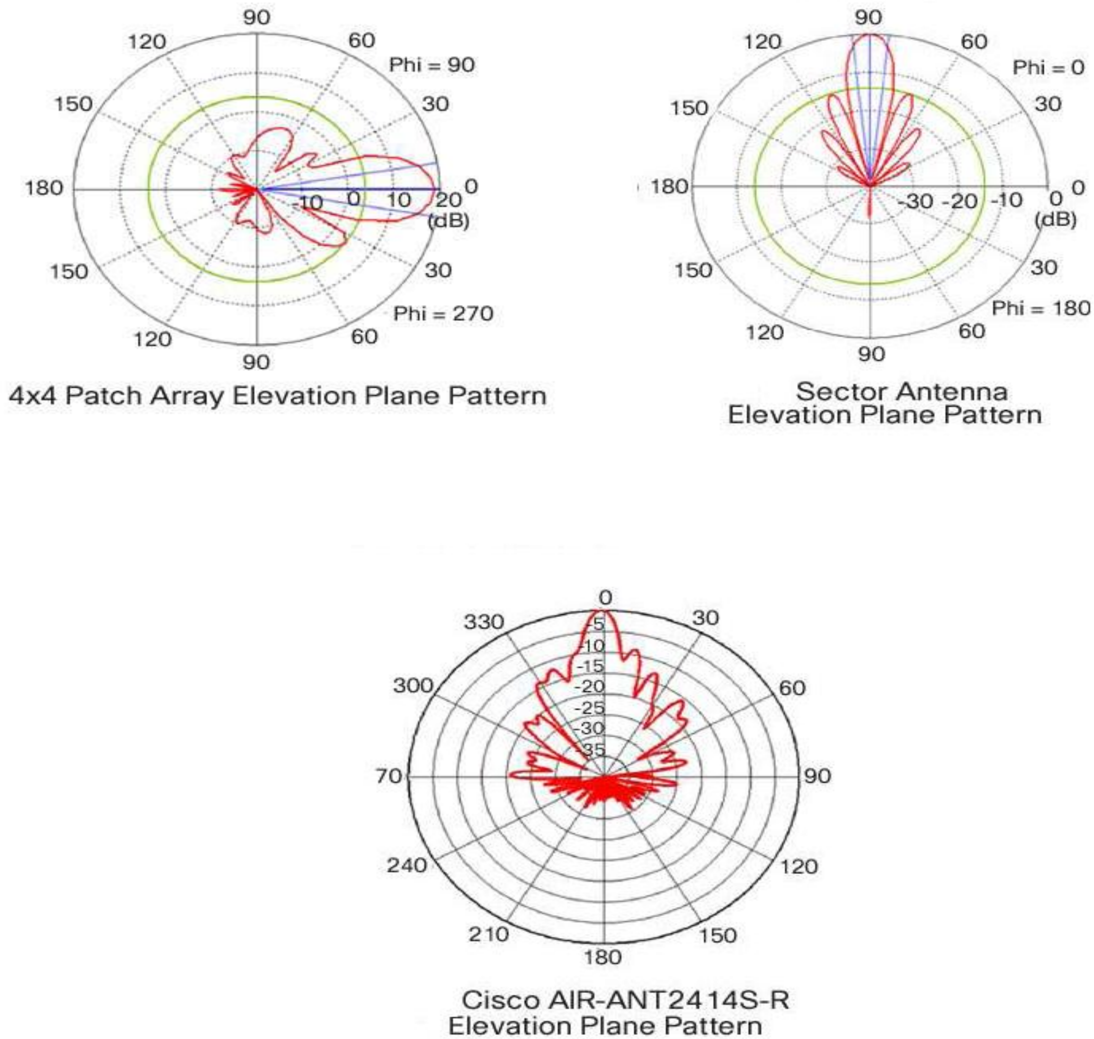


Figure 3.3: Sample practical patterns showing the main lobe and side lobes of some advanced antenna designs.

CHAPTER 4

4. INTERFERENCE MODEL

4.1 Power Calculations

To explain the interference constraints and the way to simulate them, we need to describe the interference model and the power calculations in closer detail. The desired numbers of nodes are created and randomly scattered all over the network area. We then create source-destination pairs randomly from the already created network of nodes and arrange them in a single row. We then calculate the distances between the source-destination pairs, and also the ‘danger distances’ for each link, which are basically the regions around the transceiver that are considered too close to the transceiver, because any node that is so close to another transceiver is bound to interfere with its communication irrespective of the direction in which they radiate. This danger distance is due to the minor or side lobe energy that is leaked to or received from the area around a transceiver.

When an interferer is pointed away from the nodes in the communication between a different pair of nodes, there are two kinds of this danger distance depending upon the location of the interferer. If the interfering node is in the side lobe of the transceiver, then this distance is small since the gain in the side lobe is very low compared to main lobe. This danger distance, even though small, cannot be neglected as it may pose a serious problem for an efficient communication. We denote this danger distance as some factor of the distance between the transmitter and receiver. We use the variable ‘*ddfactor*’ for this side lobe based danger distance. The second kind of danger distance is when the interfering node is inside the main lobe of the transceiver that is being considered. This is different from the side lobe danger distance that we just discussed about because the main lobe gain is much higher, and therefore this danger distance is much greater than the side lobe danger distance. (For example, if main lobe gain is 25dB, then the calculated side lobe gain is -5dB.) We use the variable '*ddfactor1*' for this main lobe based danger distance. Now let us see the derivations for obtaining formulae for these danger distances. For that we need to assume a few parameters based on the current day values, such as receiver sensitivity, wavelength, path loss exponent and signal to interference and noise ratio (SINR).

As we discussed in section 3.2, the assumed antenna pattern in 2 dimensions is shown in Figure 3.1. In the Figure 4.1 we can better understand the assumed pattern in 3 dimensions. The work done in [4] has already derived the formulae for the beamwidth and side lobe gain for this assumed antenna pattern. The main lobe is assumed to be a cone with uniform gain 'gtm', beamwidth 'BW' and its apex at the center of the sphere shown. The sphere is basically the assumed side lobe of the antenna pattern with beamwidth (2π-BW) and gain 'gts'.

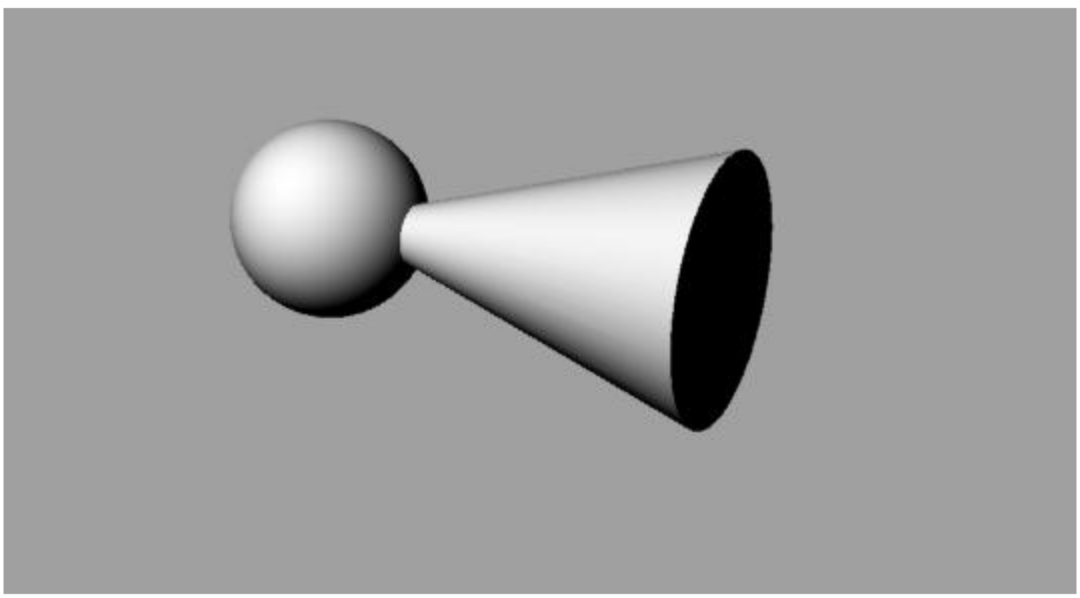


Figure 4.1: Assumed Antenna Pattern showing all three dimensions.

The total energy according to law of conservation of energy is always constant. So for a given main lobe gain, there should be a limit on BW, because no antenna is perfect and every antenna leaks some energy through its side lobes, which here is the sphere with a gain 'gts'. Let us say this limit on BW is BW_{max}. For a given main lobe gain the power density leaving the sphere through the cone's beamwidth BW_{max} is basically the ratio of total transmit power to the surface area on the sphere for a beamwidth of BW_{max}. Let us assume the radius of sphere is 'R'. This surface area on the sphere through which the cone or main lobe radiates is approximated as a circle with radius $R*\tan(BW_{max}/2)$ as shown in the Figure 4.2 below. Similarly the power density leaving through the whole sphere is the ratio of transmit power to the surface area of the sphere. Gain through the main lobe is the ratio of power density through the main lobe to the power density through the surface area of the sphere. $\pi R^{2\,*} \tan^2(BW_{max}/2)$

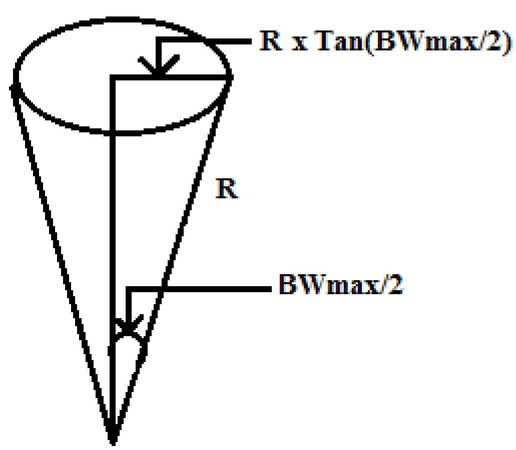


Figure 4.2: Figure showing the main lobe radiating through a surface on the sphere.

We use the variable 'P_t' for the transmit power. Thus from the above discussion we have

$$g_{tm} = \frac{P_t/\pi(r^2 tan^2(\frac{BWmax}{2}))}{P_t/4\pi(r^2)}$$

$$BWmax = 2tan^{-1}(\sqrt{\frac{4}{g_{tm}}})$$

Now we have to choose a 'BW' that is less than BW_{max} , so that the difference is leaked through the side lobes. We chose a value that is a multiple of five that is less than BW_{max} purely for rounding off to practical integer numbers.

Similarly 'gts' using the same principle of conservation of energy discussed in [4] is given as,

$$eta*P_t = g_{tm}(P_t/4\pi(r^2))(\pi(r^2 tan^2(\frac{BW}{2}))$$

$$+ g_{ts}(Pt/4\pi(r^2))(4\pi(r^2) - \pi(r^2 tan^2(\frac{BW}{2})))$$

$$g_{ts} = \frac{eta\left(\frac{4}{tan^2(\frac{BW}{2})}\right) - g_{tm}}{\frac{4}{tan^2(\frac{BW}{2})} - 1}$$

Here eta is the efficiency of the antenna. For a given 'g_{tm}' now we can calculate beamwidth BW and also a feasible and practical approximate of 'g_{ts}'. These 'g_{tm}' and 'g_{ts}' are transmit main and side lobe gains respectively. Similarly receiving main and side lobe gains as 'g_{rm}' and 'g_{rs}'

Now for assumed values of minimum required power P_{req}, wavelength 'lambda', pathloss 'L', path loss exponent 'n =4' we calculate values of beam width and side lobe gain 'g_{ts}' for each value of main lobe gain 'g_{tm}'. The path loss exponent is chosen depending upon the kind of environment the antennas radiate in. Path loss exponent is approximated to be 4 for sub-urban environments. We explore 4 different possibilities of interference when a node is around another on-going communication.

Let us assume 4 nodes or 2 pairs of connections, AB and CD. Node A and node B are communicating with each other, node C is closer to A and C is communicating with D. Transmit main lobe gain for connection AB is denoted as g_{tmAB}, similarly for receive side lobe gain for AB is denoted as g_{rsAB}. So the above said 4 possibilities are

1. Main lobe of node A towards node B (g_{tmAB}) is facing towards the main lobe of node C intended towards node D (g_{rmCD}).
2. Main lobe of node A towards node B (g_{tmAB}) is facing towards the side lobe of node C (g_{rsCD}).
3. Side lobe of node A (g_{tsAB}) is pointed towards the main lobe of node C towards node D (g_{rmCD}).
4. Side lobe of node A (g_{tsAB}) is pointed towards the side lobe of node C (g_{rsCD}).

We use receiving gain accordingly because either node is receiving power, which is basically interference to them. Now we see each possibility and decide on whether or not a node should be given medium access.

Recall some of the variables mentioned thus far and are to be used, which are already assumed or calculated:

- 'P_{req}' is the minimum required power at the receiving end of any communication.
- Wavelength – 'lambda' is the wavelength of the transmission or reception
- Losses during transmission – 'L'
- Path loss exponent – 'n'

- Distance between nodes – ‘d’

Recalling the Friis Transmission equation, assuming node A is transmitting to node B and node C is in the vicinity of node A.

$$\mathrm{P_{req}} = \frac{\mathrm{P_{tAB}}\ g_{tmAB}\ g_{rmAB}}{d_{AB}^{n}\ K}$$

$$\mathrm{P_{tAB}} = \frac{\mathrm{P_{req}}\ d_{AB}^{n}\ K}{g_{tmAB}\ g_{rmAB}}$$

Where,

$$K = \frac{(lambda)^2}{(4\pi)^2 L}$$

Now consider the four possibilities:

<u>Possibility 1</u>:

In this case since both the interferer and transmitter are pointing towards each other, we cannot allow both the connections to go through at the same time without causing severe interference. So we do not give medium access to both pairs at the same time.

<u>Possibility 2</u>:

Interfering Power received at node C through its side lobe from node A’s main lobe is,

$$P_{rAC} = \frac{P_{tAB} g_{tmAB} g_{rsCD}}{\mathrm{d}_{\mathrm{AC}}^{n}}\ C$$

Now after replacing $\mathrm{P_{tAB}}$ with the equation we wrote above for the communication between node A and node B we get,

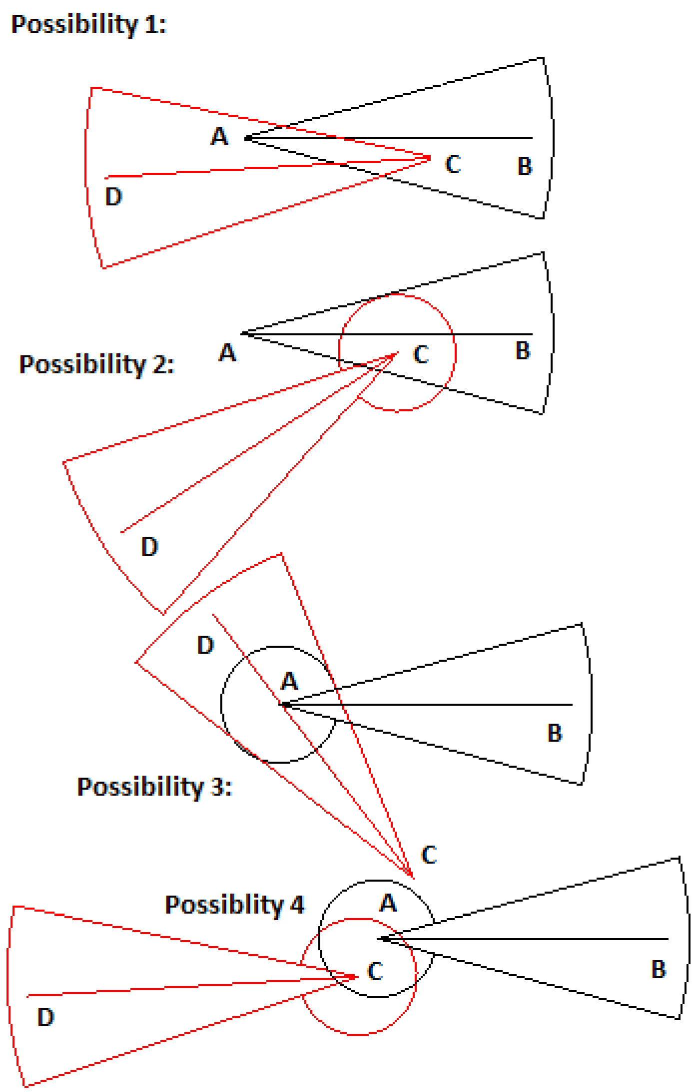


Figure 4.3: Showing the four possible cases for interference

$$P_{rAC} = \frac{\mathrm{P_{req}}\, d_{AB}^{n}\, g_{rsCD}}{\mathrm{d_{AC}^{n}}\, g_{rmAB}}$$

$$\frac{P_{req}}{P_{rAC}} = \left(\frac{d_{AC}}{d_{AB}}\right)^{n} \frac{g_{rmAB}}{g_{rsCD}}$$

Here the ratio to the left is nothing but the Signal to Interference Ratio (SIR), if we assume that all the nodes have the same minimum required power P_{req}.

So if we need our required signal at any receiver to be ten times that of the interference present, then SIR is 10 or in decibels 10dB. So,

$$d_{AC} < d_{AB} \sqrt[n]{SIR \ \frac{g_{rsCD}}{g_{rmAB}}}$$

Earlier in this section we have defined the danger distance, so '*ddfactor1*' the danger distance factor in the main lobe of the transceiver, is the nothing but,

$$\sqrt[n]{SIR \ \frac{g_{rsCD}}{g_{rmAB}}}$$

We have assumed SIR to be 10, and we calculated g_{rsCD} for a assumed main lobe gain g_{rmAB} earlier in this section. And the path loss exponent for the radio channel is 4 for semi-urban environments. So we now we have a formula for the danger distance for an interferer in the main lobe of any transceiver.

<u>Possibility 3</u>:

In this case the main lobe of node C is pointed towards side lobe node A, which is similar to the case 2 that is, main lobe of node A is pointed towards side lobe of node C. The power calculations in this case will be the same as the case above; and we will get to the below result,

$$d_{AB} < d_{AC} \sqrt[n]{SIR \ \frac{g_{rsAB}}{g_{rmCD}}}$$

Possibility 4:

Here, an interfering node is present in the side lobe of another node. So it is a case where nodes are so close to each other that they cause serious interference to each other. But how close is too close? We now find an expression to find that factor of the distance between the nodes, which is considered to be too close to any node. This is as per our earlier discussion in this section names as '*ddfactor*'.

$$P_{rAC} = \frac{P_{tAB}\, g_{tsAB}\, g_{rsCD}}{\mathrm{d}_{\mathrm{AC}}^{n}}\ C$$

Now after replacing P_{tAB} with the equation we wrote above for the communication between node A and node B we get,

$$\frac{P_{req}}{P_{rAC}} = \left(\frac{d_{AC}}{d_{AB}}\right)^{n} \frac{g_{rmAB}\, g_{tmAB}}{g_{rsCD}\, g_{tsAB}}$$

$$SIR = \left(\frac{d_{AC}}{d_{AB}}\right)^{n} \frac{g_{rmAB}\, g_{tmAB}}{g_{rsCD}\, g_{tsAB}}$$

And thus,

$$d_{AC} < d_{AB}\ \sqrt[n]{SIR\ \frac{g_{rsCD}\, g_{tsAB}}{g_{rmAB}\, g_{tmAB}}}$$

This distance is should usually be very small around the transmitter as the side lobes do not extend far away from a transceiver. So now we have '*ddfactor*'.

Now that we have covered all four cases to decide on the interference severity around a transceiver and we also have expressions for the danger distances around a transceiver, we can go ahead in to using this interference model to make medium access decisions.

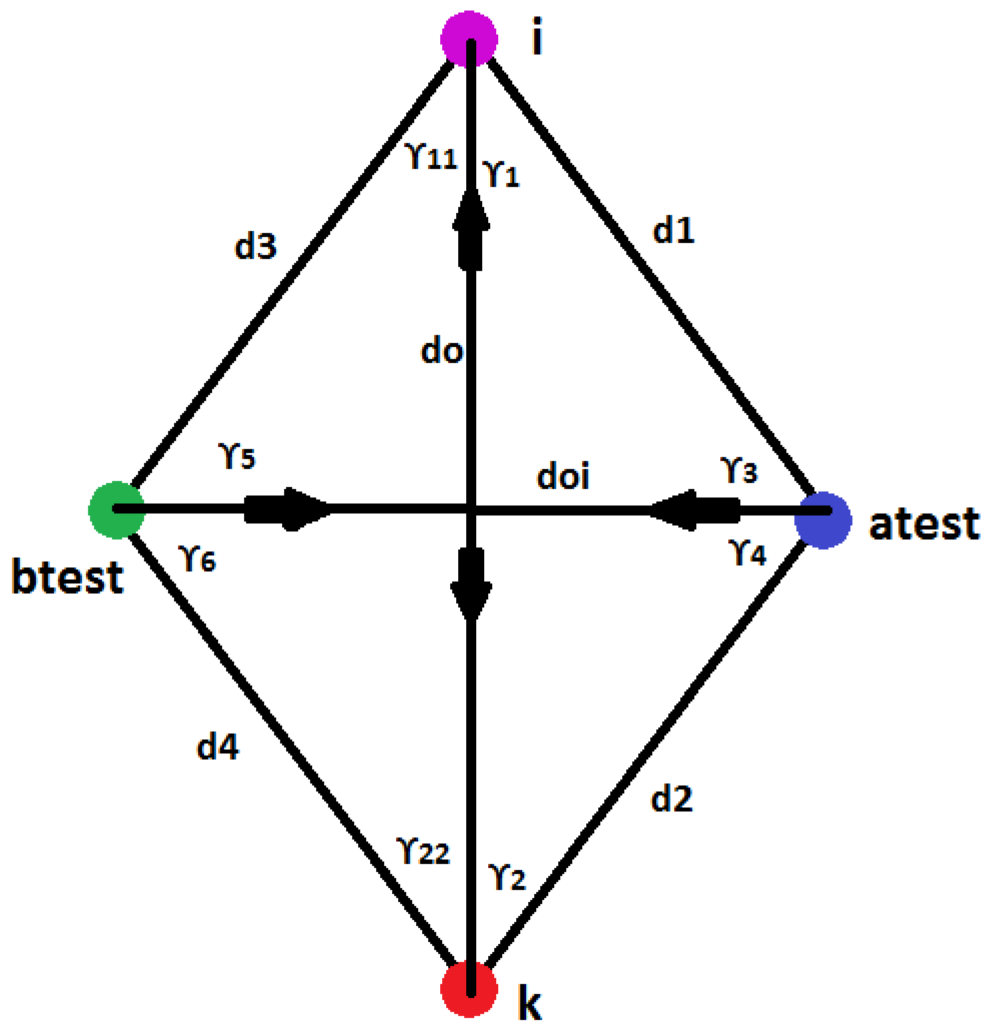


Figure 4.4: The node pair i-k and node pair that is being tested atest-btest with the distances and angles between them.

The desired numbers of nodes are created and randomly scattered all over the network area. We then create source-destination pairs randomly from the already created network of nodes and arrange them in a single row. Then starting with one connection as a reference, we go through all the previously allowed connections to decide on which connections can go along with this reference connection in the same time slot. After that we go through the other connections in the network as well. We decide whether a given connection in the network is interfering with the reference connection of the loop. The interference constraints can be explained with the help of Figure 4.4 above. The node pair i-k is considered to be the reference pair for the loop, and the node pair atest - btest is tested using various constraints on being a potential interferer. The constraint can be put in words in one or two simple sentences, but to simulate it, we will need a group of conditions. Since the position of all the nodes is assumed to be known accurately, all the distances can be calculated easily. All the angles included in the Figure 4.4 are calculated using the law of cosines. At the end when all of the connections that are good to go through the same timeslot without interfering are sent in a timeslot and the ones that fail to go in that timeslot are shuffled to the top of the queue and they may end up being accepted before the other connections in the next time slot.

4.2 Model Validation

Now that we have an interference model, a medium access process in place, we simulate these into a complete network model, we now analyze our model and the simulation based on the plots we make and the decisions we take for medium access. The following plots show the various interference conditions that need to be tested to verify the accuracy of the simulation and thus our model in total.

Figure 4.5 shows one of the causes for interference, when the nodes are too close to each other. This should be treated as serious interference even though they are not facing each other. The nodes are within the danger distance (corresponding to '*ddfactor*') of each other and are, hence, in each other's side lobes.

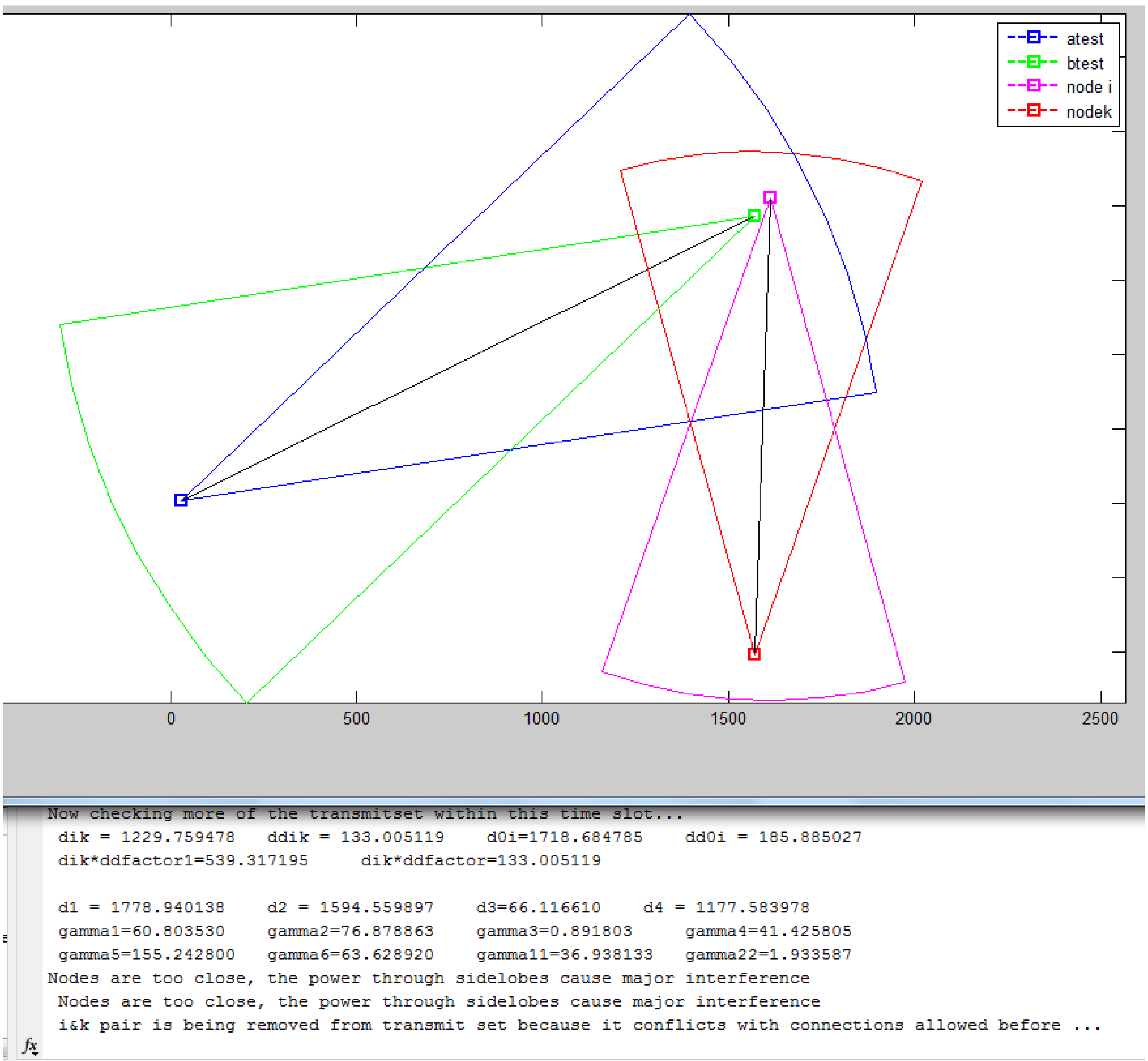


Figure 4.5: Showing nodes too close to each other being removed from current time slot.

As you can see in the values printed at the bottom of Figure 4.5, d1 through d4 are distances between nodes and distance ‘d3’ is less than the danger distance ‘dd0i’ and also the danger distance for the i-k pair, ‘ddik’. This shows that the simulation has worked fine in this case. Figure 4.6 shows a case where a node is inside the main lobe of a transceiver and the power received through the side lobes is causing severe interference to the node k. So both the pairs cannot communicate in the same timeslot.

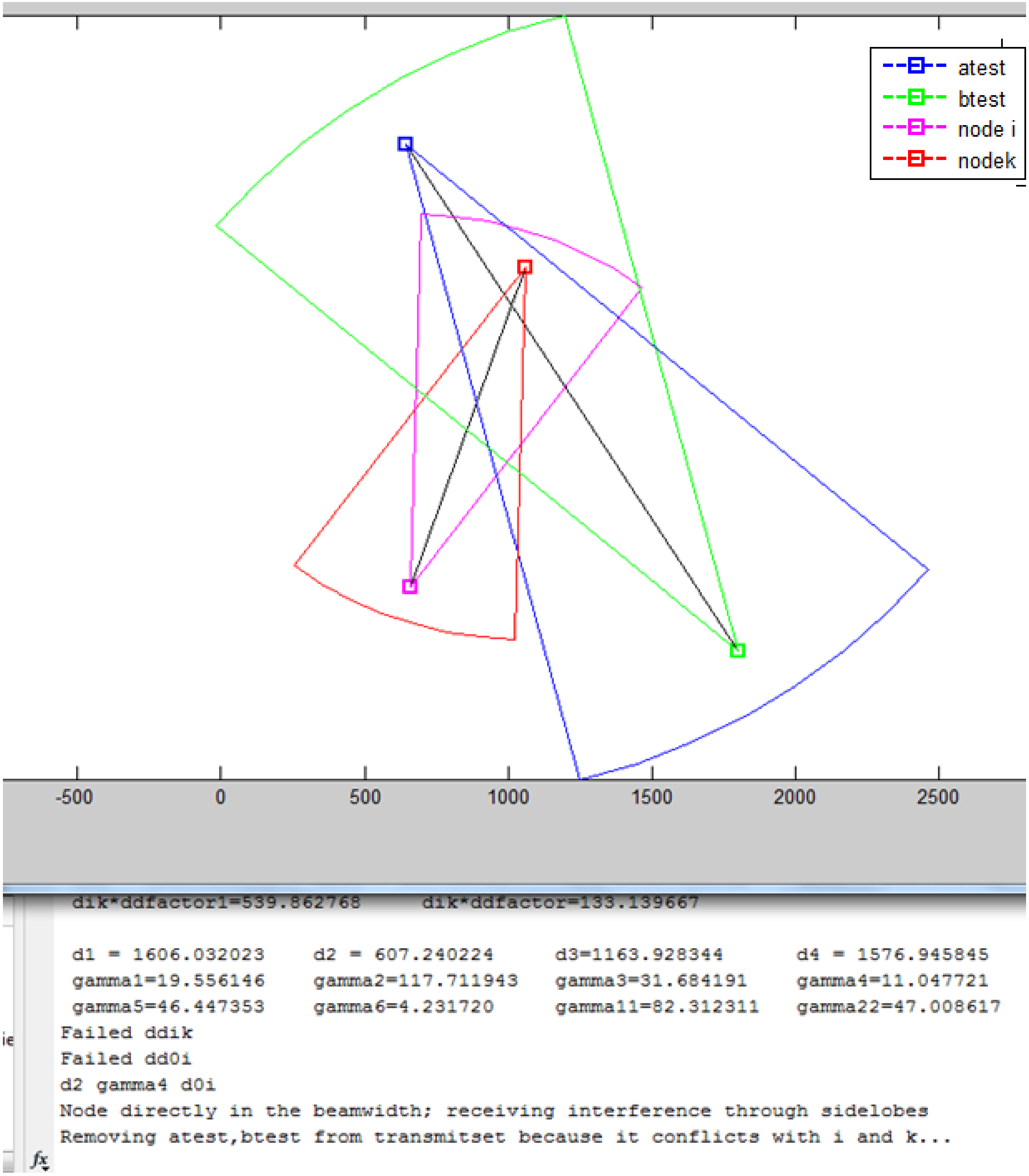
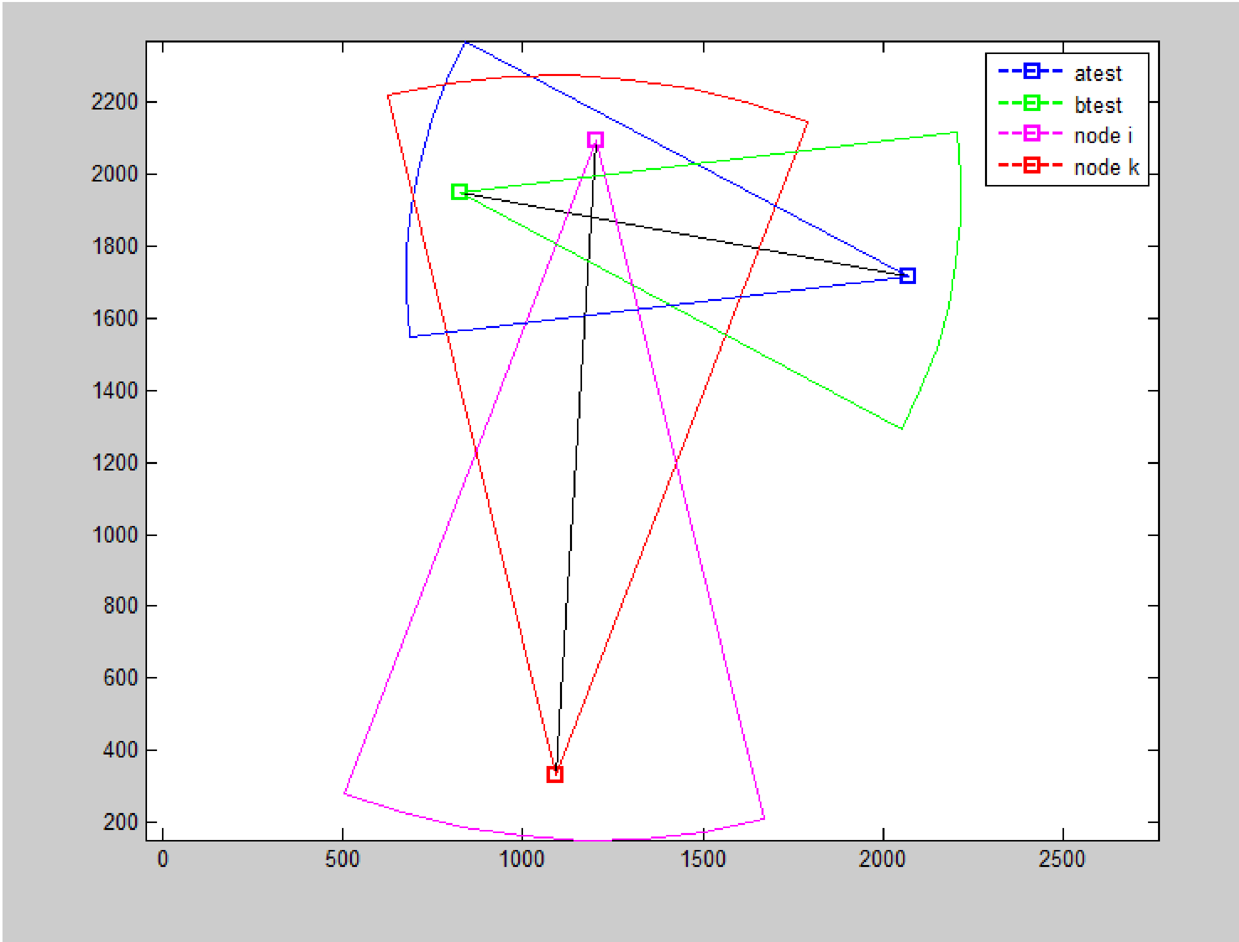


Figure 4.6: Node inside the main lobe, receiving power from side lobes.

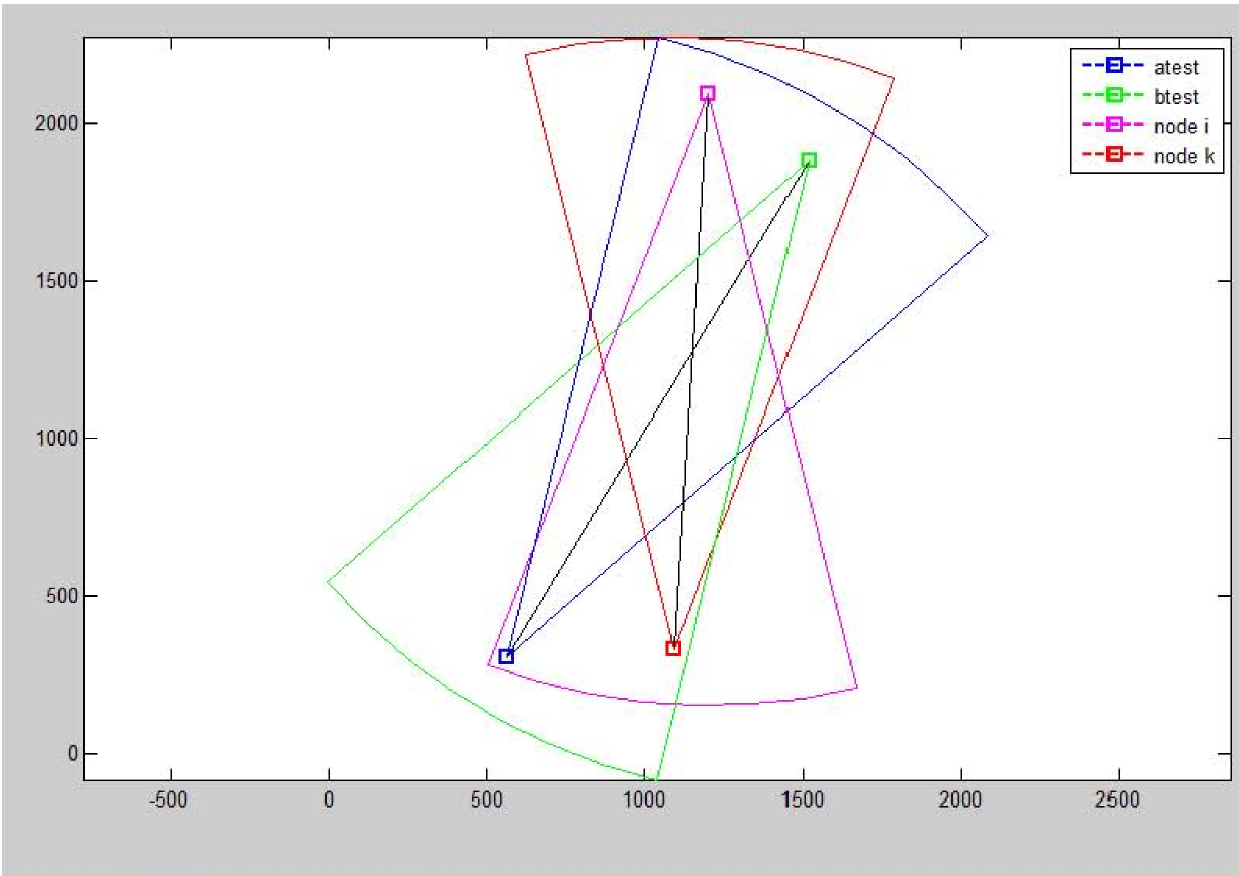



```
 dik = 1764.672901    ddik = 190.858890     d0i=1264.638839     dd0i = 136.777510
 dik*ddfactor1=773.906162      dik*ddfactor=190.858890

 d1 = 944.100049      d2 = 1693.179459     d3=405.147049    d4 = 1637.207743
 gamma1=70.019971     gamma2=31.602947     gamma3=13.021052     gamma4=65.356031
 gamma5=31.670250     gamma6=70.049840     gamma11=65.288728    gamma22=12.991182
Failed ddik
Failed dd0i
d4 gamma22
failed d4 ddfactor1 & failed facetoface
d1 gamma3 d0i
failed d1<d0i*ddfactor1 & failed facetoface
_________Connection allowed in this time slot__________
```

Figure 4.7: Node in the main lobe and not being removed.

Figure 4.7 shows another scenario where a node is in the beamwidth of another node, but pointing in a different direction. Even though nodes are inside each other's beam widths, they are not facing each other and the calculated power through the side lobes is below the severe interference level, so all of these four nodes are allowed in the same time slot as the result shown in Figure 4.7.




```
failed d1 ddfactor1 & failed facetoface
_________Connection allowed in this time slot__________

 dik = 1764.672901   ddik = 190.858890    d0i=1839.085064    dd0i = 198.906966
 dik*ddfactor1=773.906162     dik*ddfactor=190.858890

 d1 = 1896.466149    d2 = 528.164887     d3=382.696026    d4 = 1604.911341
 gamma1=16.071342    gamma2=96.269143    gamma3=11.628164    gamma4=56.031351
 gamma5=92.764618    gamma6=15.838754    gamma11=59.535876   gamma22=11.860752
Failed ddik
Failed dd0i
d1 gamma1
Node directly in the beamwidth; node i and node atest pointing towards each other
Removing atest,btest from transmitset because it conflicts with i and k...
```

Figure 4.8: Node in the main lobe and pointing towards each other.

In Figure 4.8 we have a scenario where a node is in the main lobe of another connection and directly pointing towards either of the transceivers, so in this case also both connections cannot go in the same time slot. The decision taken by our simulation also verifies the same.

In all the above four cases the interference model and the medium access process have been predicting the interference and thus the medium access decisions correctly. So now we go ahead and see the network capacity with different beam widths and varying number of nodes in the network.

CHAPTER 5

5. SIMULATION

5.1 Simulation Parameters

The simulation of the model is performed using the following procedures. We define and initiate some variables which are physical parameters, calculated values, or simply variables used for simulations or loop variables. For the simulation to study the efficiency of the network with varying beamwidth and the number of nodes in the network, we defined the following variables.

- *gtm* is the Transmit antenna main lobe gain.
- *gts* is the Transmit antenna side lobe gain.
- *grm* is the Receive antenna main lobe gain.
- *grs* is the Receive antenna side lobe gain.
- *lambda* is the wavelength.
- *n* is the path loss exponent which depends upon the environment.
- *preq* is the minimum required power at the receiver for a certain Signal to Interference Ratio (SIR).
- *beamwidth* is the 3dB or half power beamwidth of the antenna.
- *avgvect* is a 5-by-5-by-5 3-D matrix used to save the efficiencies and average them for different beam widths and nodes in order to study the performance of the network.
- *ddfactor* is a factor to determine the distance around a transceiver that is prone with most interference irrespective of the direction the antenna pattern is oriented towards.
- *ddfactor1* is a factor to determine the distance to the interfering node inside the main lobe of the transceiver that is being considered, to avoid any severe interference.

- *transmitset* is a vector that initially stores all of the source destination pairs in a single row matrix. As we go through the interference constraints some pairs are taken out and placed in a different vector, since these pairs cannot transmit in the current slot with the other pairs in the transmitset.
- *nextransmitset* is a vector that stores the source destination pairs that fail to go through the current timeslot and is used in the next time slot with *transmitset* appended to it. This gives the pairs that could not transmit previously a priority in the next time slot.

We assume the value of main lobe gain along with some of the basic parameters such as *lambda*, path loss exponent *n*, *preq* and calculate the other parameters such as side lobe gain, beamwidth, *ddfactor*, and *ddfactor1*.

The algorithm for the interference model basically consists of two major nested loops. Before going into the loops we randomly place the nodes in a square area and create source-destination pairs. Then we calculate the transmit power, danger distance and also the distances between the source-destination pairs. All these values are stored in different vectors and indexed in the order of nodes so they can be reached by the same loop variable.

5.2 Algorithm

5.2.1 Network Model Simulation

Here is the pseudo code that explains some of the core aspects of our model. This pseudo code may not contain all the required variable declarations and assignments unless required to explain the procedure involved in building the network model.

```
Creating node locations, with a maximum distance between them as a=3000 meters.
x=rand(1,numpoints)*(a/sqrt(2));
y=rand(1,numpoints)*(a/sqrt(2));
transmitset=1:numpoints;
Then, randomly shuffle and create source destination pairs.
for f=1:1000
        source=ceil(rand*numpoints);
        dest=ceil(rand*numpoints);
```

```
        temp=transmitset(dest);
        transmitset(dest)=transmitset(source);
        transmitset(source)=temp;
end


for main lobe gain=[10 13 15 20 25]
        Calculate the power, side lobe gain and beamwidth involved and the danger distances for
        all the nodes.
        for timeslots=1:10
                Start at the beginning of the transmitset with a loop variable, say ii
                Start with considering that first pair is allowed in current timeslot
                while ii<= length of the transmitset
                        variable 'i' is given the index of the beginning for the transmitset
                        variable 'k' is given the index of i's destination
                        another loop variable 'j' is initiated with the beginning of the
```

5.2.2 First Loop

Looping through all of the previously accepted connections to see if pair [i k] will affect previously accepted connection [atest btest] which are for this loop [ii,ii+1]

```
                        while j<=(ii-1)
                                atest=transmitset(ii);
                                btest=transmitset(ii+1);
                                Calculate all the variables required to test all the interference
                                conditions.
                                dik= distance between i and k
                                d0i= distance between atest and btest
                                ddik=dik*ddfactor
                                dd0i=d0i*ddfactor;
                                d1 = distance between i and atest
                                d2 = distance between k and atest
                                d3 = distance between i and btest
                                d4 = distance between k and btest
                                Calculate gamma1 gamma11 gamma2 gamma22 gamma3gamma4
                                gamma5 gamma6 using the law of cosines. All are shown in the
                                Figure 4.4. These are the various angles between the nodes i, k,
                                atest and btest.
                                Nodeallowed is a variable which indicates if a node is allowed in
                                the current time slot or not. Nodeallowed=1 implies the node is to
                                be removed from transmit set and if equal to 2 implies it is
                                allowed. Default intermediate state is 0.
                                if d2<ddik || d1<ddik || d3<ddik || d4<ddik  % Within the danger
                                distance for either node
                                                nodeallowed(ii)=1;
                                                nodeallowed(ii+1)=1;
```

```
                % fprintf('Nodes are too close, the sidelobes cause
                major interference \n');
        elseif d2<dd0i||d1<dd0i||d3<dd0i||d4<dd0i
                  nodeallowed(ii)=1;
                  nodeallowed(ii+1)=1;
                 % fprintf(' Nodes are too close, the sidelobes cause
                major interference \n');
         else
                  nodeallowed(ii)=0;
                  nodeallowed(ii+1)=0;
                   %fprintf('failed ddik \n');
         end

       if d1<dik*1.1 && gamma1<beamwidth/2 && nodeallowed(j)==0
            %fprintf('d1 gamma1\n');
              if gamma3<beamwidth/2
              nodeallowed(ii)=1;
              nodeallowed(ii+1)=1;
               elseif(d1<dik*ddfactor1)
              nodeallowed(ii)=1;
              nodeallowed(ii+1)=1;
              else
              nodeallowed(ii)=0;
              nodeallowed(ii+1)=0;
               % fprintf('failed d1 ddfactor1 & not pointing towards each
              other\n');
              end if
        end

       % The above if statement is only for one node, checking for
   interference. We need to repeat the above statement for all other nodes,
   checking to see if there is any interference in its main lobe.

    if nodeallowed(ii)==1 and nodeallowed(ii+1)==1
   % remove then ii and ii+1 nodes from the transmitset.
   end
   j is incremented by 2
end while loop
```

5.2.3 Second Loop

In this second loop we go through the rest of the connections in transmitset to see if they conflict with the currently accepted connection(s). If they conflict, we put them in the 'nexttransmitset' so they will not be considered further for the current time slot.

```
if node i is allowed in the current timeslot
        j=ii+2
        while j<=length of transmitset-1
                atest=transmitset(j);
                btest=transmitset(j+1);
                Calculate all the variables required to test all the interference conditions.
                dik= distance between i and k
                d0i= distance between atest and btest
                ddik=dik*ddfactor
                dd0i=d0i*ddfactor;
                d1 = distance between i and atest
                d2 = distance between k and atest
                d3 = distance between i and btest
                d4 = distance between k and btest
                Calculate gamma1 gamma11 gamma2 gamma22 gamma3gamma4
                gamma5 gamma6 using the law of cosines. All are shown in the Figure
                4.4. These are the various angles between the nodes i, k, atest and btest.
                Nodeallowed is a variable which indicates if a node is allowed in the
                current time slot or not. Nodeallowed=1 implies the node is to be removed
                from transmit set and if equal to 2 implies it is allowed. Default
                intermediate state is 0.
                        if d2<ddik || d1<ddik || d3<ddik || d4<ddik  % Within the danger
                        distance for either node
                                        nodeallowed(ii)=1;
                                        nodeallowed(ii+1)=1;
                                % fprintf('Nodes are too close, the sidelobes cause
                                major interference \n');
                         elseif d2<dd0i||d1<dd0i||d3<dd0i||d4<dd0i
                                        nodeallowed(ii)=1;
                                        nodeallowed(ii+1)=1;
                                  % fprintf(' Nodes are too close, the sidelobes cause
                                major interference \n');
                          else
                                        nodeallowed(ii)=0;
                                        nodeallowed(ii+1)=0;
                                         %fprintf('failed ddik \n');
                          end

                        if d1<dik*1.1 && gamma1<beamwidth/2 && nodeallowed(j)==0
                            %fprintf('d1 gamma1\n');
                            if gamma3<beamwidth/2
                                nodeallowed(j)=1;
                                nodeallowed(j+1)=1;
                            elseif(d1<dik*ddfactor1)
                                nodeallowed(j)=1;
                                nodeallowed(j+1)=1;
```

else
nodeallowed(j)=0;
nodeallowed(j+1)=0;
% fprintf('failed d1 ddfactor1 & not pointing towards each other\n');
end
end

% The above if statement is only for one node, checking for interference. We need to repeat the above statement for all other nodes, checking to see if there is any interference in its main lobe.
if nodeallowed(j)==1 and nodeallowed(j+1)==1
% remove the j and j+1 nodes from the transmitset.
end
j is incremented by 2
end while loop
ii is incremented by 2
end while loop (that started before the first loop section)
Before ending the for loop , we collect the statistics for each node and the whole time slot.
end for loop(that started before the first loop section)
Plot the collected statistics by averaging them for varying beamwidths and number of nodes.

5.3 Simulation Results

Now that the simulation model for the complete network has been built, let us see how the results can be analyzed. At the end of each time slot, a variable keeps the count of the number of times each node is allowed in a communication or, in other words, given access to the medium. After all the time slots for each case of main lobe gain (and thus beamwidth) and each case of node density, we average the statistics accordingly to arrive at a value for each case. In Figure 5.1 we can see a plot that averages the statistics over 10 slots and 15 different layouts of nodes for each value of main lobe gain and nodes in the network.

Concentrating on the beam width and main lobe gain, as the main lobe gain increases the beam width decreases. For less number of nodes and thus less network density, as the beamwidth decreases the chance of a node being in the main lobe of another node decreases, and as a result more number of nodes can share the wireless medium and this increases the network capacity. So for 20 nodes in the network, our plot in the Figure 5.1 shows that on an average about 80% of the connections are given medium access in a timeslot, for a main lobe gain of 25dB and beamwidth of 10 degrees. This value decreases to about 68% for a main lobe gain of 20dB and beamwidth of 20 degrees. So as the beamwidth increases the chance of an interfering node being in that beamwidth increases, so the chance of it actually interfering also increases and thus decreases the network capacity. Also as the number of nodes in the network increases from 40 through 100 the network efficiency decreases drastically since node density increases.

Now coming to Figure 5.2 we compare our network model with the conventional omni-directional and directional cases. For omni-directional case, we use the same program and assume ddfactor is slightly greater than one. This is because in omni-directional networks the beamwidth is basically a sphere all the way to the destination. For this to be simulated we just increase the danger distance as far as to include the destination. This will make sure we create a circle with the source as the center and the destination is inside the circle. Along with making the danger distance greater than one, we also need to make sure we do not allow connections and/or the nodes inside the circle to communicate at the same time.

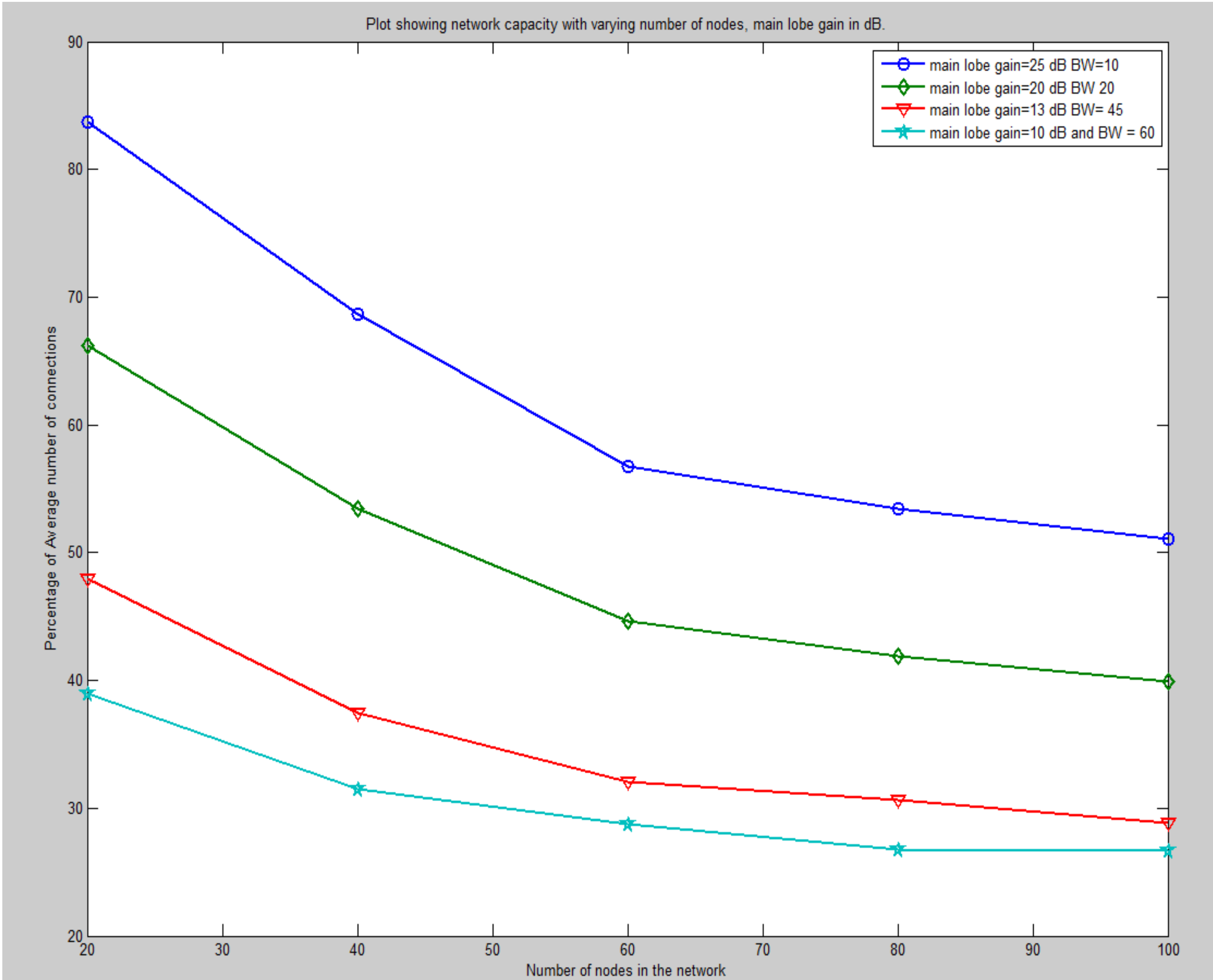


Figure 5.1: Plot showing number of connections with varying beamwidth and number of nodes.

In the conventional directional case, one makes sure any node inside the beamwidth of another node is not given the medium access regardless of where the connections are pointing. After simulating about 20 network layouts the statistics are averaged and plotted. The final plot comparing the three network models can be seen in Figure 5.2. The enhancement in the network efficiency is clearly visible. For lesser node density (20 nodes), we have a difference in average number of connections is greater than 17%.

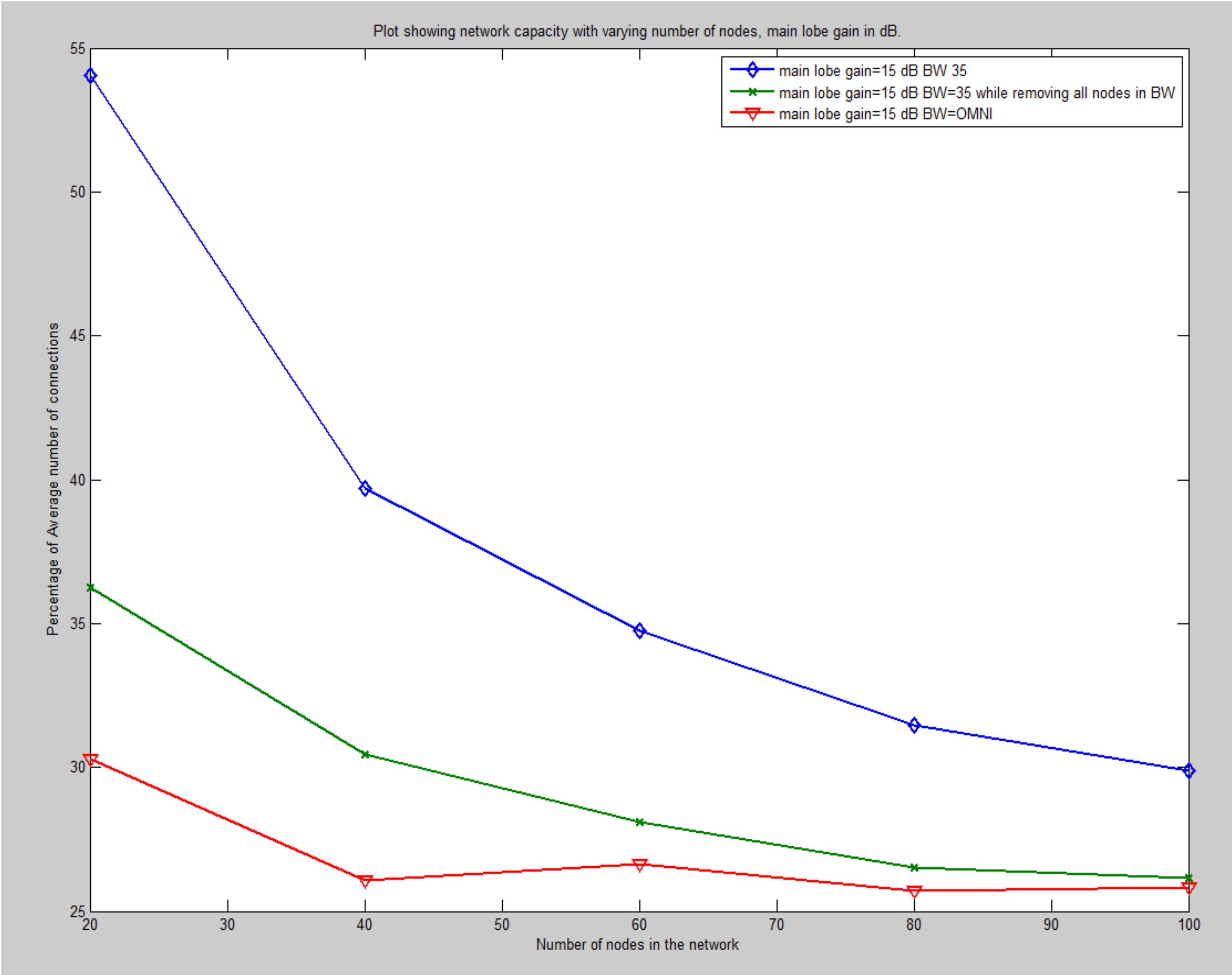


Figure 5.2 Plot comparing our model with conventional models.

CHAPTER 6

6. CONCLUSIONS AND FUTURE WORK

Based on the results from the simulation we have drawn a few conclusions; the network simulation has been successful and the network enhancement has been observed. Also some key parameters of the antenna help in analyzing the plots obtained through simulation; for example, the beamwidth of an antenna is crucial to network capacity and interference analysis. If we have a higher beamwidth the interference prone area for other nodes increases. For less number of nodes in the network, the enhancement in the network capacity is high; the difference in capacities from the conventional models decreases as node density increases.

Even though this model has given a substantial network enhancement, it can be made into a much better solution with a better scheduling scheme which takes advantage of the interference model and power calculations. A network with de-centralized way of communication, unlike the assumed centralized mode is something that is very important in the case of ad-hoc networks. Future work can also focus in the areas of beam steering along with the current interference model to decrease interference severity to a lesser level. Further work can be done by simulating the side lobes into several angular wedges instead of the circles used in this study. We also intend on studying the relevance of multi-hop and multi beam concept and their implementation with the network model discussed in this study. Multi-path has not been taken into consideration for modeling the interference conditions in this study, so modeling multipath would also be an essential part for a complete system solution.

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VITA

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