BEAMSTEERING AND NULLSTEERING IN INTERFERENCE AWARE WIRELESS NETWORKS WITH POINT TO POINT BEAM FORMING WITH DIRECTIONAL ANTENNAS

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BEAMSTEERING AND NULLSTEERING IN INTERFERENCE AWARE WIRELESS NETWORKS WITH POINT TO POINT BEAMFORMING WITH DIRECTIONAL ANTENNAS

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ABSTRACT

The concept of beamforming and beamsteering has been gathering immense popularity since the idea's inception. Many in the field of Wireless Communication and in the defense community have tried and succeeded in utilizing the benefits of beamforming and beamsteering with directional antennas. With the increasing popularity of decentralized adhoc networks, it only becomes necessary that the concept of beamsteering be formulated with respect to the network that is being studied. In relation to RF Engineering, the idea of beamsteering has been studied and explored diversely, by proposing beamsteering/ nullsteering algorithms pertaining to Digital Signal Processing.

We however, make an attempt to understand beamsteering and nullsteering from the perspective of the physical layer of an Ad hoc network. Hence, it becomes essential that several network parameters like Signal to Interference Ratio, and contention in between individual connections be considered along with the RF parameters like antenna beamwidth, mainlobe and sidelobe gains, Relationship between sidelobes and nulls, Positions of sidelobes and nulls with change in the beamwidth and the number of elements in the directional antenna array. All these different parameters generate a sequence of combinations of results and change the performance of the network accordingly. The crux of this thesis is the antenna pattern model that is consistent with a practical directional antenna pattern, with a mainlobe, several sidelobes and nulls. This antenna pattern is able to derive a network that is much more efficient than its predecessor models that did not use the nulls and sidelobes in their antenna patterns. An algorithm implemented in this thesis shows the vast improvement in the network efficiency, when the different network entities use beamsteering and the alignment of nulls along interfering nodes. It is noticeable that the performance of the network improves by a factor of almost 30 percent due to the implementation of beamsteering as compared to only alignment of nulls along interfering nodes; and by a factor of 37 percent when compared to a model where no Sidelobes and nulls are considered.

APPROVAL PAGE

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

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I am very grateful to Dr. Baek Young Choi and Dr. Ken Mitchell for serving as members on the supervisory committee providing valuable inputs and suggestions.

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CHAPTER 1

INTRODUCTION

1.1 Purpose

The concept of ‘smart antennas’, or as the Wireless Communications/RF engineers call ‘directional antennas’ has become one of the most extensively studied topics in the past few years. The reason for the concept to have gained such popularity is the fact that a directional antenna proves to be much more efficient than the ever-so-popular omnidirectional antenna, in terms of low transmit power for equivalent distance, higher antenna gain and lower conflicts/interference with neighboring transmitters. One of the first works in this area was to prove the benefits of Directional antennas over omnidirectional antennas. Fig. 1.1 shows the spatial comparison of the antenna field of that of omnidirectional antenna to that of a directional antenna.

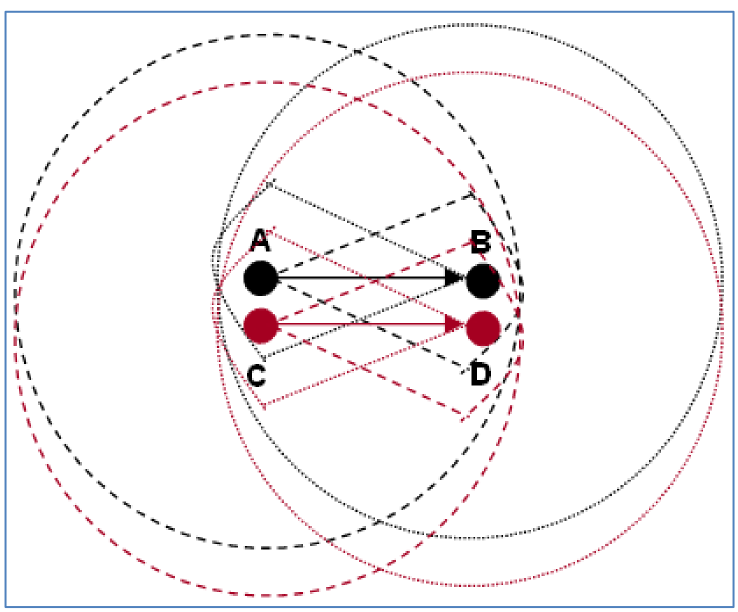


Fig. 1.1: Spatial Comparison of Omnidirectional vs. Directional Antennas

It's perceptible from the figure that an omnidirectional antenna would cause much more interference to neighboring transmitters than would a directional antenna. Also, directional antennas increase the potential for spatial reuse and longer range of transmission.

One proposed model to visualize the directional antenna model would be as a "Cone-and-a-bulb" [4] [16]. This approximation considers the mainlobe of the antenna to be a "cone" and the sidelobes to be a "bulb", the bulb being an enclosed sphere, as shown in Fig. 1.2. This approximation fails to consider what we call "nulls" that are present along the mainlobe and with not one but several sidelobes of the antenna.

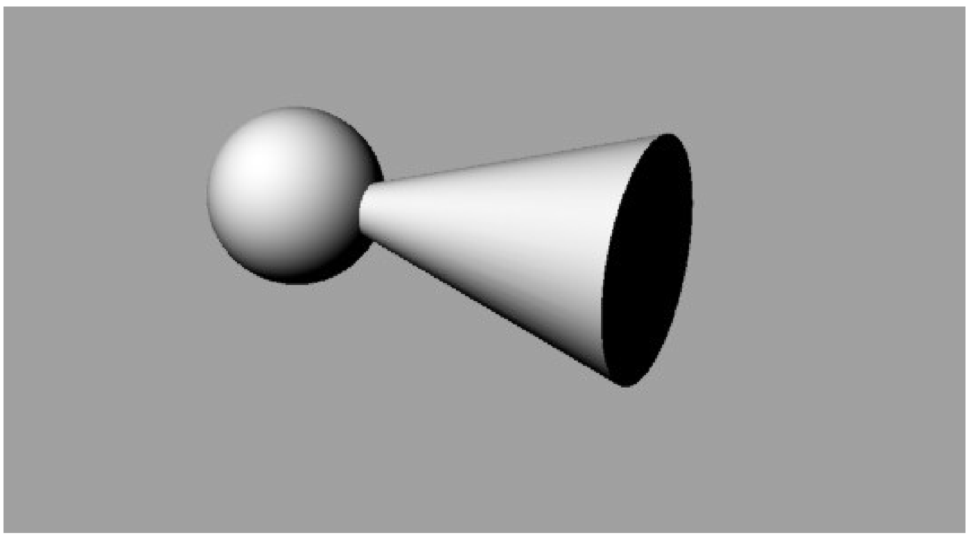


Fig. 1.2: Representation of a Smart Antenna Pattern as a "Cone-and-Ball"

The purpose of this thesis is to study the contention in a network of nodes with directional antennas, with a modeled approximation consisting of a mainlobe, number of sidelobes, and nulls present between the consecutive sidelobes. The thesis also explores the concept of beamsteering that when applied to such a network, can reduce the number conflicts from what that were already present.

1.2 Directional Antenna Fundamentals

At this point, it is perhaps essential that some necessary jargon be discussed before beginning the work done on directional antennas.

- Antenna Gain: “Amount of Power that is transmitted in the direction of peak radiation to that of an isotropic source.” [17]
- Mainlobe: “The region around the direction of maximum radiation (usually the region that is within 3 dB of the peak of the main beam).” [17]
- Sidelobes: “These are smaller beams that are away from the main beam. These sidelobes are usually radiation in undesired directions which can never be completely eliminated. The sidelobe level is the maximum value of the sidelobes (away from the main beam).” [17]
- Transmit Power: is a measure of how much power is radiated by an antenna when the antenna is connected to an actual radio (or transmitter).
- Receiver Sensitivity: A measurement of the weakest signal a receiver can receive and still correctly translate it into data.
- A simple dipole antenna (Omnidirectional antenna): “In radio communication, an omnidirectional antenna is an antenna which radiates radio wave power uniformly in all directions in one plane, with the radiated power decreasing with elevation angle above or below the plane, dropping to zero on the antenna's axis.” [17]
- Array antennas (Directional antennas): “An antenna array (often called a 'phased array') is a set of 2 or more antennas. The signals from the antennas are combined or processed in order to achieve improved performance over that of a single antenna.” [17]

- Field Regions: “The far field region is the most important, as this determines the antenna's radiation pattern. Also, antennas are used to communicate wirelessly from long distances, so this is the region of operation for most antennas and the region we are interested in. The far field is the region far from the antenna. In this region, the radiation pattern does not change shape with distance. Also, this region is dominated by radiated fields, with the E- and H-fields orthogonal to each other and the direction of propagation as with plane waves.” [17]

1.3 Ad Hoc Networks with Smart Antennas

A wireless Mobile Ad hoc Network, popularly known as a MANET, is a decentralized network of nodes that form the set of Transmitting and Receiving pairs, which may or may not be devices equipped with directional antennas. The advantage of using directional antennas with an ad hoc network is that it provides a longer transmission range of signals, something that translates into fewer hops in an average ad hoc network. Another factor that significantly affects the ad hoc network is the signal strength. With a directional antenna, the transmitted signal strength significantly increases due to the high antenna gain that the antenna introduces. However, the constant switch from one connection to another makes the ad hoc network susceptible to interference from other network devices, something that is not possible to mitigate while using omnidirectional antennas. A similar problem arises when multipath is considered in an ad hoc network with omnidirectional antennas. A network with such problems can be improved and made much more efficient, when it is built with directional antennas with Beamsteering and Nullsteering, discussed in Section 1.5. Beamsteering is associated with directional antennas that form a beam shaped radiation pattern, and transmit/receive in only that direction. Such a pattern, also includes energy radiation in directions other than the mainlobe, which are called the sidelobes. The transmission/reception of energy through the sidelobes, even though much lesser than that of the mainlobes, are enough to cause interference if within close proximity. However, the presence of nulls intermittently between the sidelobes reduces the chances of interference even more.

Fig. 1.3 shows a two node network with directional antennas considering sidelobes and nulls (left), and how it affects the performance of the network when compared to a network based on the “Cone-and-ball” model mentioned in Section 1.1 (right).

Fig. 1.3: Antenna Model with Sidelobes and Nulls Vs. Antenna Model “Cone-and-ball”

1.4 Previous Work

As pointed out in section 1.1, the research that has been done in the field has mainly had significance in relation to a model that contains the mainlobe of an antenna pattern and a sidelobe that has an angular spread over $360° - Mainlobe\ Angle$. Two such works that this thesis draws its relevance from are [4] and [18]. The work done in [4] uses the “Cone and ball” model and derives the network parameters from that assumption, while [18] uses the same model and derives the network and antenna parameters using the relative distance between the nodes.

Let us consider a network of nodes that are randomly placed in a given area, Fig. 1.4. The simulation figure imitates an adhoc network with 40 nodes, or 20 connections.

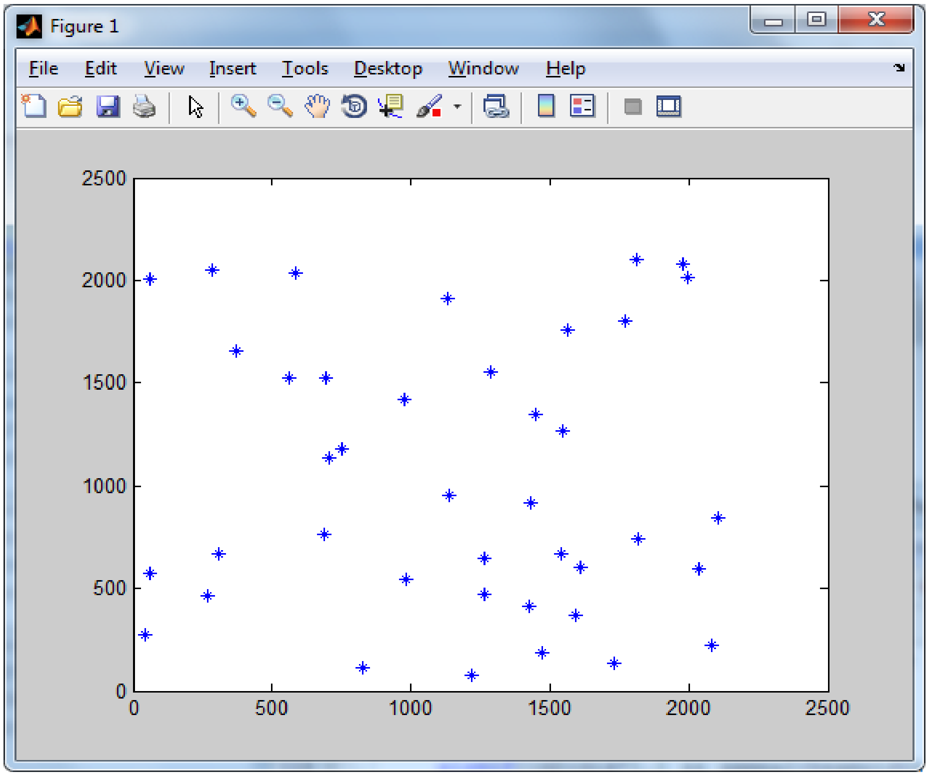


Fig. 1.4: Network of Nodes, showing randomly distributed 40 nodes

This network, when allowed to transmit and receive generates a “transmit set”, which is essentially a set of transmitting and receiving pairs. The contention in this network is now studied on the basis of the position of the nodes, which are chosen randomly by the simulator. Our work makes a few very important assumptions that are consequential to the understanding of the network and its conflicts. Some of them are as mentioned in the table 1.1

Table 1.1 List of terms used in previous and current work

Name	Detail
Danger Distance	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 depending on the direction in which they radiate.
Transmit Set	A set of pairs of nodes allowed to form a transmitting/receiving connection for that particular time slot. Nodes may pass and enter the current transmit set or fail and go to the next transmit set.

1.5 Comparison of Conflicts in a network with the "Cone and ball" model and that with "Sidelobes-Nulls" model of antennas

The Conflicts in the network can occur in many ways:

1. Cause: An interferer node can lie inside the mainlobe of another connection and face the transmitter or receiver directly.

   Effect: Direct interference faced by the transmitting/receiving node from an equally strong source of signal.

2. Cause: An interferer can lie inside the mainlobe of another transmitting/receiving pair and its sidelobes may face the nodes mainlobe.

   Effect: The interferer may or may not cause a problem to the existing connection depending on its proximity to the node itself, or within the danger distance.

3. Cause: An interferer can lie inside the sidelobe of another node.

   Effect: The proximity in this case is already close, and the interferer will cause problems with the existing node.

This work addresses the above Cause and Effect Cases by possibly mitigating interference as follows.

1. Cause: An interferer node can lie inside the mainlobe of another connection and face the transmitter or receiver directly.

   Effect: The beam can be steered to not face the interferer anymore, even while still communicating with the destination node, thereby letting both connections transceive at the same time. If steered away, the interferer will now lie within the null adjacent to the mainlobe.

2. Cause: An interferer can lie inside the mainlobe of another transmitting/receiving pair and its sidelobes may face the nodes mainlobe.

   Effect: If the interferer is within the danger distance of the node, the beam can be steered to remove the interferer from the interfering range, thereby letting both connections pass at the same time. If however, the interferer lies inside the mainlobe, and within the danger distance and its null faces the node, it can be allowed. We can also steer the interferer such that its null faces the node.

3. Cause: An interferer can lie inside the sidelobe of another node.

   Effect: The proximity in this case is already close, but the beam may lie in one of the nulls which would mean that there is no existing interference because of the interferer. If however, the interfering node does lie inside a sidelobe, the beam can be steered such that it falls into one of the adjacent nulls.

1.6 Beamforming, Beamsteering and Nullsteering

As pointed out in section 1.4, there can be numerous improvements made to the previous work done in the field of directional antennas. These changes would incorporate the use of beamforming and steering those beams to evade existing interference and nullsteering, which is an addendum to beamsteering, whereby we try to place the nulls towards a conflicting node.

Beamforming is essentially a technique used in phased antenna arrays, where digital signal processing techniques are used to make the antenna gain pattern directional, giving it an appearance of a beam. The beam with the highest gain is called the mainlobe, whose gain can be from 30 to 40 dB more than that of an omnidirectinal antenna. Beamsteering involves the movement of the beam along an angular axis in clockwise or anticlockwise direction such that an existing conflict can be removed from the vicinity of the mainlobe. Nullsteering, is mostly beamsteering itself, but with the consideration that if and when a beam is steered, the conflicting nodes should lie inside a null for the conflict to removed.

Let us consider a part of a network as shown in Fig. 1.5. Here, one of the nodes, Node b, lies in the mainlobe of connection AB and faces it directly, making it impossible for the two connections to go together at the same time. But steering of the mainlobe of Node B counterclockwise would ensure that the Node b no longer lies inside the mainlobe of Node B and hence both connections can simultaneously exist. Node B can steer the beam up to half of its beam width; it would still be able to communicate to Node A and be able to avoid Node b. Just outside the mainlobe of Node B would then have a null pointing at Node b.

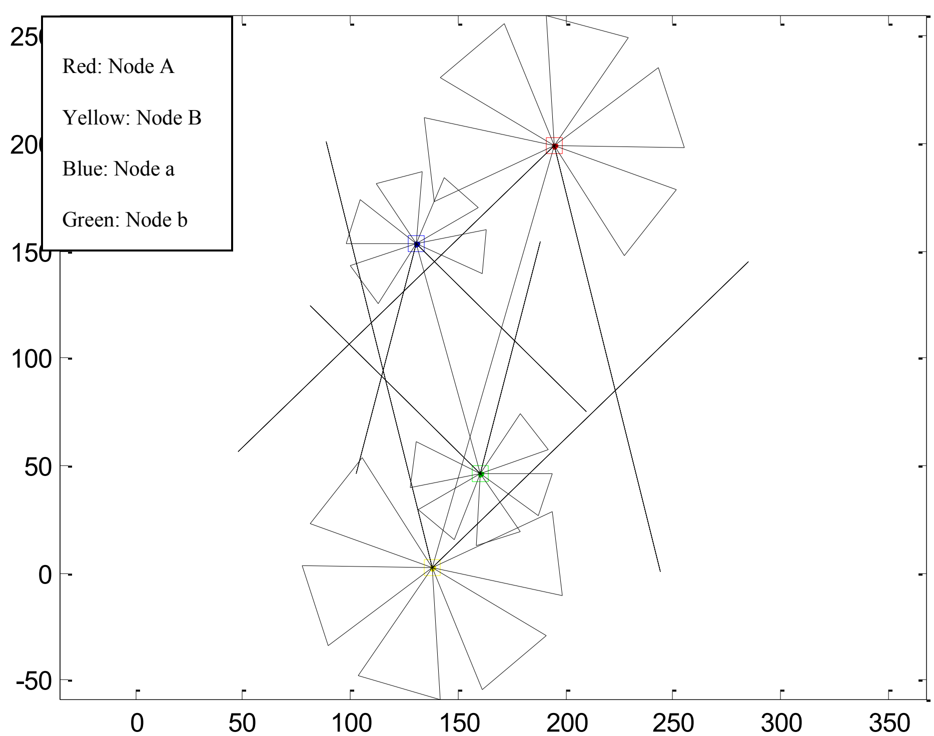


Fig. 1.5: Network of Nodes – Conflict – Node in Mainlobe of another, facing each other

The next figure., Fig. 1.6 shows a network with a contention due to one node being in close proximity with another and with each others' sidelobes. Such is a case where the use of nullsteering is of the most importance. By steering the beam by a known factor and a pre-decided limit, it can be ensured that the conflicting node may now lie inside a null.

It is very interesting to notice that all the above mentioned techniques may or may not prove to have a profound effect on the network, but cases where it makes a positive impact, prove to be very helpful in increasing network capacity. It is extremely important that the antenna parameters mentioned in Section 1.2 be taken into account before using these techniques, as any change in the parameters affects the radiation pattern, and changes the whole network.

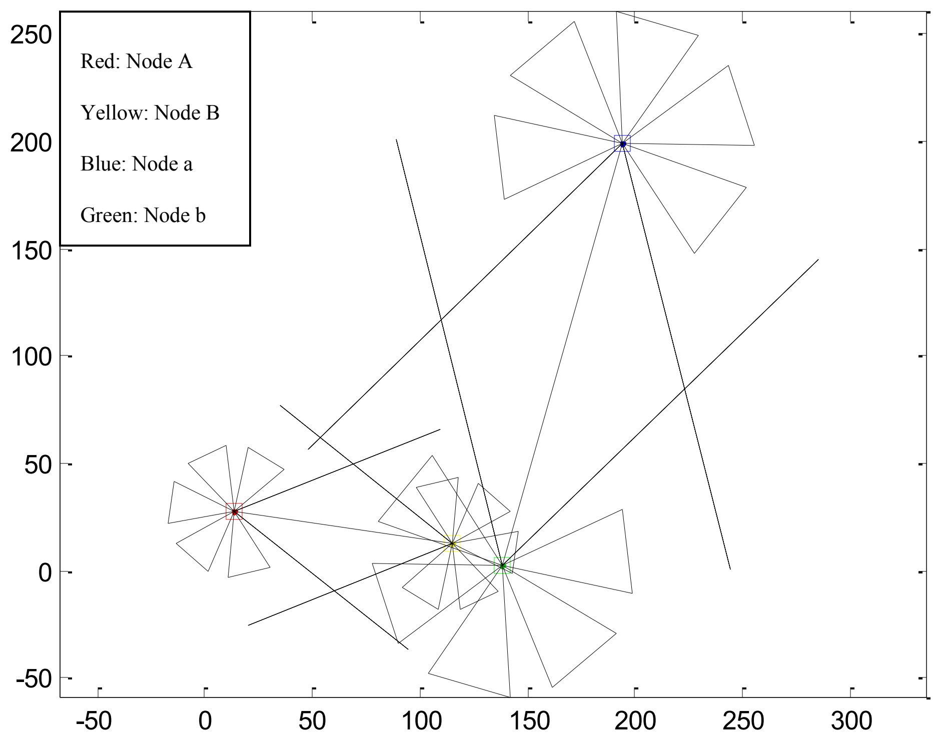


Fig. 1.6: Network of Nodes – Conflict – Node in sidelobe of another, within Danger Distance

CHAPTER 2

AD HOC NETWORK WITH DIFFERENT TYPES OF ANTENNA MODELS

2.1 Adhoc Networks with Omnidirectional antennas

As seen in Fig. 2.1, a network with omnidirectional antennas would mean that the radiation pattern would cover a circular path around the node. The plot shows a radiation pattern that has a radius equal to the maximum gain of the antenna in dB; such an antenna has a gain equal to almost $\frac{1}{10}th$ (in dB) as much that of a directional array antenna. Fig. 2.1 shows the polar plot of the radiation pattern of an omnidirectional antenna.

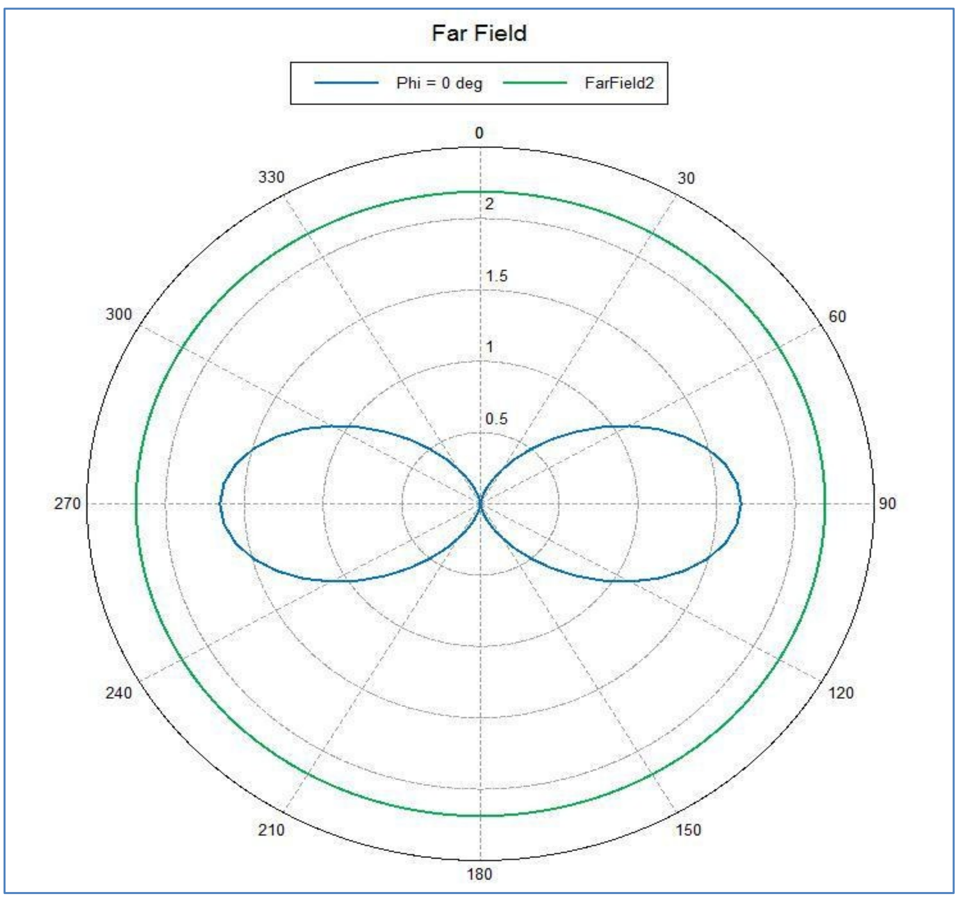


Fig. 2.1: Polar Plot of Radiation Pattern of an Omnidirectional Antenna

As seen in the Fig.2.1, the gain in dB of this antenna is a little over 2 dB. A network with such antennas, as shown in Fig. 2.2, would not be as efficient as a network with directional antennas. A transmission with pattern like Fig. 2.1 and 2.2 will include in its path many other existing nodes of the network. Hence the number of conflicts would be much higher. The network, if equipped with directional antennas, would look like Fig. 2.4, which may not include the conflicting nodes in its transmission path.

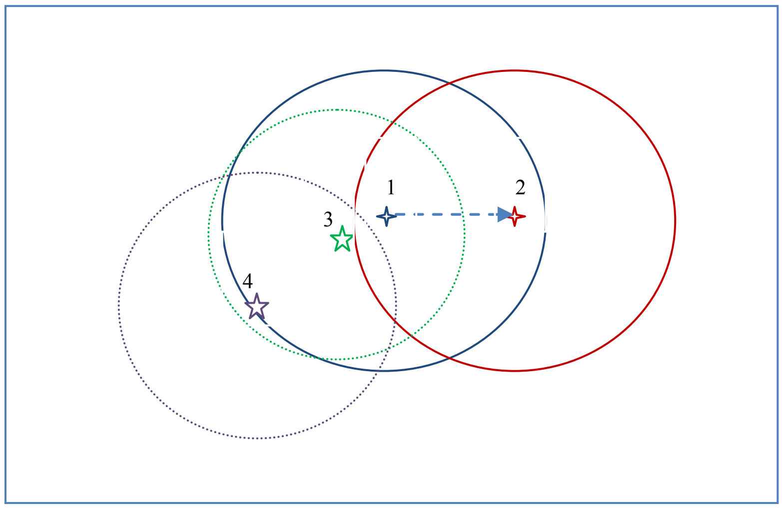


Fig. 2.2 – Network with Omnidirectional Antenna

2.2 Ad hoc network with Directional antenna with no beamsteering and nulls

The radiation pattern of a directional antenna looks like what is shown in Fig. 2.3 for a dipole array antenna of 5 elements in a linear arrary. The boresight gain in this case is 10dB, as seen from the figure. The high gain means that the effective transmitted power would be more, and hence a stronger signal. Apart from the high gain, many interfering nodes that would have lied in the isotropic pattern of the antenna would now either lie in a null or would not be inside the mainlobe of the directional pattern, even if the relative position of the interferer is the same if there was an omnidirectional antenna.

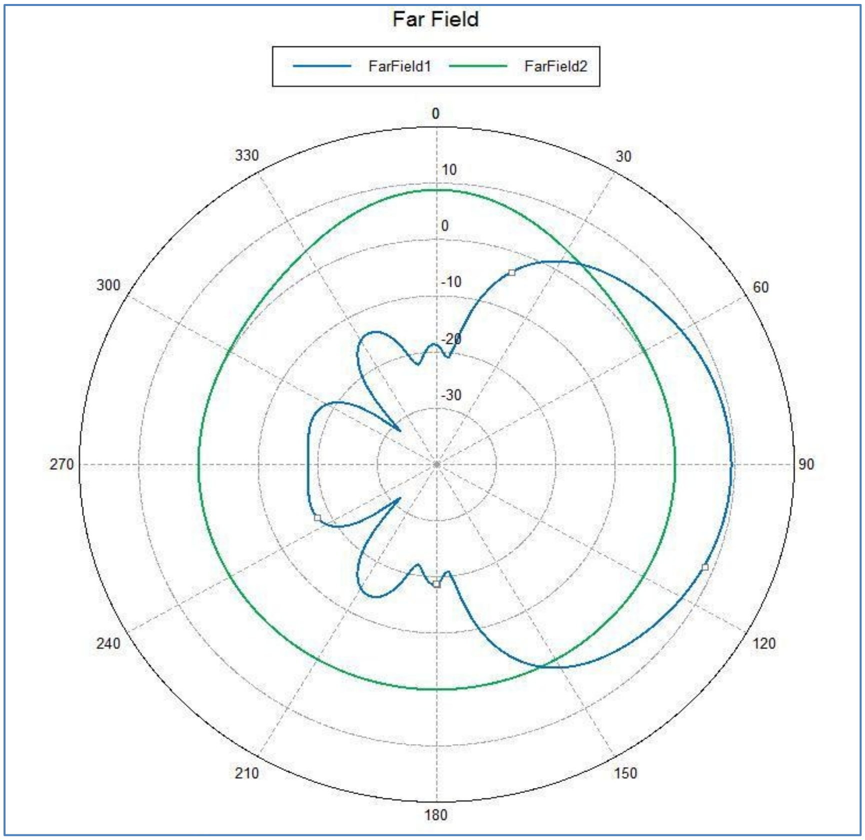


Fig. 2.3: Polar Plot of Radiation Pattern of a Directional Antenna

A pattern like that means that a network with such antennas will have a directed beam for transmission and reception meaning that the circular pattern of the omnidirectional antenna which led to the inclusion of Nodes 3 and 4 as conflicts would no longer exist. The network studied in Fig. 2.2, considering exactly the same position of the nodes, would now look like Fig. 2.4.

If noticed in Fig. 2.4, the interfering node 3 would now lie not in the mainlobe but in the sidelobe of Node 1. This is the concept that the ball-and-cone model follows, [4] [16]. According to this model, now, the previously existing conflict of Node 3 will exist, but that of Node 4 will completely be removed.

If we assume the efficiency of the network to be the number of nodes allowed to transmit at the same time, the maximum number of nodes being 4, it can be said that the efficiency of the network for Fig. 2.2 (Case with omnidirectional antennas), was $\frac{2}{4} = 50\%$ since a maximum of 2 out 4 nodes can be allowed at the same time. For section 2.2, it was $\frac{3}{4} = 75\%$ because a maximum of 3 nodes out of 4 can be allowed at the same time. Node 4 can now transmit in this case.

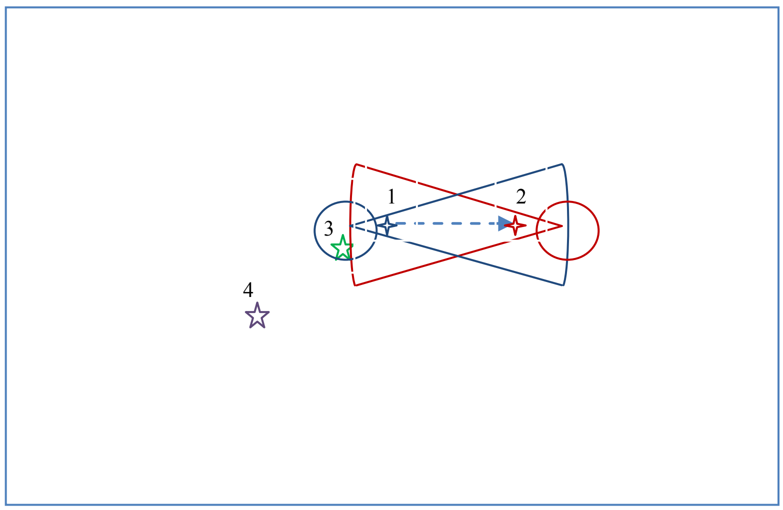


Fig. 2.4 – Network with Directional Antennas with no Nulls and Steering

2.3 Adhoc Network with Directional Antenna with Beamsteering

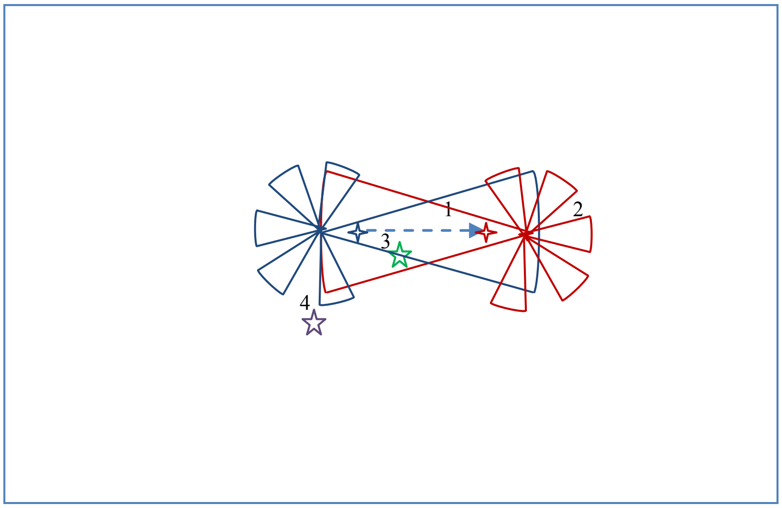


Fig. 2.5 – Network with Directional Antennas with Nulls and Steering

A network as seen in Fig. 2.5 would have beamforming (ensuring directionality), beamsteering (ensuring spatial reuse) and nullsteering (to avoid high proximity interferers). As seen from the figure, Node 3, which used to be an interferer in Section 2.2, Fig. 2.4, now lies in a null in Fig. 2.5. So, in this case, out of the 4 nodes in the network, all four can transmit/receive simultaneously, without posing any threat any other node in the network, despite the same respective distance and position from each other as Figs. 2.2 and 2.4. The efficiency of this network can hence be considered as $\frac{4}{4} = 1$, or 100%. In a practical network, with more than 50 ad hoc nodes, such high efficiency is impossible. It is however possible to increase the efficiency of the network by increasing the number of allowable nodes at the same time.

The comparison of Figs. 2.2, 2.4 and 2.5 demonstrates how important it is to design a network of ad hoc nodes taking an antenna pattern such as Fig. 2.3, which is both practical and advantageous to get better efficiency in a network.

CHAPTER 3

NETWORK MODEL - "SIDELOBES AND NULLS" MODEL

3.1 Assumptions

The ideal antenna pattern looks like the one shown in Fig. 2.2, but for the required calculations, it is necessary to consider a more geometrically defined structure for the antenna pattern. Then a set of equations can be defined for the coverage area that can be quickly used. We have therefore assumed that when the nodes are transmitting and receiving, and there are two other nodes present in the network at the same time, the geometry would look like what is shown in Fig. 3.1. In this, the line joining A and B is the boresight for that connection, and the lines joining A and a, A and b, B and a and B and b are the distances between these nodes, also giving the angles formed between them.

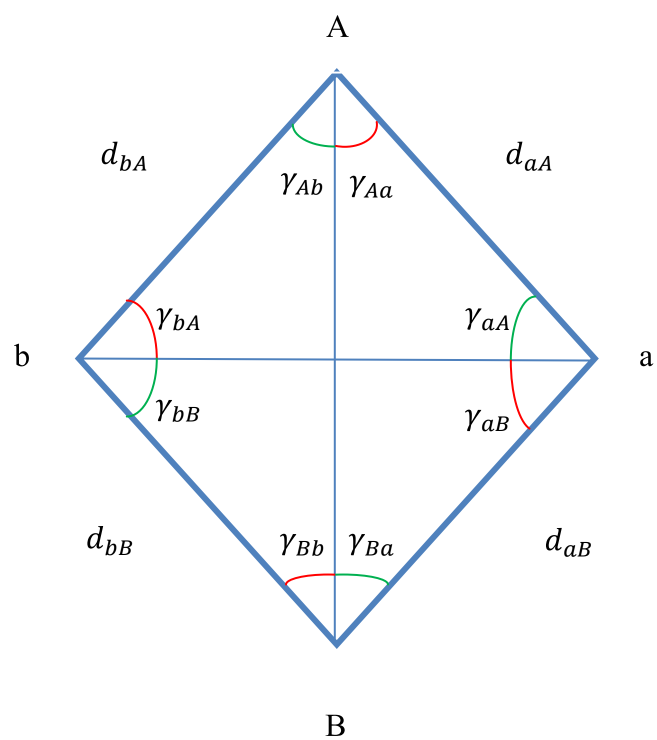


Fig. 3.1 – Four Node Network with Angle Measurements and Distances

The wedge antenna pattern structure as shown in Fig. 3.2 takes into account the distances $d_{aA}, d_{bA}, d_{aB}, d_{bB}$ and the angles γ_{Aa}, γ_{Ab}, γ_{aA}, γ_{aB}, γ_{Ba}, γ_{Bb}, γ_{aB}, γ_{bB} for determining whether or not the current node is an interferer or not. For example, if the distance d_{Aa} is smaller than the "danger distance" (defined in Section 1.5), the node might lie within proximity such that it will cause interference regardless of the orientation of the ab connection. Similarly, if the angle γ_{Aa} is smaller by $Beamwidth/2$, the node is inside the mainlobe and could be an interferer. In this particular case, as seen in Fig. 3.2, angles γ_{Aa}, and γ_{Ba} decide whether or not Node a lies inside the mainlobe of connection AB, and the distances d_{Aa} and d_{Ba} decide whether or not it is within a range to cause interference.

The geometry of triangle ABa can be utilized in our network by using the law of cosines by, $\cos\gamma_{Aa} = \frac{daB^2 - dAa^2 - dAB^2}{-2\times dAB\times daA}$. This formula is used to find the values of all the angles that are formed between the different nodes.

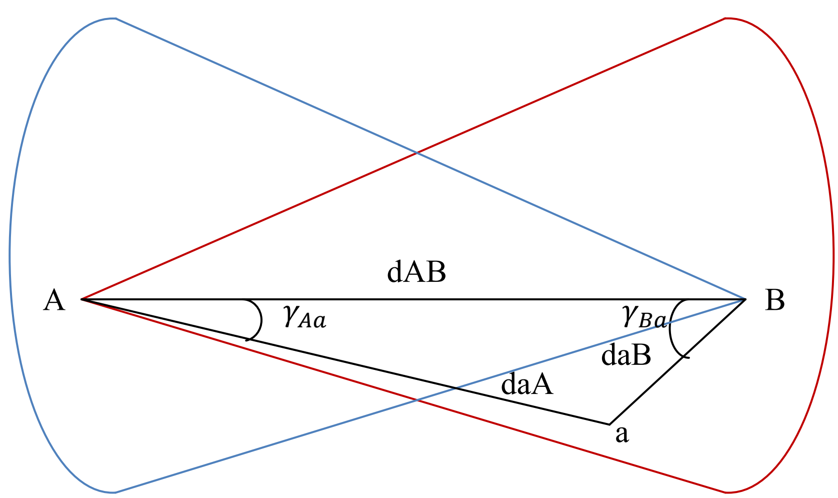


Fig. 3.2 – Two Nodes in a Network with an Interferer inside the Mainlobe of A

The antenna and network parameters of a directional antenna, irrespective of the network it is used in, are always first configured according to the required specifications of the network. This thesis makes an assumption of one of the parameters and relates the rest accordingly.

- Beamwidth – The definition of the beamwidth is as specified in section 1.2, and in this thesis it would be the angle formed by the wedge. The value of this angle is 60°.
- Sidelobe width – The region of sidelobes and nulls will be the region of the "ball" in the "cone-and-ball" model [4]. The sidelobe angular spread is θ and considering the angular spread of the nulls to be half as much as the sidelobes, they can be $\frac{\theta}{2}$. The angle that the sidelobes and nulls subtend can be calculated as,

$$Beamwidth + 5\theta + \frac{6\theta}{2} = 360$$

$$8\theta = 360 - Beamwidth$$

$$\theta = \frac{360 - Beamwidth}{8}$$

  With a beamwidth of 60°, it calculated that the sidelobes are at 37.5°
- Nullwidth – The region between each consecutive sidelobe is the region of null. The gain in this region is such that it would not cause interference. The angle subtended by the nulls is $\frac{Sidelobe\ angle}{2} = 18.75°$
- Transmit Set – It is the set of connections (pairs of nodes) that are allowed to transmit/receive at the same time in a network. The "current transmit set" and

"next transmit set" are formed after it is decided if one connection is posing a threat to an existing connection. If yes, it is put in the "next transmit set", else it is out in the "current transmit set". The "next transmit set" is used as the first set of connections that are considered for transmission in the next time slot.

- Danger Distances - 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.

3.2 Network Model

The network is designed as sets of randomly placed nodes with changing coverage area. The individual nodes are recognized by their coordinates in the x-y axis. The distance between the nodes that form a connection is given as,

$$d(n) = \sqrt{(x(n) - x(n+1))^2 + (y(n) - y(n+1))^2}$$

The network is characterized by "Transmit Sets" that are sets of connections that can coexist in the same timeslot. These transmit sets can contain a number of connections depending on the number of conflicts present in at that point. For example, if a network has 10 ad hoc connections, [1 2 3 4 5 6 7 8 9 10], out of which 5 can coexist at the same time, viz. [2 4 6 8 10] and the other 5 cause interference to the first 5, then the second two are put into the next transmit set where they now check for conflicts with the first five connections. This goes on for a fixed number of timeslots until a point has reached that all possible conflicts are resolved. The efficiency of the network, which is the total number of connections possible would be the average of all timeslots. The transmit sets that are formed are as follows:

current transmit set = [2 4 6 8 10]

next transmit set = [1 3 5 7 9 2 4 6 8 10]

Please note that the numbers 1, 2, 3,…. are connections (sets of nodes) and not the nodes themselves.

We follow a basic algorithm to determine whether or not a connection would conflict with another. We check every incoming connection and see if it could become a member of the set of incoming connections that had already been accepted into the current transmit set. We check if it would lie in a previously existing connection's mainlobe, sidelobe or null, and then check for available steering options for that connection. The non-conflicting connections are then put in the current transmit set and the conflicting connections are put in the next transmit set.

Different scenarios arise when beamsteering is considered, the main concern being whether or not the new position would now affect the previously accepted connections. This thus makes the algorithm run a second time after the beamsteering part is calculated, because we run the algorithm again to check if the new angle after beamsteering would now include any previously accepted connections. This model, however takes the *nodes* into consideration for calculation of conflicts instead just connections [16], because steering happens when a node moves its main beam but the pair remains connected and the other node may not change its main beam at all.

3.3 Mathematical Calculations

The mathematical calculations used while coding this network model are:

1) Friis' Equations

Although originally designed for free space propagation, the Friis' Equation is commonly used for general environments with a pathloss exponent $n \neq 2$. Nodes adjust their transmit power to only reach their intended destination. These equations are used to determine the transmit power in an established connection and then calculate the "danger distance" for the same connection. The equation for connection AB is given by:

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

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

Where, $\mathrm{P_{RS}} = Receiver\ Sensitivity$

$\mathrm{P_{tAB}} = Transmit\ Power$

$g_{tmAB} = Transmitter\ Gain\ for\ the\ mainlobe$

$g_{rmAB} = Receiver\ Gain\ for\ the\ mainlobe$

$d_{AB}^{n} = Distance\ between\ A\ and\ B$

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

$n = Pathloss\ Coefficient = 4$, for a shadowed urban environment

2) Danger Distance Calculation

Let's consider an interfering connection 'ab' inside the mainlobe of connection 'AB'. Then, using the Friis' Equation for this transmission/reception, we have,

$$P_{rAa} = \frac{P_{tAB} g_{tmAB} g_{rsab}}{\mathrm{d}_{\mathrm{Aa}}^{n}}$$

Where, $g_{tmAB} = Transmitter\ Gain\ for\ the\ mainlobe$

$g_{rsab} = Receiver\ Gain\ for\ the\ sidelobe$

Replacing P_{tAB} with the equation above, we have,

$$P_{rAa} = \frac{\mathrm{P_{RS}}\, d_{AB}^{n}\, g_{rsab}}{\mathrm{d}_{\mathrm{Aa}}^{n}\, g_{rmAB}}$$

$$\frac{P_{RS}}{P_{rAa}} = \left(\frac{d_{Aa}}{d_{AB}}\right)^{n} \frac{g_{rmAB}}{g_{rsab}}$$

Since P_{RS} is the required power for the connection to exist (receiver sensitivity signal power) and P_{rAa} is the interference power, $\frac{P_{RS}}{P_{rAa}}$ is the signal to interference ratio (SIR). We need the SIR to be more than 10 dB, in which case,

$$d_{Aa} < d_{AB} \sqrt[n]{SIR \ \frac{g_{rsab}}{g_{rmAB}}}$$

The value d_{Aa} gives us the "ddfactor_ML_SL" (mainlobe to sidelobe danger distance) which is the distance beyond which the interference will be strong enough for the existing connection to sustain.

Now, if the same condition is examined when an interferer lies inside a sidelobe. In this case,

$$P_{rAa} = \frac{P_{tAB} g_{tsAB} g_{rsab}}{\mathrm{d}_{\mathrm{AC}}^{n}}\ C$$

Again replacing P_{tAB},

$$\frac{P_{RS}}{P_{rAa}} = \left(\frac{d_{Aa}}{d_{AB}}\right)^{n} \frac{g_{rmAB} g_{tmAB}}{g_{rsab} g_{tsAB}}$$

$$SIR = \left(\frac{d_{Aa}}{d_{AB}}\right)^{n} \frac{g_{rmAB} g_{tmAB}}{g_{rsab} g_{tsAB}}$$

$$d_{Aa} < d_{AB} \sqrt[n]{SIR\ \frac{g_{rsab} g_{tsAB}}{g_{rmAB} g_{tmAB}}}$$

Here, we have a danger distance “ddfactor_SL_SL” (sidelobe to sidelobe danger distance) given by d_{Aa}.

From the above equations it is clear that the distance between the Existing node and the interfering node, if lesser than the danger distance, will eliminate the possibility of coexistence of the nodes or raise a condition for beamsteering.

CHAPTER 4

BEAMSTEERING

Beamsteering, in this thesis is seen as the factor that is responsible for the maximum improvement for a network of nodes in a particular area, its most conspicuous advantage being seen in a network with as many as 100 nodes, having a demand of as many as 50 connections at a time in the same area. In a network as such it becomes very difficult for even a directional antenna to provide good efficiency owing to the vast number of connections overlapping each other and forming conflicts that might not have been there in the case of a fewer number of nodes. It is actually found that the use of beamsteering can increase the efficiency of the network by almost 30 percent when compared to a network that aligns the nulls along interferences. The case where only the alignment of nulls is used is a rather rare one, where the interferences are avoided only if they fall in one of the nulls instead of the mainlobe or sidelobes. Since the null-size or null-level is half as much the sidelobes, and present only between two sidelobes, it becomes a rare case. However rare, it does add to the betterment of the efficiency of the network when compared to the Cone-and-Ball model.

Beamsteering, on the other hand is a case where the implemented algorithm tries to steer away every possible conflict that it finds, unless avoiding one conflict means adding another conflict in the same set of connection. This section diagrammatically explains the concept of beamsteering that has been implemented in the algorithm. In Fig. 3.1 we see what is to be the ideal arrangement of four nodes in a network, equidistant from each other. This arrangement is used only to attain a measurable geometry, around which the generalized arrangement of nodes can work. Now, if we consider the same geometry and try to understand the steering of the nodes, we find that to steer the mainlobe of A, and to have the same transmit power to B as it had before steering takes place, would mean that in the geometry of Fig. 3.1, we now have a virtual B_new that is now the direction of the boresight and we have to consider to use the same angles that connected the nodes A and B. Fig. 4.1 shows the arrangement if both nodes A and B steer and we have virtual nodes A_new and B_new to accommodate the angles and distances between the nodes.

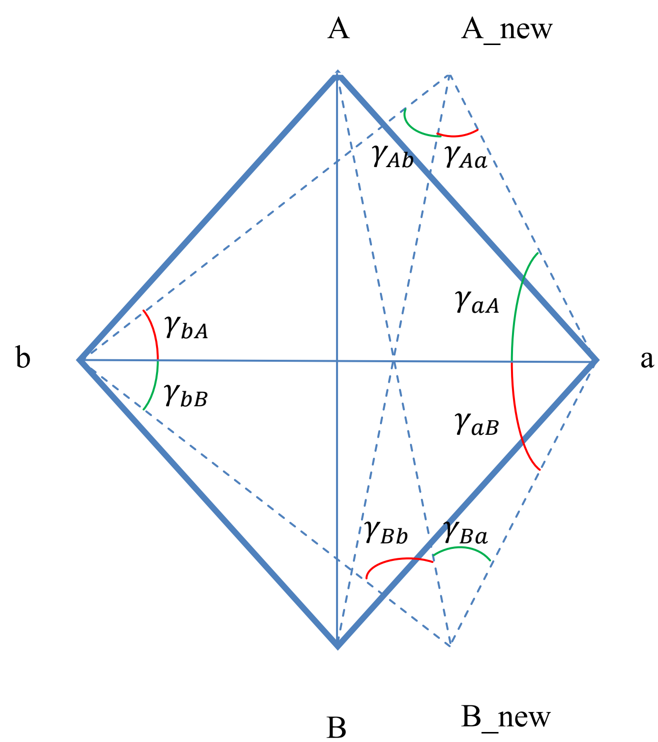


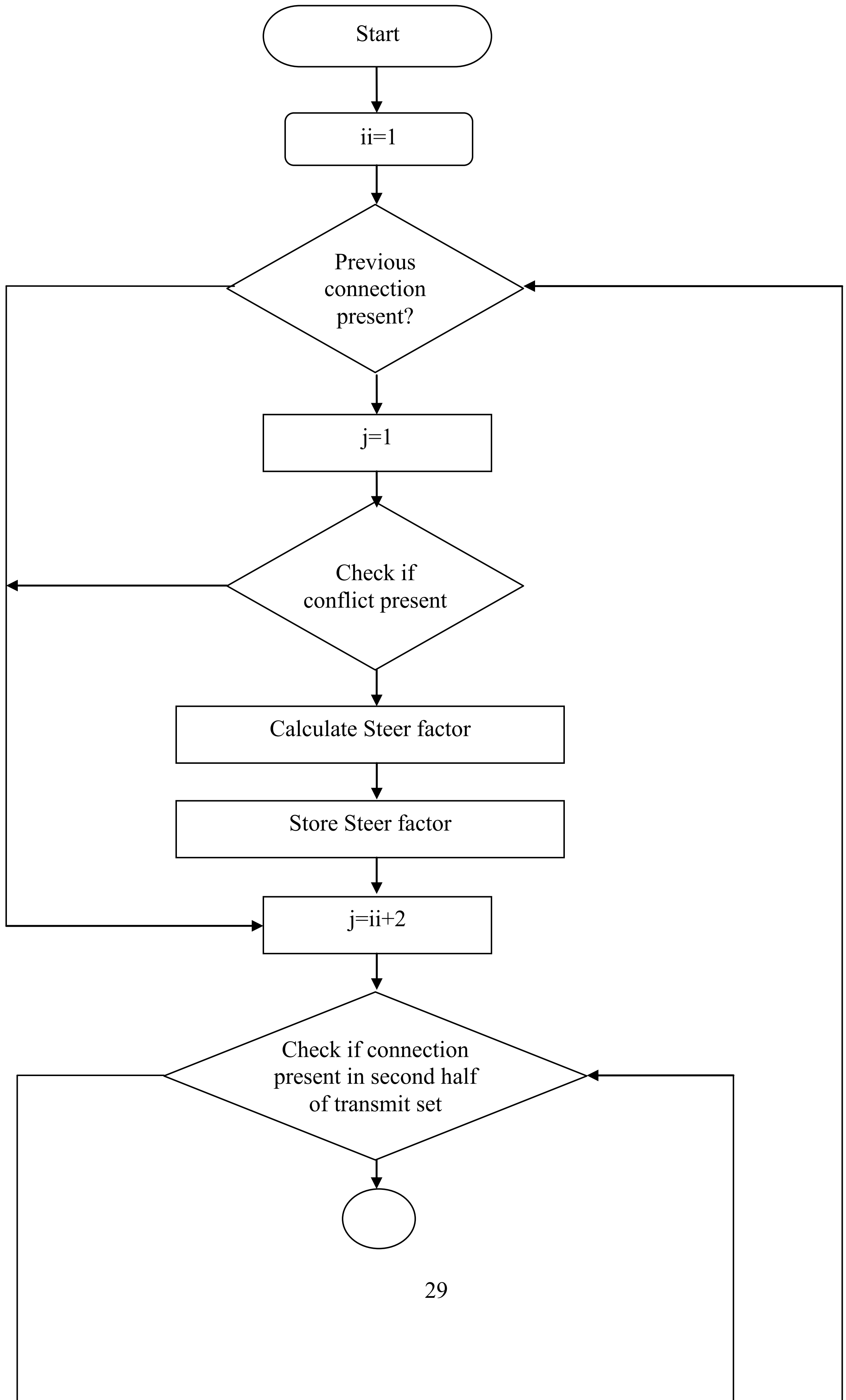
Fig. 4.1 Angle measurements when A and B have Steered

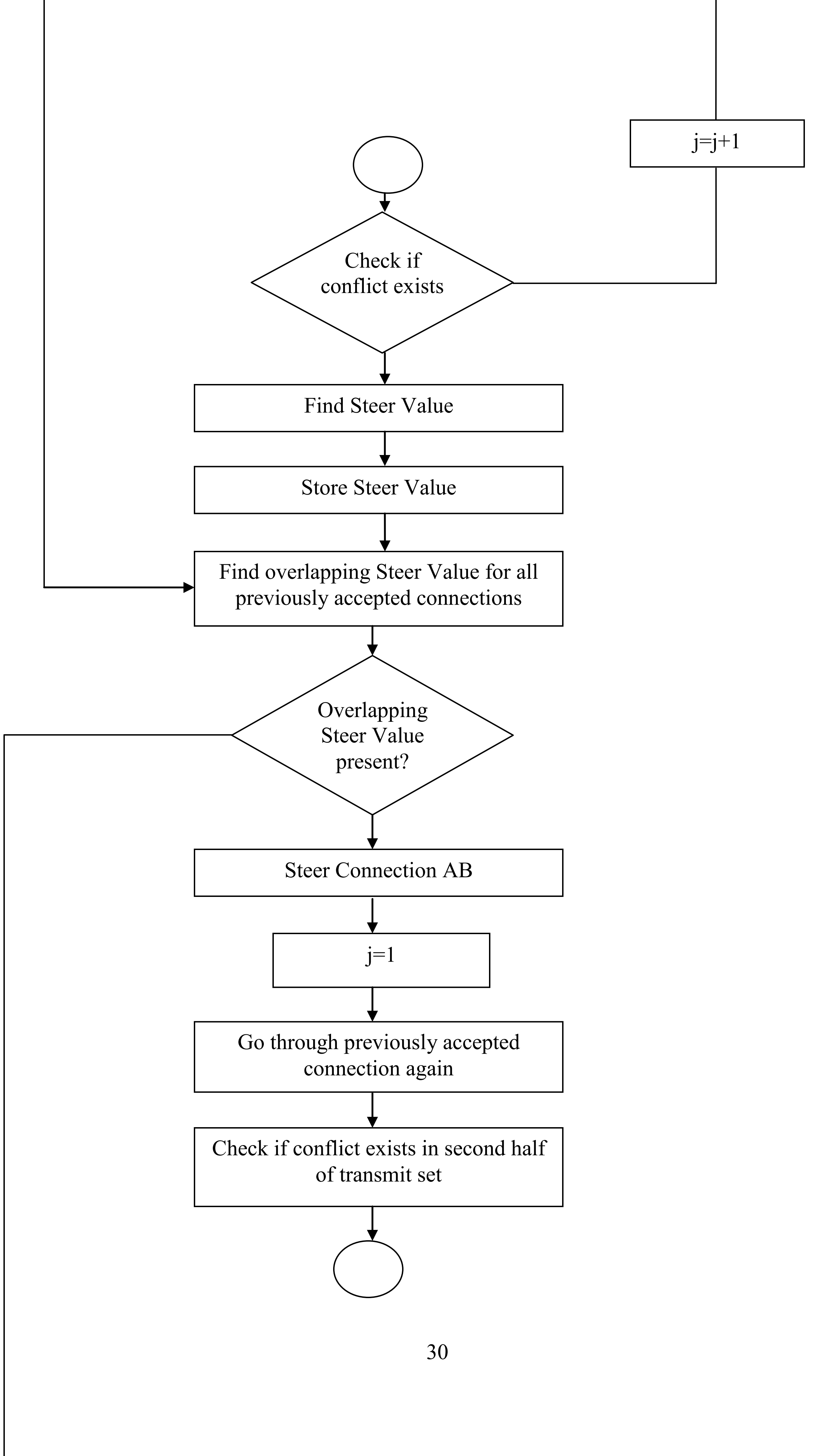
CHAPTER 5

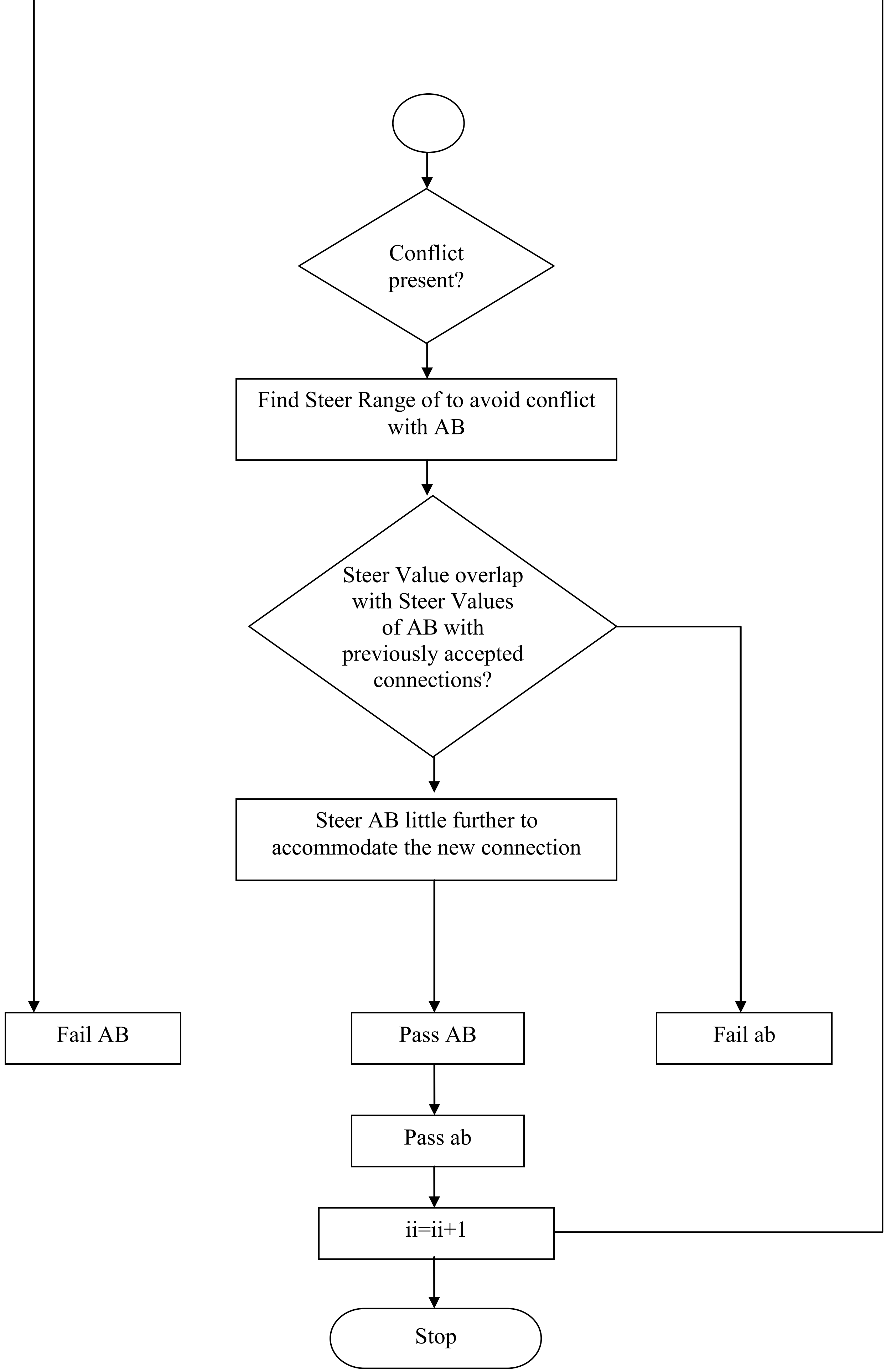
ALGORITHM

The algorithm implemented in this thesis checks if a connection has conflicts and finds steer values to see if it can find a steer factor that overlaps with the steer values of all of the previously accepted connections. It then uses the one common steer factor to steer the current connection to avoid these existing conflicts. While checking to see if a conflict exists, first the algorithm checks to see if two connections at a given time do not interfere with each other at all, in this case, it can be a clear pass, which would have been the case in the Cone-and-Ball model too. Next, it checks if one connection, even if dangerously close lies in one of the nulls of another. This eliminates the possibility of a conflict despite the proximity. Lastly, it checks if one node lies in the mainlobe or one of the sidelobes of another. This gives us the possibility of steering it into one of the adjacent nulls by steering the connection with respect to its boresight.

In the flowchart shown below, we have the connection ‘A-B’ as the connection we are currently looking to steer in case of conflict. First we look through all of the previously accepted connection pairs to see if the current connection conflicts with another. If they do, we find a steer factor for each one of them and find an overlapping steer factor common to all of them that would remove all conflicts. In this case, the previous connections are taken as ‘a-b’. Next we look at the remaining connections in the transmitset that follow the current connection and try to find yet another steer factor that would also accommodate them. If however, we don’t find one for these connections, we drop them from the current transmitset and add them in the nexttrasnmit. In this case too we consider the nect conections as ‘a-b’.


Start
ii=1
Previous connection present?
j=1
Check if conflict present
Calculate Steer factor
Store Steer factor
j=ii+2
Check if connection present in second half of transmit set


j=j+1
Check if conflict exists
Find Steer Value
Store Steer Value
Find overlapping Steer Value for all previously accepted connections
Overlapping Steer Value present?
Steer Connection AB
j=1
Go through previously accepted connection again
Check if conflict exists in second half of transmit set


Conflict present?
Find Steer Range of to avoid conflict with AB
Steer Value overlap with Steer Values of AB with previously accepted connections?
Steer AB little further to accommodate the new connection
Fail AB
Pass AB
Fail ab
Pass ab
ii=ii+1
Stop

CHAPTER 6

NETWORK SIMULATION

6.1 Simulation Parameters

The simulation parameters are derived from the assumptions and the mathematical analysis as shown in Section 3.2 and 3.3. One of the factors as "beamwidth" is assumed to be a value of 60° and then the rest of the parameters are derived from it. All the parameters for this network are as follows.

- *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.
- P_{RS} is the minimum required power at the receiver for a certain Signal to Interference Ratio (SIR), or the Receiver Sensitivity.
- *beamwidth* is the 3dB or half power beamwidth of the antenna.
- *Ddfactor_ML_SL* 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.
- *Ddfactor_ML_ML* 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.

6.2 Simulation Results

As seen in the set of results in Table 4.1 and 4.2 are the sets of steering values obtained after the steering factor is considered in the model, as shown in Table 4.1 and 4.2. The meanings of the values are:

- Inf: Connection passes inherently – no conflict.
- 0: Connection would have failed in the "ball-and-come" model, but passes in the "sidelobe-and-nulls" models due to nulls.
- Value other than 0 or Inf: Steering value calculated by the Steer function.

The tables below illustrate the values that are collected during the check for conflicts present.

For Node A:

Table. 6.1 – Values obtained after simulating the network (for Node A)

a_left		**a_right**		**b_left**		**b_right**	
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
24.3719	33.7469	0	0	0	0	0	0
0	0	0	0	0	0	0	0
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf

a_left		a_right		b_left		b_right	
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
0	0	0	0	0	0	0	0
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf

As seen in the table above, the connection would have failed, had it not been for the steering value found to resolve the conflicts.

For Node B:

Table. 6.2 – Values obtained after simulating the network (for Node B)

a_left		**a_right**		**b_left**		**b_right**	
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
0	0	0	0	10.3131	19.6881	0	0
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
0	0	0	0	0	0	0	0
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
0	0	0	0	0	0	0	0
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
0	0	0	0	0	0	0	0
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf

a_left		**a_right**		**b_left**		**b_right**	
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
0	0	0	0	0	0	0	0
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
0	0	0	0	0	0	0	0
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
0	0	0	0	0	0	0	0
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
Inf	Inf	Inf	Inf	Inf	Inf	Inf	Inf

CHAPTER 7

RESULTS AND DISCUSSION

The results that were obtained after the simulations were found using the model described in Section 3.2 and the algorithm described in Chapter 5. The 4 cases whose comparison was carried out were omnidirectional antennas, directional antennas – cone-and-ball model, directional antennas – sidelobes-and-nulls model and directional antennas – beamsteered model. Fig. 7.1 shows the comparison of the four cases in terms of the average number of allowable connections in the network vs. total number of connections in the network.

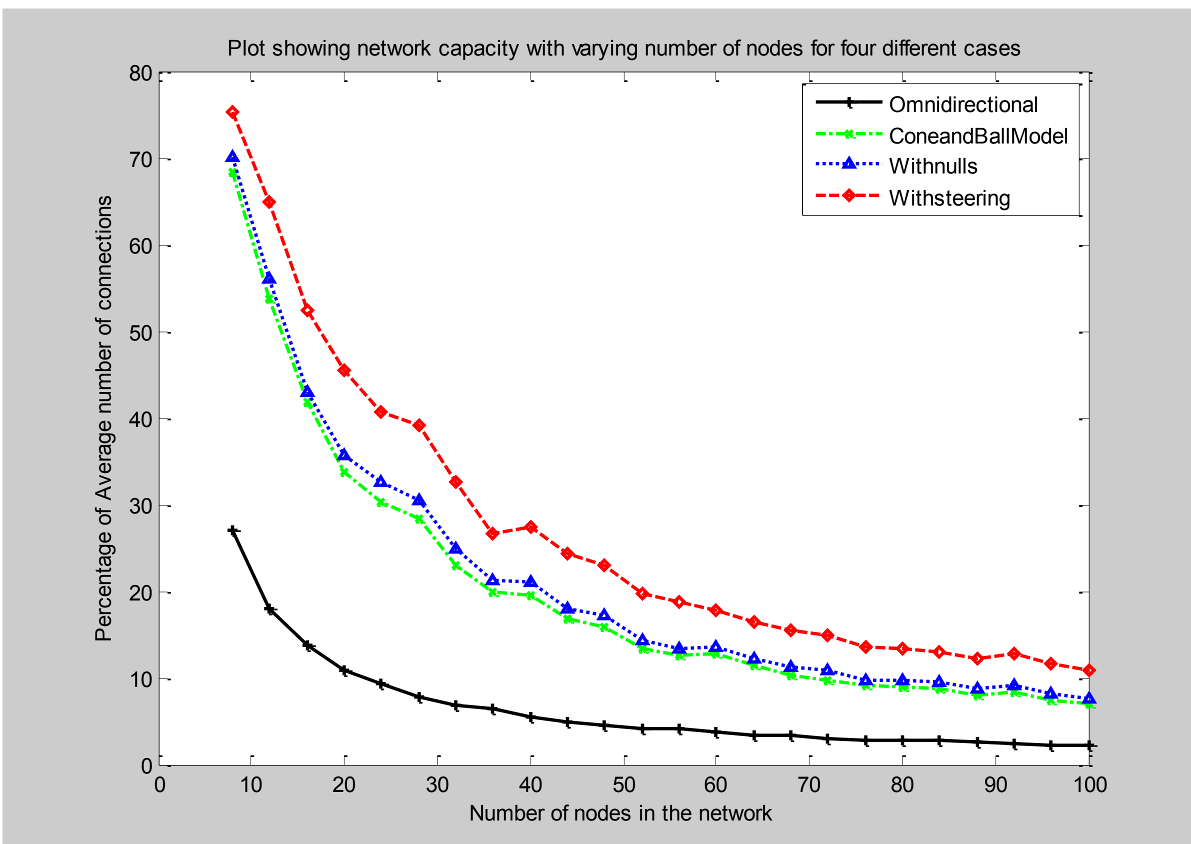


Fig. 7.1 – Comparison of Efficiency of the Network with 4 different Network Models

It can be seen from the figure that the efficiency of the network is least when omnidirectional antennas are used. At the place where number of nodes is 30, a set of data is collected, using which we can see that the efficiency goes considerably higher, by a factor of 20 percent when the ball-and-cone model is used (ie., directional antennas are used in place of Omnidirectional antennas) and is a little better, a factor of less than a 7 percent from that of the Cone-and-Ball model when the sidelobes-and-nulls model is used, without steering. However, there is noticeable increase in the efficiency when we have a beamsteered model. It increases the efficiency by a factor of about 30 percent as compared to the sidelobes-and-null model and about 37 percent increase when compared to the cone-and-ball model.

The vast increase in the efficiency in the beamsteered model, is due to the fact that, for every conflict that the algorithm encounters, it tries to steer the conflict away, and drops the connection only when steering is absolutely impossible. The case where only the Nulls are aligned towards the conflicts doesn't seem to increase the efficiency as much because the probability that a conflict would lie in a null is both rare and extremely random.

Next we have different cases of interference:

Case 1: No interference

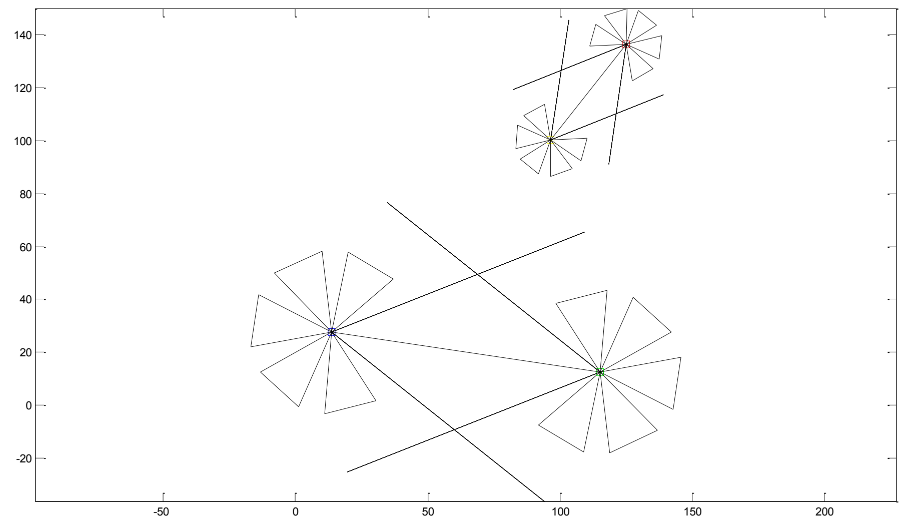


Fig. 7.2 – Case with No interference

Case 2: Interference in mainlobe

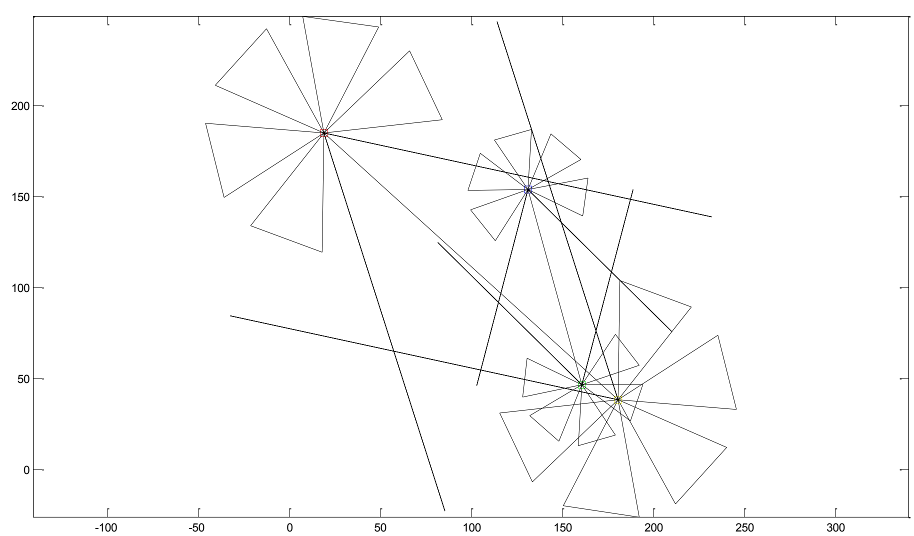


Fig. 7.3 – Case with Interference in mainlobe

Case 3: Interference in Sidelobe

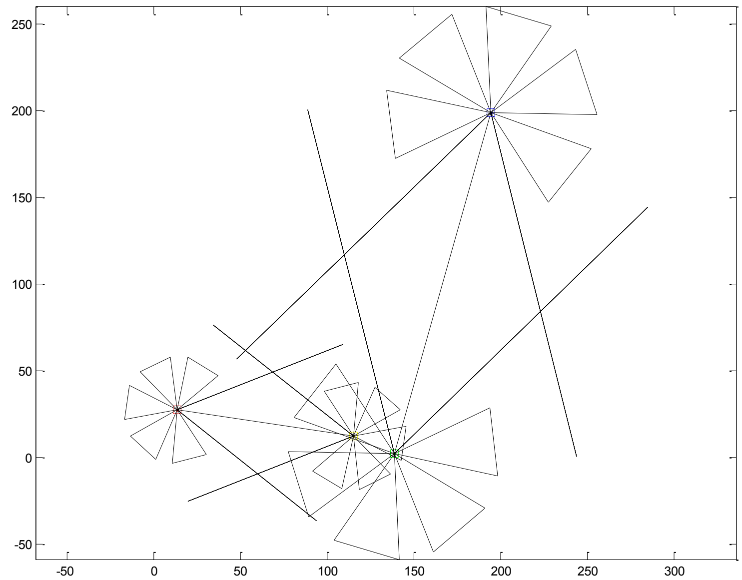


Fig. 7.4 –Case with Interference in sidelobe

Case 4: Interference in Null

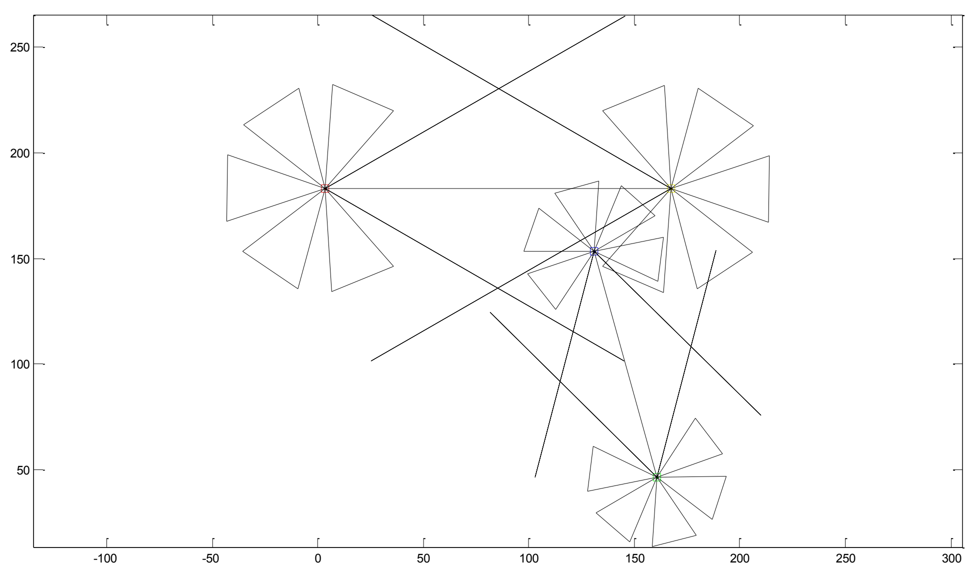


Fig. 7.5 – Case with Interference in Null

If we look at a case of steering closely, it can be explained through the figures below:

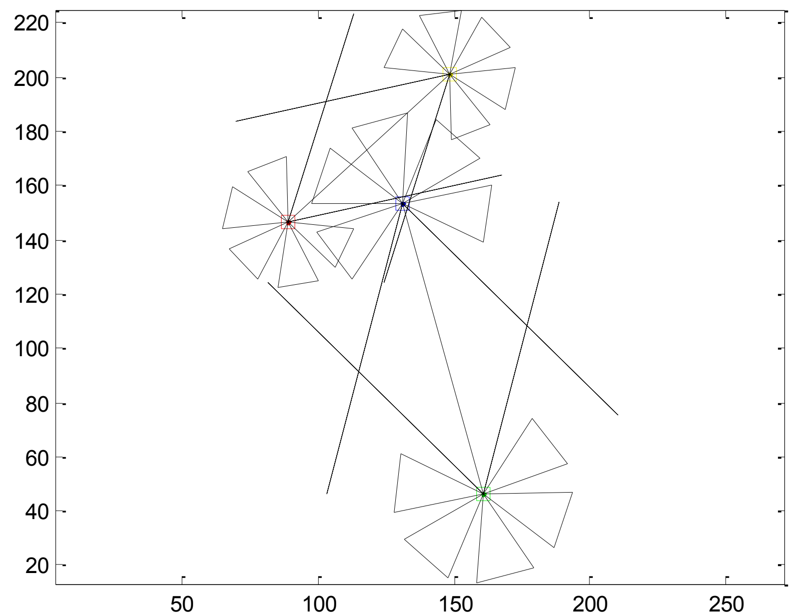


Fig. 7.6 Interference 'a' in mainlobe of 'A'

If steered, the above figure will look like the one below, where 'A' has steered itself to avoid 'a'.

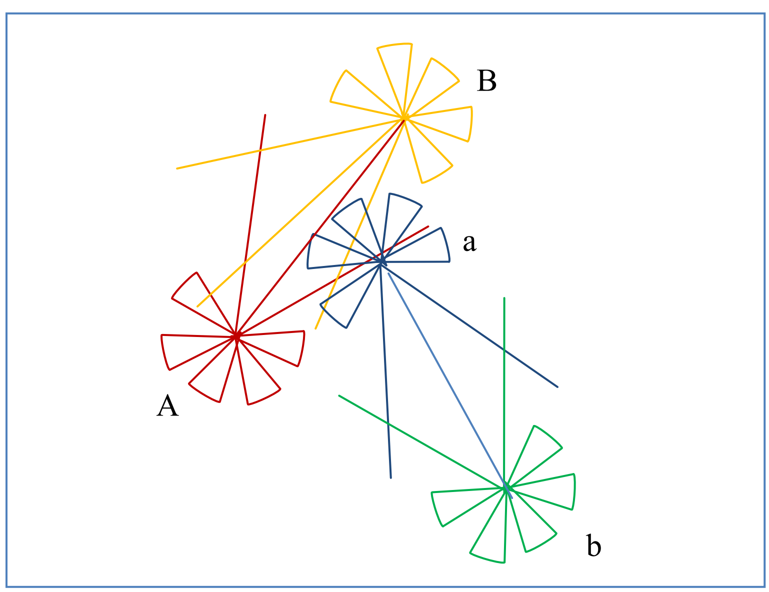


Fig. 7.7 Node 'A' Steering to avoid interference 'a'

CHAPTER 8

CONCLUSIONS AND FUTURE WORK

The network model and the proposed algorithm bring us to a few conclusions. It can be said that the concept of using a practical antenna pattern may increase the complications from the Signal Processing point of view, but after that has been successfully implemented, at the physical layer level, where the most important entity would be the spatial arrangement of the antenna pattern, which when implemented using various algorithm increases the capacity of the same network by a vast number. The spatial distribution of the nodes, however are a major point of concern in a network with as many as 90 to 100 modes or 45 to 50 connections, and hence need to be dealt with a beamsteering algorithm that can give the maximum possible capacity in the network.

The proposed algorithm in this model tries to accommodate as many connections as possible into the same transmit set, and increase the capacity of the network. However, this algorithm takes into consideration the steering being possible for only one connection at one point of time. There can be more complex algorithms that can check the conflicts in more than two connections and attempt at steering all the nodes at the same time. This however increases the complexity of the network and the calculations and results end up being more exponential than polynomial related, which can be categorized as the N-P Complete Complexity Theory.

This network model has given a substantial network enhancement, than what the simple Cone-and-Ball model had given in some of the previous work [4] [18]. There can however be scheduling schemes which take advantage of the interference model and power calculations. These scheduling schemes if implemented in the same network where beamsteering has been implemented, can see the increase in efficiency of the network manifold. At the same time, the centralized or decentralized nature of the network would change the network capacity again. The most challenging work would probably be implementing a beamsteering algorithm and a scheduling algorithm to a decentralized Ad hoc network. This network would take all of the research advantages into consideration and would perhaps emerge as the most advantageous network model with extremely high network capacity.

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VITA

Anudhriti Kashyap was born on January 10th 1986 in Sivasagar, Assam, India. She finished her schooling in the city of Mehsana, Gujarat, India. Given her keen interest, she earned a bachelor's degree in technology with Electronics and Communications Engineering as major parts of the course work. She graduated from Sikkim Manipal Institute of Technology in the year 2009 with a Bachelor of Technology degree.

Anudhriti joined University of Missouri – Kansas City in the fall term of 2010 to pursue her Master's degree in Electrical Engineering. She began her research on Wireless Networks using directional antennas with Dr. Cory Beard as part of her Master's Thesis. Upon earning her master's degree she plans to continue her research in the future and work as an engineer in the Cellular and Telecommunications industry.