Experimental Validation of Simultaneous Operation in an 802.11 Multi-hop Mesh Network

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by

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Certificate

This is to certify that the work contained in the thesis entitled "*Experimental Validation of Simultaneous Operation in an 802.11 Multi-hop Mesh Network*", by *Sreekanth Garigala*, has been carried out under our supervision and that this work has not been submitted elsewhere for a degree.

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Abstract

Internet and cellular telephony has been growing exponentially from the past decade but, much of this growth has been confined to developed countries and metropolitan pockets in the developing world. A low cost access technology is necessary to develop a similar growth in rural areas. In the Digital Gangetic Plains (DGP) project, 802.11 technology is being used as a low-cost and long distance technology. As part of DGP, an extensive testbed has been built in the rural areas consisting of multi-hop 802.11 point-to-point links, the testbed spanning up to 80km at its longest.

Since 802.11 was designed for indoor use only, trying to use it outdoor poses many challenges spanning several layers of the OSI networking stack. In this thesis, we address some of the issues at MAC layer. 802.11 uses CSMA/CA for medium access but, it is not suitable in networks where all the links are point-to-point and setup before-hand, since there is no arbitrary contention in the network. In contrary, Spatial-reuse Time Division Multiple Access (STDMA) Protocol where scheduling transmissions is done before-hand is more appropriate. STDMA performance depends on how much spatial reuse of the channel is possible. 802.11 defines at least 11 channels out of which three (1, 6 and 11) are non-overlapping. If we use omni-directional antenna, we can setup at most 3 links with 3 independent channels simultaneously. Since we are using directional antennae, if we provide sufficient Signal-to-Interference ratio, we can transmit/receive independent information on different links at a node on the same channel. We call this as *simultaneous transmission/reception* and collectively *simultaneous operation*. Now we can schedule the links such that a node alternates between transmit and receive modes for all its links simultaneously. This is called two-phase scheduling and is used in addressing the problem of medium-access in point-to-point multi-hop 802.11 network. We experimentally validated the *simultaneous operation* and calculated the Signal-to-Interference ratio required for error-free operation of the links.

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Chapter 1

Introduction

Internet and cellular telephony has been growing exponentially from the past decade but, much of this growth has been confined to developed countries and metropolitan pockets in the developing world. The reason for this is that communication technology (wired and cellular) is value-priced for western markets. As much of the population in developing countries is in rural areas (Ex. In India rural population constitutes 74% [1]), communication technologies have not been widespread in developing countries. Land-line access technologies are too expensive and difficult to deploy and wireless networks such as 802.16 [10] and Ricochet [8] may be easy to deploy but they also are not cost-effective. In contrast, 802.11 family of wireless technologies [4] have the following advantages.

- *Low Cost*: prices of technology and products are coming down rapidly because of increasing availability and mass production.
- *Interoperability*: achieving interoperability between products from multiple vendors.

In the Digital Gangetic Plains (DGP) project, 802.11 technology is being used as a low-cost access technology for data and VoIP connectivity to rural villages.

The main aim of the DGP project is to provide voice and data communications in rural areas at a low cost. As part of the DGP project, an extensive testbed has been built. This testbed covers several tens of kilometers of sparsely populated rural areas connected by long distance 802.11 point-to-point links spanning up to 80 kms at its longest forming a multi-hop wireless access network. 802.11 technology is also used for last hop access with in a village.

The DGP testbed currently has 11 nodes located at different villages and 11 point-to-point links. The testbed is depicted in Fig 1.1. All the links work based on the 802.11b variant of the technology. We use off-the-shelf 802.11b access-points (AP) at all locations.

Although 802.11 was designed for indoor use only, it is being used in a different setting where all the links are distant, static and point-to-point. Several technical challenges must be addressed before such a network can become viable. These issues span several layers of the OSI networking stack [19]. In this thesis, we focus on some issues at the Medium Access Layer (MAC).

802.11 uses carrier sense multiple access with collision avoidance (CSMA/CA) protocol [5] for medium contention resolution. This protocol fits the situation where there are a small number of nodes contending for a channel in an indoor setting. But, this is not the case in our testbed because there is no arbitrary contention as all the links (except those with in a village where we use CSMA/CA for medium access) are static point-to-point and setup before-hand. As opposed to contention-based protocols, consider Spatial-reuse Time Division Multiple Access (STDMA) schemes [18]. In these schemes, scheduling of transmissions is done before-hand to guarantee contention free operation. These schemes achieve spatial reuse of the spectrum and their performance depends on how much spatial reuse of the channel is possible. The amount of spatial reuse depends on how many transmissions can go on simultaneously without mutual interference. With omni directional antenna, a node can broadcast same information to all the neighbours at a time but cannot transmit independent information simultaneously. But, in our setting, at a node we have multiple directional antennae each pre-mounted and pre-aligned towards a particular neighbour as shown in Fig.1.2. This motivates us to consider the possibility of *simultaneous operation* to achieve maximum spatial-reuse.

Fig.1.2 shows a node N with two directional antennae forming two links. There are three possible cases.

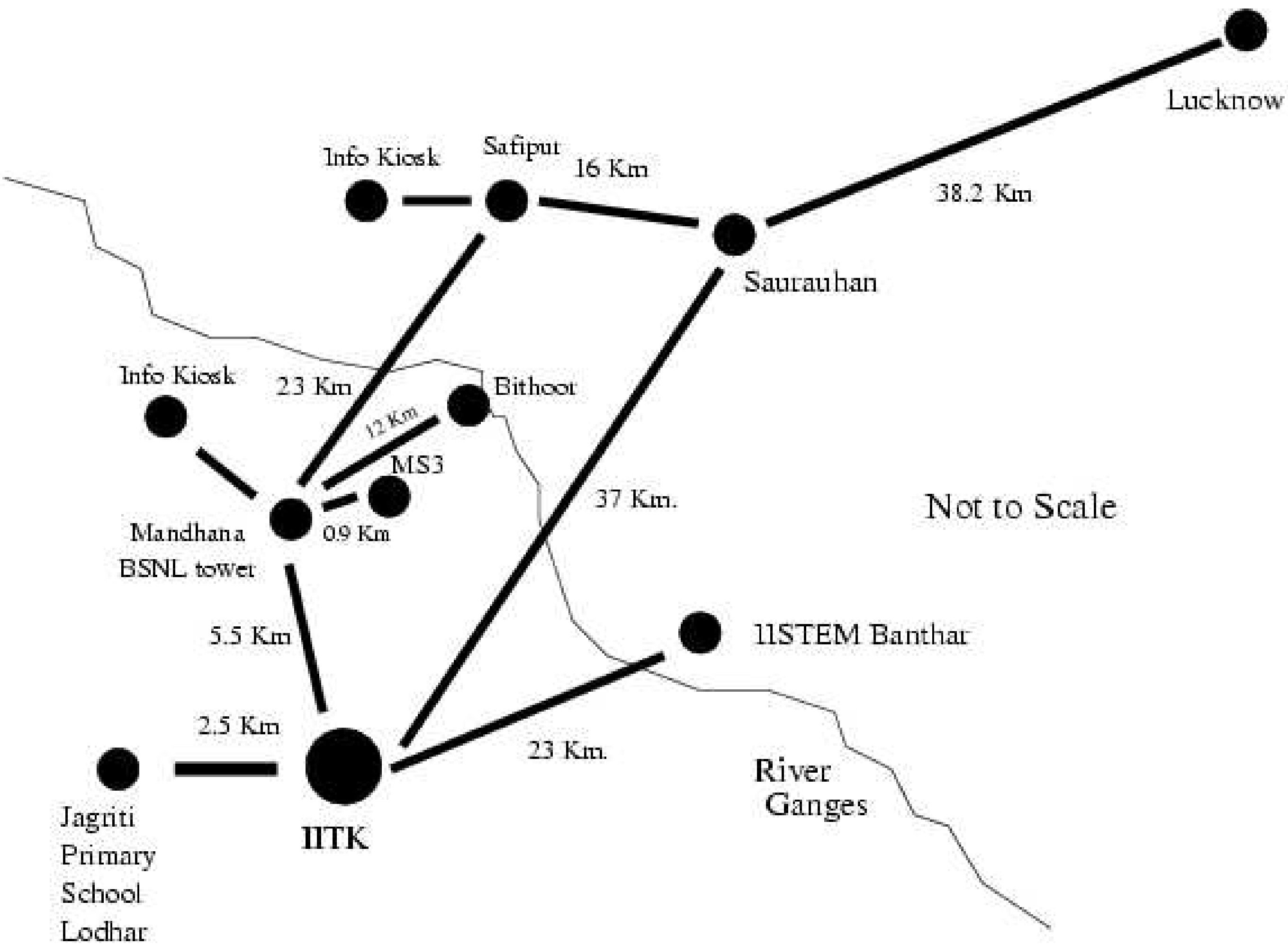

Figure 1.1: Digital Gangetic Plains Project Testbed

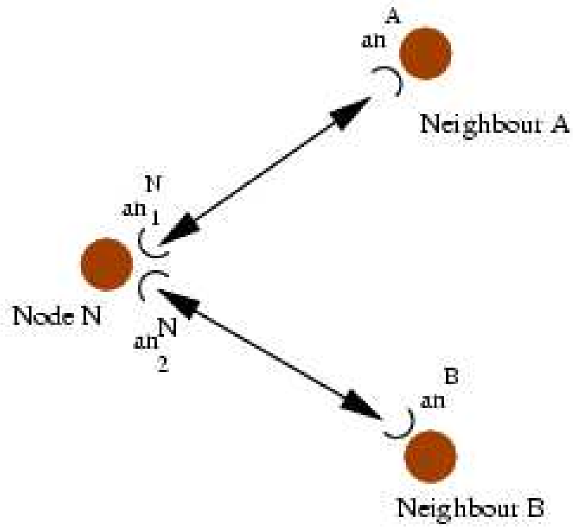

Figure 1.2: Multiple directional antennae at a node

1. Node N transmitting along both antennae an_1^N and an_2^N. This is called *Simultaneous Transmission*

2. N receiving along both antennae. This is called *Simultaneous Reception*

3. N transmitting along one link and receiving along other link.

The third case is not possible because when a link is transmitting, transmission power near to it will be quite high interfering with other link. We denote *simultaneous transmission* with *sim-Tx*, *simultaneous reception* with *sim-Rx* and the third case as *mix-Rx-Tx*. We collectively term *Simultaneous Transmission* and *Simultaneous Reception* as *Simultaneous Operation*. Only theoretical proof of *Simultaneous Operation* is not sufficient because there are many factors like leakage of signals, multi-path effects which cannot be properly taken into consideration in theoretical calculation. We have done experiments both indoor and on the testbed and validated the simultaneous operation through results.

A significant point in the above discussion is the assumption that all the simultaneous transmissions are in a single channel. Indeed, 802.11b defines at least 11 channels out of which three (1,6 and 11) are non-overlapping. If we use omni directional antennae at a node, we can send independent information to multiple neighbours only if we use independent channels for different transmissions. The issue of medium contention arises only when we use the same channel or overlapping channels. If two links are allocated independent channels, they can be scheduled independent of each other. Since there are only three independent channels available, only three links can be up at a node simultaneously (Fourth channel can be squeezed as described in [15], but this is reserved for local access within a village). If we use directional antennae at a node, simultaneous operation of the links in the same channel is potentially possible.

We have experimentally proved that *Simultaneous Operation* on the same channel is possible. We also proved that case 3, in which at a node some links are in transmit mode and others are in receive mode, is not possible.

Now based on the flexibility of *Simultaneous Operation*, a 2-phase scheduling mechanism combined with a channel allocation scheme can be used for addressing medium access problems as described in [11].

In this 2-phase scheduling scheme, each node alternates between transmit and receive modes (for all its links simultaneously) and when a node transmits, all of its neighbours receive and vice-versa. This achieves maximum link utilization: a link is always active, and hence is effective scheduling mechanism.

For simultaneous operation of the links, we need to consider signal levels at which the links are working. In order for correct operation of the links, signal power must be some extent greater than noise and interference levels. We measure this as Signal to Noise and Interference ratio (SNIR). We ignore noise by assuming reception power is significantly above ambient noise level and we call this as Signal-to-Interference ratio (SIR). SIR should be beyond a certain threshold level for correct operation of the links which we denote as SIR_{reqd}.

For 802.11b 11Mbps transmission, relation between SIR (Signal-to-Interference Ratio) and Bit Error Rate (BER) is given by [12]

$$\begin{aligned} BER \; &= \tfrac{128}{255} \times \Big[24 \times Q\left(\sqrt{4 \times SIR}\right) + 16 \times Q\left(\sqrt{6 \times SIR}\right) \\ &+174 \times Q\left(\sqrt{8 \times SIR}\right) + 16 \times Q\left(\sqrt{10 \times SIR}\right) \\ &+24 \times Q\left(\sqrt{12 \times SIR}\right) + Q\left(\sqrt{16 \times SIR}\right)\Big] \end{aligned}$$

where

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_{x}^{\infty} e^{\frac{x^2}{2}}\, dx$$

From the above equation, for a desired BER of 10^{-8}, SIR_{reqd} is about 10 dB.

We also experimentally measure SIR_{reqd} and compare with above theoretical result. To see how we provide SIR_{reqd} in our network, consider case 1 in Fig.1.2, while an_1^N is receiving signal from an^A, it also sees interference from an^B because of the side-lobe leakage of the directional antennae. *Simultaneous reception* or *transmission* will happen only if this interference is below certain level of main signal. The radiations along "side" and "backward" directions are called "side-lobes" and will be below radiation along the "main" direction. This difference between radiations along main and side directions is called side-lobe *rejection level*. The side-lobe rejection level varies with the angle from main direction. So, we can change SIR by adjusting angular separation between an_1^N and an_2^N. when SIR equals or exceeds SIR_{reqd}, *Simultaneous Operation* is possible.

There are many challenges in doing the experiments both indoor and on the testbed.

1. We use attenuators for finer control over the power levels but, they are susceptible to errors in the outdoor environment.

2. Since we are dealing with Radio Frequency (RF) waves over long-distances, it may be possible that results obtained in one experiment run might not match with the other run with same experiment setup because RF behaviour depends on atmospheric conditions, obstacles in the path and also multi-paths.

To get rid of the problems ,we initially performed our experiments indoor. We have addressed the first problem in the indoor setting by using RF cables instead of open air medium. The second problem is inevitably solved indoor. Still there are some other problems indoor: Access points (AP) interfere with each other if there is no proper physical separation between them. If one AP sees any interference from the other AP, it will back-off according to CSMA/CA mechanism and hence we cannot transmit with both APs simultaneously. To avoid this, we physically separated Access Points to avoid interference between them by keeping them in two different rooms. Another implementation problem we faced is unreliability of the individual equipment. Since a single experiment involves many equipment like Access Points, Laptops, RF cables, PCMCIA cards, Antennae, it is very difficult to predict what might go wrong. After doing the experiments indoor, we moved on to the testbed and have done several runs of the same experiment in order to confirm the results.

One more implementation issue we addressed is avoiding the bidirectional traffic along a link. Consider the simultaneous transmission case in Fig.1.2. When Node N is transmitting to both the neighbours, there should not be any traffic from the neighbours towards N. If there is any transmission, it comes under case 3 described previously, where one link is in transmit mode and the other is in receive mode. This situation is not possible as discussed above. If we use TCP traffic to send data from N to its neighbours, there will be TCP acknowledgments from those neighbours which we do not want. If we use UDP *unicast* traffic, still there are MAC acknowledgments from those neighbours. So we avoid acknowledgments by using the UDP *broadcast* traffic.

Our results can be summarized as follows.

- Successfully proved that case 3 in Fig.1.2 is not possible, as expected theoretically.
- Calculated the SIR_{reqd} in the indoor experiment, which is about 10 to 15 dB depending on the power of transmission.
- Successfully verified *Simultaneous Transmission* on the testbed.
- Successfully verified *Simultaneous Reception* and calculated the SIR_{reqd} on the testbed which is 10 dB.

Our approach of *simultaneous operation* can be applied to any wireless multi-hop mesh network with the following physical layer properties.

- All the links are point-to-point
- All nodes have directional antennae towards each of its neighbours.
- Sufficient side-lobe rejection level (such that it provides SIR_{reqd}) is provided between the antennae at a node.

1.1 Related Work

The Nokia Rooftop [7] is a commercial system providing outdoor wireless connectivity to users. They provide internet connectivity to users by using omni-directional antenna at each node and directional antenna at the gateway of internet. However they use omni-directional antennae between nodes which do not have the flexibility of simultaneous operation.

[6] describes a rooftop wireless Ad-Hoc network built using off-the-shelf 802.11 hardware. They use omni-directional antennae at the nodes and CSMA/CA protocol for medium access. But with this kind of infrastructure, simultaneous operation is not possible.

Seattle wireless networks [9] is also an outdoor wireless network using omni-directional antennae. It uses CSMA/CA protocol; and the problem of scarcity of channels is not addressed.

The Wireless Internet Gateways (WINGS) [13] is a part of the DARPA Global Mobile (GloMo) Information systems Program. WINGS addresses some of the issues in wireless networking. It uses a MAC layer protocol called FAMA-NCS that is somewhat similar to 802.11 which performs better than CSMA/CS in some cases. However this protocol considers only omni-directional antenna at a node.

[21] and [22] describe outdoor wireless mesh networks based on 802.11b. As in our testbed, they also use directional antennae between the nodes. They tried to solve the problem of providing coverage over an area by careful selection of the channels, antennas, and the locations. However they have not considered the flexibility of simultaneous operation. The problems with this design are that it is very tedious to provide coverage in a fairly big area and also the entire link capacity may not be used all the time.

Christchurch Wireless Community network [2] is an outdoor wireless network providing network connectivity to users. They used parabolic antenna at each node but, they have not considered simultaneous operation.

In [14], STDMA protocol over directional antennae has been proposed. The use of directional antenna patterns reduces the multiple access interference and produces substantial improvement in throughput. But they have not considered the flexibility of simultaneous operation in STDMA.

In [20], for medium access, CSMA/CA has been modified to take the advantage of directional antennae but, since there is no arbitrary contention in our network, STDMA is more suitable than CSMA/CA mechanism.

[17] describes an outdoor wireless network to provide broadband to rural communities. They envision the need for a new MAC protocol for their mesh network with a mixture of directional and omni-directional antennae.

In [16], they have emphasized the advantages of directional antennae over omni directional antennae in terms of interference reduction. They have assumed that a node with multiple directional antennae can communicate with only 3 neighbours at 3 different frequency channels and allocated the channels by constructing a network graph of degree 3 (maximum). But they have not explored the possibility of a node communicating with different neighbours simultaneously on a single channel.

1.2 Organization of the Report

The rest of the report is organized as follows. In Chapter 2, we discuss in detail about the medium access issues. Chapter 3 describes the indoor experiment to prove that mix-Rx-Tx is not possible. Chapter 4 describes the indoor Signal-to-Interference calculation experiment. In Chapters 5 and 6, we describe the simultaneous transmission and reception experiments performed on the testbed. In Chapter 7, we detail our conclusion and the scope for future work.

Chapter 2

Medium Access Issues

In this chapter, we first discuss about the scenario of directional antennae at a node in our network. In section 2.1, we discuss why CSMA/CA MAC is not suitable and in section 2.2, we describe STDMA protocol and how spatial reuse can be maximized with simultaneous operation. Then we describe the three possible cases of simultaneous operation and the available channels in 802.11b. Next we discuss about the SIR issues, radiation pattern of the parabolic grid antenna and the effect of side-lobes on simultaneous operation. Finally in section 2.3, we describe the 2-phase scheduling MAC protocol which is based on the simultaneous operation.

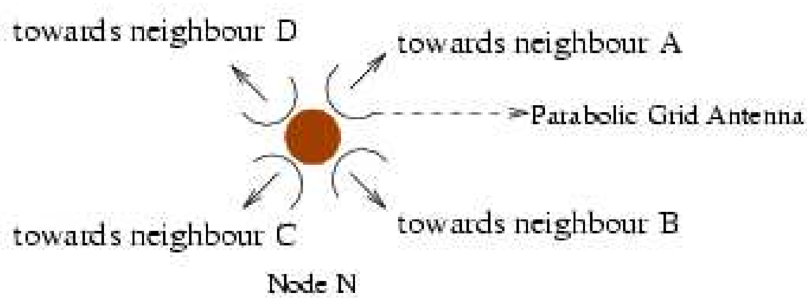

Figure 2.1: Directional antennae at a node

Fig 2.1 shows a node with parabolic grid antennae in our testbed. Each antenna is pre-mounted and pre-aligned towards the direction of a particular neighbour. As discussed in Chapter 1, 802.11b technology is used in our network. 802.11b uses CSMA/CA technology for medium access. Now we discuss about CSMA/CA protocol and why is it not suitable in our network.

2.1 Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol

CSMA/CA protocol works as follows: A node desiring to transmit senses the medium; if the medium is busy then the station will defer its transmission to a later time and if the medium is free for a specified time then the station is allowed to transmit and the correctness of transmission is confirmed by the acknowledgment from the receiving node.

In order to reduce the probability of two stations colliding because they cannot hear each other, a Virtual Carrier Sense mechanism is used. A node willing to transmit a packet will first transmit an RTS (Request To Send) packet, which will include the duration of the following transmission and the destination node will respond (if the medium is free) with a CTS (Clear To Send) packet, which will include the same duration information. All nodes receiving either RTS and/or CTS will use this information along with the Physical Carrier Sense when sensing the medium. However, in an environment where the nodes are concentrated and can hear each other, RTS and CTS are not necessary and a direct sensing of the medium is sufficient.

CSMA/CA is not suitable in our network because all the links are point-to-point and setup beforehand, and hence there is no arbitrary contention for the medium. That is, a node with a directional antenna towards a particular neighbour always communicates directly with that neighbour only. As opposed to contention based protocols, consider Spatial-reuse Time Division Multiple Access protocol.

2.2 Spatial-reuse Time Division Multiple Access (STDMA) protocol

In Time Division Multiple Access (TDMA) protocol, the entire time is divided into slots and one or more slots are assigned to each node. In STDMA protocol, scheduling of transmissions is done in such a way that a time slot is shared when the radio units are geographically separated such that a minimum interference is obtained. In this way performance is improved by letting several radio units share the same slot. This is called *spatial reuse*.

The amount of spatial reuse depends on what transmissions can be carried out simultaneously. Until now, no substantial research work has been done on how to utilize the directional antennae to increase the spatial reuse. If we use omni directional antenna at a node, at a particular instant of time, it can receive from or transmit to a single neighbour only. It can broadcast the same information to all neighbours simultaneously but cannot transmit independent information simultaneously. But now, in our network we have nodes with multiple directional antennae. So, simultaneous operation will be possible which will maximize the spatial reuse. We illustrate this with the following scenario.

Consider a scenario with 3 nodes operating as in Fig 2.2.

With the above scenario, there are three possible situations.

1. *Simultaneous Reception*: Node N receiving along both the links as in Fig 2.3 which we denote as *sim-Rx*.

2. *Simultaneous Transmission*: Node N transmitting along both the links as in Fig 2.4 which we denote as *sim-Tx*.

3. Node N transmitting along one link and receiving along the other link as in Fig 2.5. We denote this as *mix-Rx-Tx*.

Now we discuss the possibilities of each case. Cases 1 and 2 are potentially possible. case 3 is not possible due to the following reason. When node N is transmitting, the radiation power near to it will be quite high which will interfere with the signal

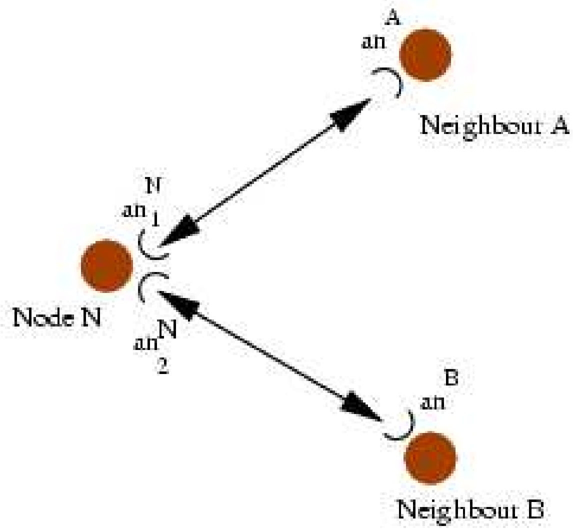

Figure 2.2: Multiple directional antennae at a node

along the receiving link. The first two cases we collectively term as *Simultaneous Operation*.

In all the above cases, we consider simultaneous operation in a single channel. A channel is a segment of the total radio frequency spectrum in a given band available for communications to and from a given radio. IEEE 802.11 defines at least 11 channels as shown in Fig 2.6.

There are at least three channels (1,6 and 11) that are completely non-overlapping. A particular channel must be assigned for each link in the network. The pair of transceivers for a particular link are tuned to the same channel. If two links at a node are allocated non-overlapping channels, they can operate without causing any mutual interference. In this way, with omni-directional antenna at a node we can have maximum of 3 links operating simultaneously, where each link is allocated a non-overlapping channel. Since we have directional antennae at a node, *simultaneous operation* in a single channel is potentially possible.

In order for *simultaneous operation* to be possible, careful consideration of signal levels at a node is needed. For the correct reception of links, at a node, main signal

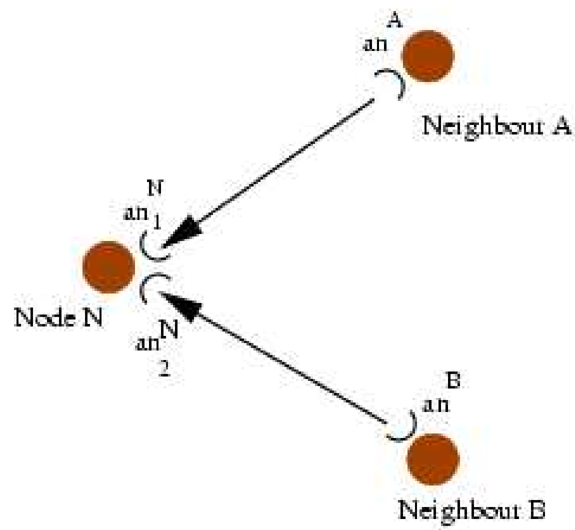

Figure 2.3: Case 1 - Simultaneous Reception: sim-Rx

level must be some extent greater than noise level, which we measure as *Signal-to-Interference Ratio* (SIR). SIR should be beyond a certain threshold for correct reception of the signal, which we denote as SIR_{reqd}.

Interference along a link at a node is caused mainly by the side-lobe leakage of the parabolic grid antenna. Consider the radiation pattern of a parabolic grid antenna shown in Fig. 2.7 [3]. This also corresponds to the receiver sensitivity while receiving along a particular direction. The radiation is maximum in the main direction with an 8 degree beam width. The side-lobe level is at least 25 dB to 30 dB below the main signal level beyond an angle of 30^o from the main direction.

Apart from the radiation along the "main" direction, there are radiations of lesser magnitude along "side" and "backward directions". The radiations along "side" and "backward" directions are called "side-lobes". There will be a leakage of transmission or reception of signals along these side-lobes. The difference between the radiation along main and side-lobes is called "side-lobe rejection level" and it varies with the angle from main direction.

To observe the effect of side-lobes on simultaneous operation, consider the case

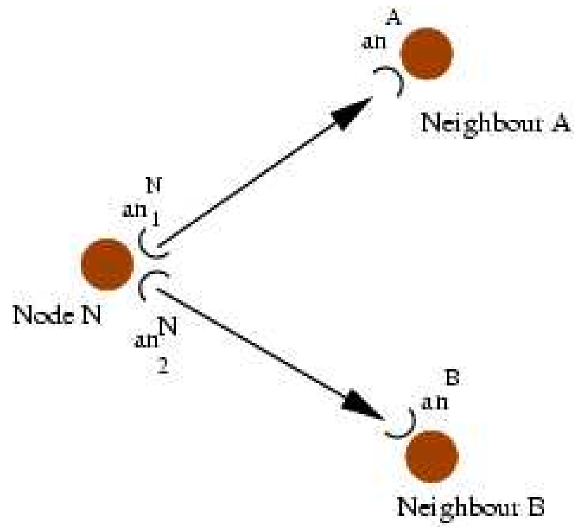

Figure 2.4: Case 2 - Simultaneous Transmission: sim-Tx

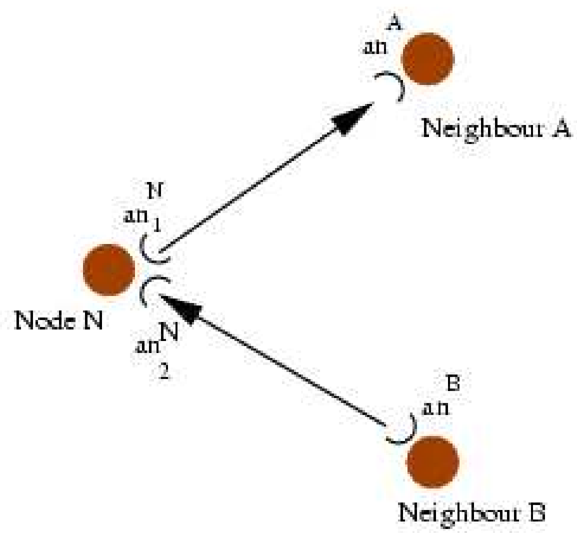

Figure 2.5: Case 3 - Transmission on one link and reception on another link: mix-Rx-Tx

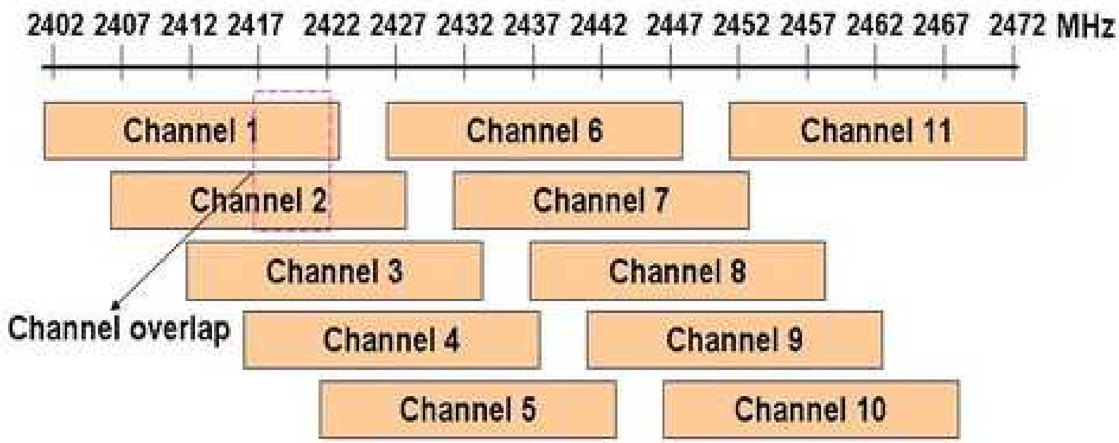

Figure 2.6: Channels in 802.11

of simultaneous reception at node N in Fig 2.3. an_1^N hears the signal from an^A as well as interference from an^B. In the same way, an_2^N hears the signal from an^B as well as interference from an^A. Similarly, in simultaneous transmission in Fig 2.4, an^A hears the signal from an_1^N as well as interference from an_2^N. In the same way, an^B hears the signal from an_2^N as well as interference from an_1^N. If this mutual interference can be tolerated, simultaneous transmission/reception is possible. Now referring to Fig 2.3, the interference signal seen by an_1^N is the signal received from an^B minus side-lobe rejection level and SIR is the main signal received from an^A minus the interference signal. If we adjust the power levels at an^A, an^B and side-lobe rejection level such that SIR equals or exceeds SIR_{reqd}, simultaneous operation is possible. Now with this simultaneous operation, we can address the problem of medium-access in 802.11 network with a two-phase scheduling algorithm.

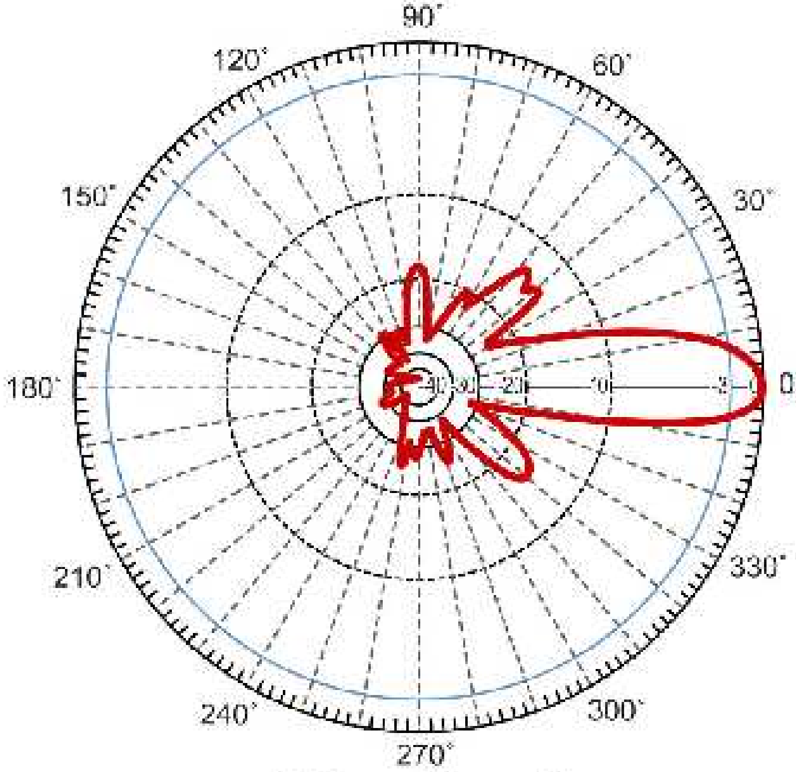

Figure 2.7: Spatial Radiation Pattern of Parabolic Grid Antenna

2.3 2-Phase Scheduling Protocol

The working of 2-phase scheduling [11] is based on the flexibility of *simultaneous operation* with the condition that all the links at a node can be either in transmit mode or in receive mode simultaneously. In this scheme, scheduling is done in a such a way that each node alternates between transmit and receive modes. When a node transmits, all its neighbours receive and vice-versa. A scheduling conflict would arise at a node if some links have to be in transmit mode and others have to be in receive mode. This situation will not arise if the network graph is bipartite. In 2-phase protocol, the network graph nodes are divided into a bipartition (V_1, V_2). The scheduling traffic of along the edges is alternated between the directions $V_1 \rightarrow V_2$ for a fraction f and $V_2 \rightarrow V_1$ for a fraction $1 - f$ of the time. In this approach, a link always active in one direction or the other and hence it achieves maximum link utilization. This method is clearly more efficient than CSMA/CA with arbitrary contention because it achieves the maximum link utilization.

Chapter 3

Indoor Experiment to prove that mix-Rx-Tx is not possible

In this chapter we describe the experiment which proves that *mix-Rx-Tx* is not possible. *mix-Rx-Tx* situation can be created in *simultaneous reception* (*sim-Rx*) with the traffic which uses acknowledgments as shown below.

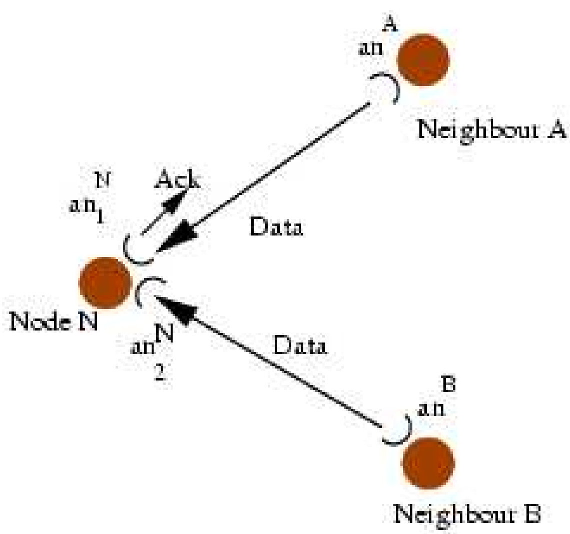

Figure 3.1: Simultaneous Reception with acknowledgments

Consider simultaneous reception situation in Fig 3.1. an^A is transmitting to an_1^N and an^B is transmitting to an_2^N independently. If suppose an_1^N sends acknowledgment to an^A then, it will become the case in which transmission happens on one link and reception happens on the other link. But, this is not possible because when a node is transmitting, the radiation power near to it will be quite high, which interferes with the receptions on the other links at that node. We prove this in our experiment.

If we use TCP traffic, there will be acknowledgments. UDP unicast traffic also has acknowledgments at the MAC level. MAC broadcast of UDP traffic has no acknowledgments. To create mix-Rx-Tx case, we use UDP unicast traffic which has acknowledgments and to create sim-Rx case, we use UDP broadcast traffic which has no acknowledgments. We compare the throughput achieved in mix-Rx-Tx and sim-Rx cases to show the drop in the throughput in mix-Rx-Tx case.

We run the experiment for different signal power levels due to the following reason. Consider Fig 3.1 in which an_2^N is receiving signal from an^B. If an_1^N sends acknowledgment to an^A then its effect on the transmission from an^B will depend on the power levels at which an^B and an_1^N are transmitting. If these transmissions happen without errors irrespective of the power levels, we can say that this case is possible. We vary the power levels using attenuators. These attenuators are prone to errors in the outdoor environment. So, we prefer indoor to do the experiment.

3.1 Experiment Setup

The indoor experiment setup is as shown in Fig 3.2. The setup mimics the situation in Fig 3.1. We have two links. Each link is between an 802.11 Access Point (AP) and a laptop with 802.11b client card. We use RF cables to achieve control over power levels. We need to make sure that one AP does not "back-off" due to other's transmission which will happen in 802.11 CSMA/CA MAC protocol. If back-off happens, there will be only one transmission at a time and simultaneous transmission will not happen. Since we cannot disable back-off in commercial APs, we physically isolated the APs by putting them in two different rooms. The two clients are laptops, with

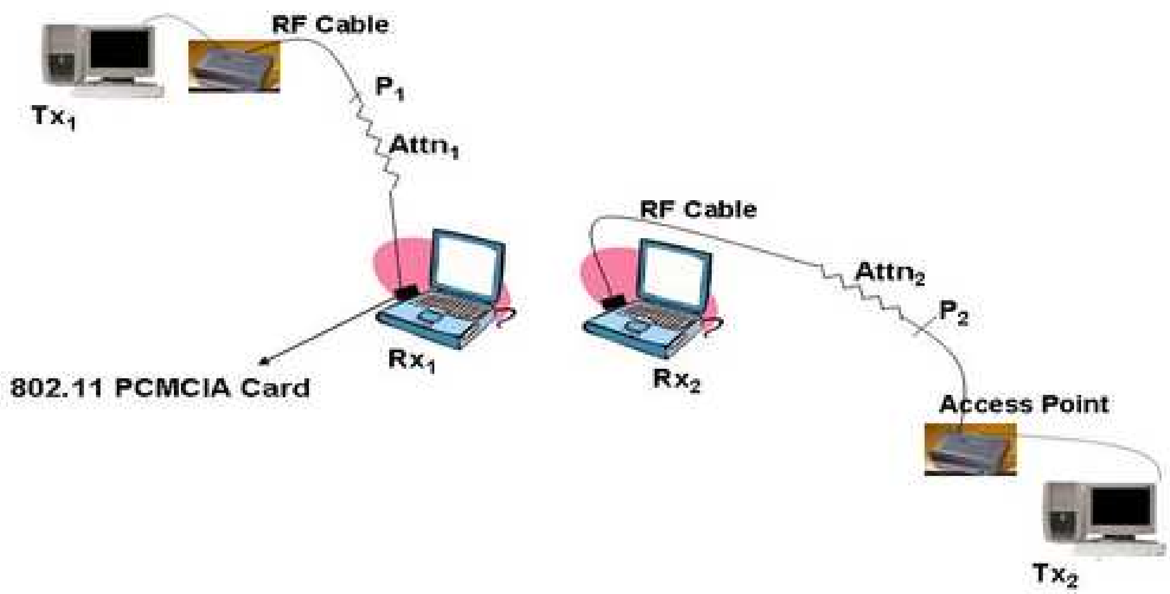

Figure 3.2: Indoor Experiment Setup to prove that mix-Rx-Tx is not possible

802.11b PCMCIA cards which are having external antenna connectors for attaching cables. A PC which is the sender of traffic is connected to each AP. We denote the PCs as Tx_1 and Tx_2 as shown in Fig 3.2. We use attenuators $attn_1$ and $attn_2$ to control the power levels on the links. Rx_1 and Rx_2 (act as an_1^N and an_2^N respectively with respect to Fig 3.1) are the receivers of traffic. Tx_1 and Tx_2 (act as an^A and an^B respectively with respect to Fig 3.1) are the transmitters of traffic. We measure the received throughput at both the clients. All the transmissions use channel 1 and we have to ensure that there are no other transmissions in this channel which can effect the experiment. For ensuring that there are no other transmissions in channel 1, before starting the experiment, we sniff for any packets in that channel and confirm that there are no other transmissions.

3.2 Motivation for the setup

The motivation behind this particular setup is as follows. According to Fig 3.1, we should have two receivers and two transmitters. So as receivers, we use two laptops with PCMCIA cards and as transmitters we use two APs. In all our experiments, we use AP at the transmitter and a laptop with PCMCIA card as the receiver. The reason is as follows. When we are using AP at the receiver, acknowledgments are coming from that AP to the transmitter even though we use UDP broadcast traffic. So we always use PCMCIA card at the receiver side. If we use PCMCIA card at the transmitter, we cannot control the power of transmission as efficient as we control it in the AP. So we always use AP at the transmitter side. Since we have to measure the power level received by the transmitters, we use RF cable to connect transmitter and receiver which has a known cable loss. We use attenuators between transmitters and receivers to vary the power levels. The PCMCIA client cards will be having a leakage. To create interference between the two receivers, we keep the two in proximity, and confirm the interference by varying the distance and measuring the throughput. The mutual interference between the client cards can be varied by varying the distance between them and we experimentally measure the distance at which they are not interfering. In our experiment, we keep the distance such that they both interfere. We confirm this as follows. We measure the throughput on one link while the other link is switched off. And we compare this value with the throughput achieved while the two links are active. If there is any difference between the two values, we can confirm that there is interference. Since our motive in the experiment is to show that *mix-Rx-Tx* is not possible, we need not measure the magnitude of interference and ensuring that interference exists from the other link is sufficient.

3.3 Experiment Run

Both the APs are configured for a transmit power of 0 dBm. The measured power level at point P_1 is -10 dBm. So, the received power level at Rx_1 as sent by Tx_1 is $-10 - Attn_1$. The measured power level at point P_2 on the second link is -8.4 dBm. So, the received power level at Rx_2 as sent by Tx_2 is $-8.4 - Attn_2$. The interference between Rx_1 and Rx_2 is caused by the leakage of the PCMCIA cards, which we call as "proximity leakage". We varied the power levels (by varying the attenuator values) on both the links and measured the throughput using UDP unicast traffic in one run and UDP broadcast traffic in another run.

3.4 Results

Table 3.4 shows the result of our experiment. At low attenuation levels, that is, at high power levels, the throughput is not much effected in UDP unicast traffic. As the power levels go down, the throughput goes down because the radiation near the client due to the transmission of acknowledgments becomes sufficient enough, which interfere with the reception at the other client. Beyond the attenuation value of 50 dBm, the throughput went down in the case of unicast traffic. If we observe the case of UDP broadcast traffic, there is almost no variation in the throughput with decrease of power levels (The magnitude of throughput in broadcast is less compared to that of unicast traffic. This is because broadcast packets are sent at 5.5 Mbps where as unicast packets are sent at 11 Mbps. Initially we could not figure out how to modify it but later, in all the experiments, we modified it by changing a parameter in AP so that broadcast traffic also are sent at 11 Mbps). Even though 802.11b specification is 11 Mbps, in UDP unicast traffic, we are able to reach a throughput of around 6.7 Mbps because of the overhead of the headers of data packets and, control packets. In UDP unicast traffic, the throughput in the case of Rx_2 is around 5.7 Mbps. This lesser value of throughput is because of the leakage of the AP. To confirm this, we interchanged the two APs, then the throughput values also interchanged. Our result proves that acknowledgments in the traffic create the situation of *mix-Rx-Tx* and also that it is not possible.

$Attn_1$	$Attn_2$	power received	power received	Throughput with ack(Mbps)		Throughput without ack(Mbps)	
(dBm)	(dBm)	at Rx_1(dBm)	at Rx_2(dBm)	Rx_1	Rx_2	Rx_1	Rx_2
0	0	-10	-8.4	6.4	5.33	4.73	4.64
10	10	-20	-18.4	6.71	5.55	4.77	4.62
20	20	-30	-28.4	6.62	5.65	4.63	4.71
30	30	-40	-38.4	6.86	5.40	4.79	4.72
40	40	-50	-48.4	6.84	5.79	4.77	4.71
50	50	-60	-58.4	3.81	1.80	4.83	4.70
60	60	-70	-68.4	3.45	1.40	4.80	4.72
70	70	-80	-78.4	2.78	0.32	4.77	4.71

Table 3.1: Table showing the effect of acknowledgments in Simultaneous Reception

In the above experiment, the physical distance between Rx_1 and Rx_2 was 64 cm. The whole experiment shows the effect of proximity leakage of the client cards. But in the testbed, we need to consider the effect of side-lobe leakage of the antennae which we have not considered in this experiment because just proximity leakage is enough to show that *mix-Rx-Tx* is not possible. We measure the effect of distance between the client cards on the throughput in the case of UDP unicast traffic.

Table 3.2 shows the result of our experiment. In the experiment, we kept attenuation values constant and change the distance between the two clients. When the attenuation value is at 50 dBm, at a distance of 154 cm., there is no interference between the clients. We conclude that there is no interference because the throughput on each link obtained at this distance, when both links are up, is same as the throughput achieved on that link when the other link is switched-off. The distance is almost same even if the attenuation levels are varied.

Our results can be summarized as follows. We successfully proved that mix-Rx-Tx is not possible and at a distance of 154 cm. between the client cards, there is no mutual interference between them.

In the next chapter, we measure the SIR_{reqd} in sim-Rx case indoor.

$Attn_1$ (dBm)	$Attn_2$ (dBm)	distance (Cm.)	Throughput with ack(Mbps)	
			at Rx_1	at Rx_2
50	50	64	3.81	1.80
50	50	72	3.87	1.83
50	50	75	3.97	1.93
50	50	82	4.05	2.07
50	50	100	4.61	2.86
50	50	154	6.77	5.74
60	60	62	3.0	1.46
60	60	82	4.09	1.47
60	60	160	6.88	3.41
70	70	64	3.54	1.61
70	70	84	3.67	1.98
70	70	160	5.54	4.95

Table 3.2: Table showing the effect of distance between the client cards on the throughput in UDP unicast traffic

Chapter 4

SIR_{reqd} Calculation for Simultaneous Operation

In this chapter we describe the indoor experiment to calculate SIR_{reqd} for *simultaneous operation*.

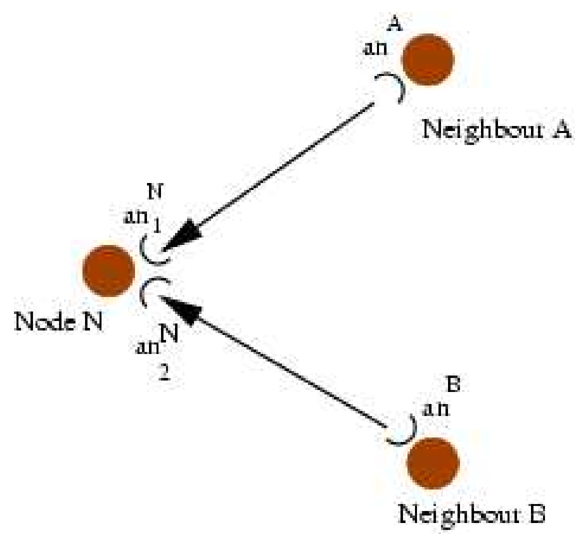

Figure 4.1: Simultaneous Reception

Consider the simultaneous reception situation in Fig 4.1. While an_1^N is receiving signal from an^A, it also hears the transmission from an^B because of side lobes. Similarly, an_2^N gets the interference from an^A. Likewise, there is mutual interference in simultaneous transmission also. In order for the correct operation of the links, we need to know the tolerable interference level. We experimentally measure the Signal-to-Interference ratio for error-free operation. We denote this as SIR_{reqd}. Then by comparing this value with the side-lobe rejection level of the directional antenna, we show that simultaneous operation is possible.

4.1 Experiment Setup

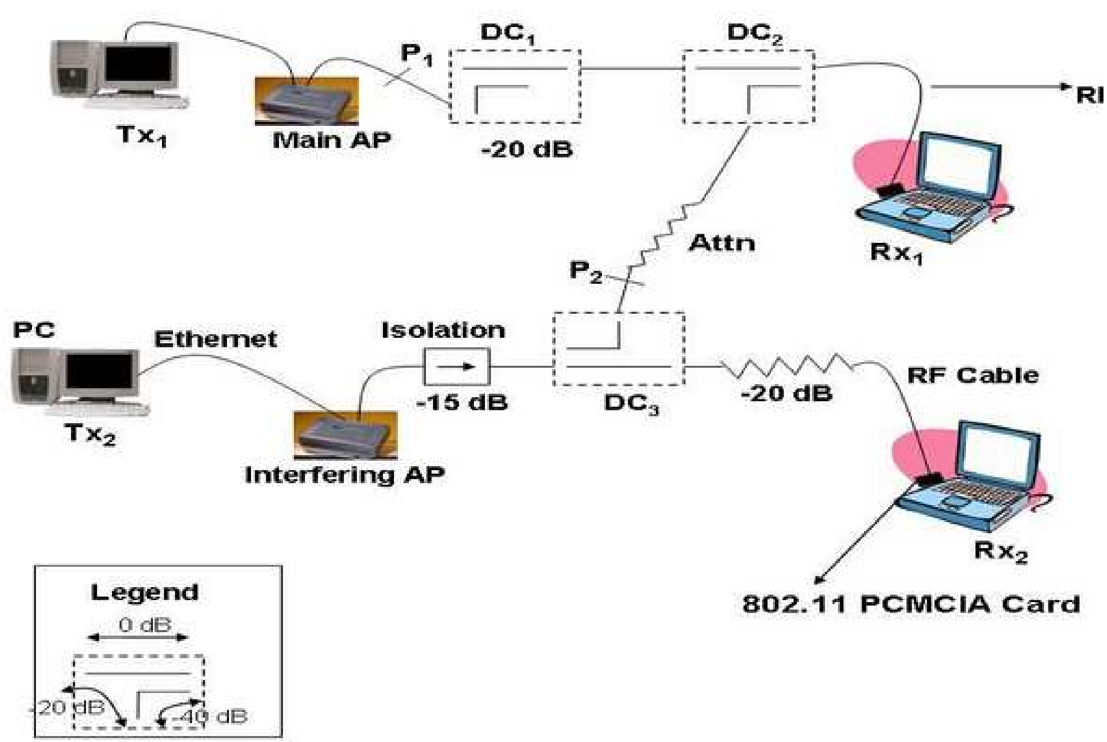

Figure 4.2: SIR calculation experiment setup

The setup to measure SIR_{reqd} is as shown in Fig 4.2. We have two links; main link and auxiliary link, in our setup. Both the links are between 802.11 access point (AP) and 802.11 client. To achieve control over the power levels, we use RF cables for the two links. We need to ensure that one AP does not "back-off" due to the signal from the other AP, as will happen in 802.11 CSMA/CA MAC. If they back-off, there will be only one transmission (simultaneous transmission will not happen). So to avoid this, we provide sufficient isolation between the two APs. The two APs are physically isolated in two separate rooms to avoid interference. We ensure isolation by the way attenuators and direction couplers are connected. Each AP is connected to a Personal Computer (PC) which is the sender of traffic. Client is a laptop with PCMCIA card having external connector. In this way we simulate the *simultaneous reception* indoor. Rx_1 and Rx_2 are the receivers of traffic (act as an_1^N and an_2^N with respect to Fig 4.1 respectively). Tx_1 and Tx_2 are the transmitters of traffic (act as an^A and an^B with respect to Fig 4.1 respectively). To simulate the effect of side-lobes, we feed a controlled amount of interference to the main link from the auxiliary link. We call $Tx_1 \leftrightarrow Rx_1$ link as main link and the other link as auxiliary. We choose like this because in this case, we vary the interference power from the auxiliary link to the main link and calculate the throughput on main link while maintaining constant throughput on the auxiliary link. Since these two links are symmetric, measuring throughput on one link is enough to calculate SIR_{reqd}. We use a continuous UDP broadcast traffic on both the links. We use broadcast traffic to avoid acknowledgments so that clients will never transmit. We measure the received UDP throughput at the main client as a function of the interference level and thus measure SIR_{reqd} for error free operation of the link.

4.2 Motivation for the setup

The motivation behind this setup is as follows. We mimic the situation in Fig 4.1 with the indoor setup. We need two receivers and two transmitters. We use a laptop with PCMCIA card as the receiver and a PC connected to an AP as the transmitter of the traffic. To have control over the power levels, we use RF cables to connect transmitters and receivers. We vary the power levels using attenuators. Now, to mimic the effect of side-lobes at node N in Fig 4.1, we feed controlled amount of interference power from the auxiliary link to the main link. For this purpose, we use direction couplers. Since we have to maintain proper isolation between the two APs, we use isolaters that give some more drop in the power level.

4.3 Experiment Run

The main AP is configured for a transmit power of 0 dBm and the interference AP for 20 dBm. The measured power level of the main AP at point p_1 is -10 dBm. Thus the received signal is -30 dBm (20 dB drop due to directional coupler DC_1). The measured power level from the interference AP at point p_2 is -8.5 dBm. So, the interference level at the main client is -8.5-Attn. The power level seen by the interference AP from the main AP is -20-Attn-7 (7 dB drop due to cable loss). In our experiment, this is at least -100 dB which is less than the typical noise level. Now we vary "Attn" value and measure the throughput.

4.4 Results

Fig 4.3 plots the throughput as a function of Signal-to-interference ratio for various power levels. Each curve shows the throughput for a particular transmission power level. At a signal level of -78 dBm, the packet error rate is very high even without any interference. This is the least signal level that can be used for the operation of an 802.11 client. In Fig 4.3, the throughput goes very low when the SIR is below a certain threshold. This threshold value is the SIR_{reqd}. This is about 10 dB for all transmission power levels except for -78 dBm which is about 15dB. Now we can use this value to show that simultaneous operation is possible. Consider Fig 4.1, the interference power seen by an_1^N from an^B is the power received by an_2^N minus side-lobe rejection level. If we adjust the transmission power levels at an^A and an^B such that, the received power levels at an_1^N and an_2^N are same, then SIR will be equal to the side-lobe rejection level. Since the side-lobe level is about 25 dB below the main signal level beyond an angle of 30^0 from the main direction, we say that simultaneous operation is possible.

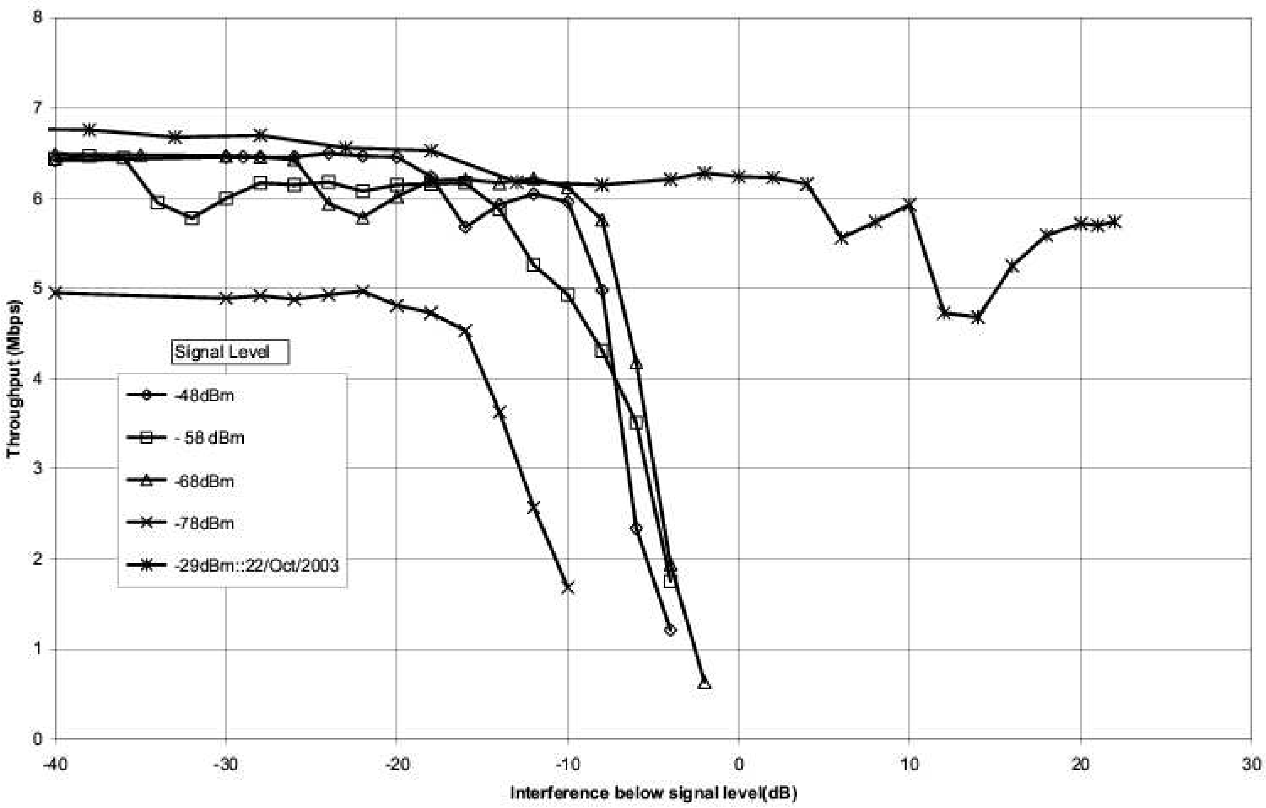

Figure 4.3: Throughput Vs Interference-to-Signal Ratio

In the next chapter, we describe the simultaneous reception experiment on the testbed.

Chapter 5

Simultaneous Reception Experiment

In this chapter, we describe the experiment to verify simultaneous reception on the testbed. We also measure the SIR_{reqd} for error-free operation. Consider the

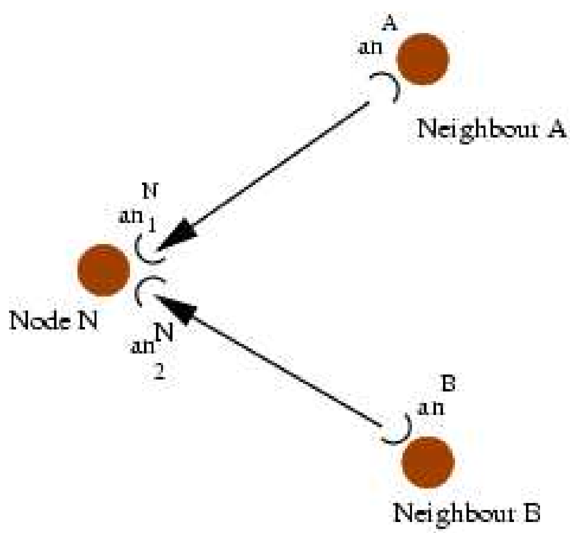

Figure 5.1: Simultaneous Reception

simultaneous reception situation in Fig 5.1. At node N, an_1^N is receiving from an^A and at the same time, an_2^N is receiving from an^B. an_1^N will see the interference from an^B because of the side-lobes. Similarly an_2^N will see the interference from an^A. We measure SIR_{reqd} by conducting the experiment with different transmission power levels. We use UDP broadcast traffic on both the links.

5.1 Experiment Setup

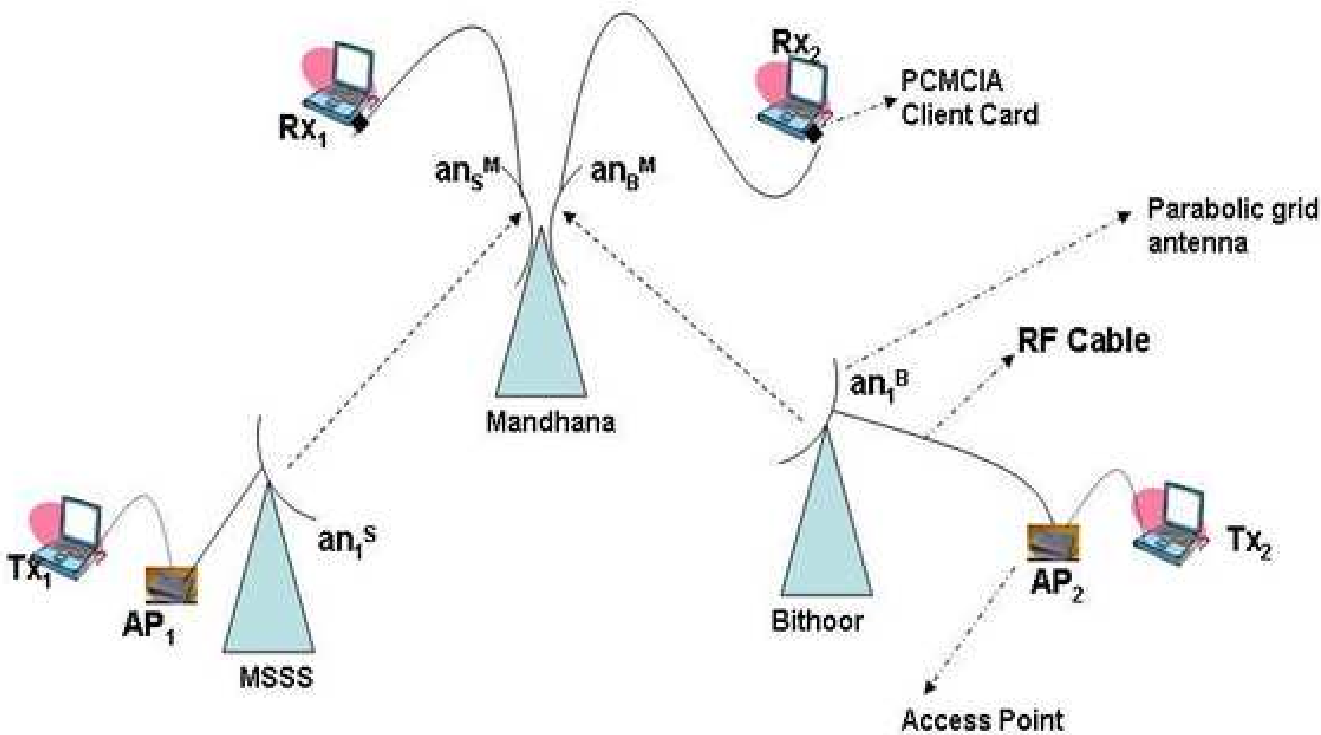

Figure 5.2: Simultaneous Reception Experiment on the DGP testbed

The experiment setup is as shown in the Fig 5.2. We perform the experiment at three villages which are part of DGP project testbed. The three villages are Mandhana, MSSS and Bithoor. At Mandhana, we have two parabolic grid antennae mounted on a tower among which an_S^M is aligned towards an_1^S which is at MSSS and an_B^M is aligned towards an_1^B which is at Bithoor.

At Mandhana, we have two laptops. Each laptop which is having a PCMCIA client card acts as the receiver (Rx) of the traffic. The PCMCIA card which is having external connector is connected to the antenna using RF cable. Rx_1 is connected to an_S^M and Rx_2 is connected to an_B^M. At MSSS and Bithoor, we have access points AP_1 and AP_2. Each access point transmitting slot is connected to the antenna using RF cable. AP_1's transmitter is connected to an_1^S which is at MSSS and AP_2's transmitter is connected to an_1^B which is at bithoor. Each access point is connected to a laptop which acts as the sender (Tx) of traffic. AP_1 is connected to Tx_1 and AP_2 is connected to Tx_2. Now we send UDP broadcast traffic on both the links and measure the throughput at the client by varying the transmission power at AP. We consider Mandhana-Bithoor link ($Tx_2 \rightarrow Rx_2$) as the main link and the other one as the auxiliary link.

5.2 Motivation for the setup

The motivation for this setup is as follows. Our objective is to produce the situation that is shown in Fig 5.1. Mandhana node acts as node N. MSSS node acts as node A and Bithoor node acts node B. The antennae already mounted at the locations serve the purpose of antennae in Fig 5.1. Now we connect the AP to the antenna with RF cable at the transmitter and we connect the PCMCIA card in the laptop to the antenna with RF cable at the receiver. We always choose the AP as the transmitter and laptop with PCMCIA card as the receiver. This is because, if we make PCMCIA card as the transmitter and AP as the receiver, there is MAC level acknowledgment from AP to the transmitter (even with UDP broadcast traffic), which we do not want.

5.3 Experiment Run and Results

We measured the side-lobe rejection level as 19 dB. We measured this value by switching off one link and measuring the signal level received at that antenna from the other link. Now the difference between this value and the signal level received at the other antenna gives the side-lobe rejection level. So, if the power at an_S^M

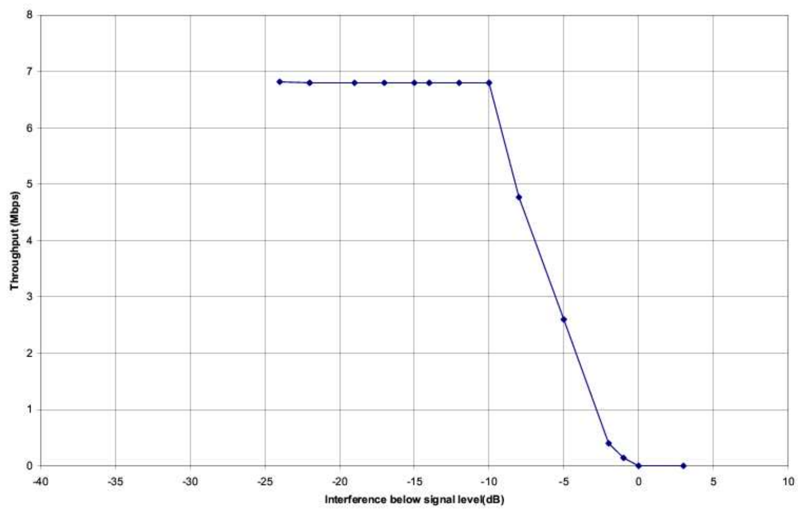

Figure 5.3: Throughput vs Interference-to-Signal Ratio

because of an_1^S is x dB, then its effect on an_B^M is x-19 dB. Since the three nodes are at different locations, once the links have been setup, we stay at Mandhana and operate the other nodes using remote shell application. Now we varied the power of transmissions by varying the power of transmissions at the APs and measured the throughput on the main link.

Fig 5.3 shows the result of our experiment. From the graph, the throughput goes down at a value of 10 dB which is the SIR_{reqd}. So we conclude that if we provide SIR equal to or above 10 dB, simultaneous operation is possible.

In the next chapter, we describe the simultaneous transmission experiment on the testbed.

Chapter 6

Simultaneous Transmission Experiment

In this chapter, we describe the experiment to verify simultaneous transmission on the testbed.

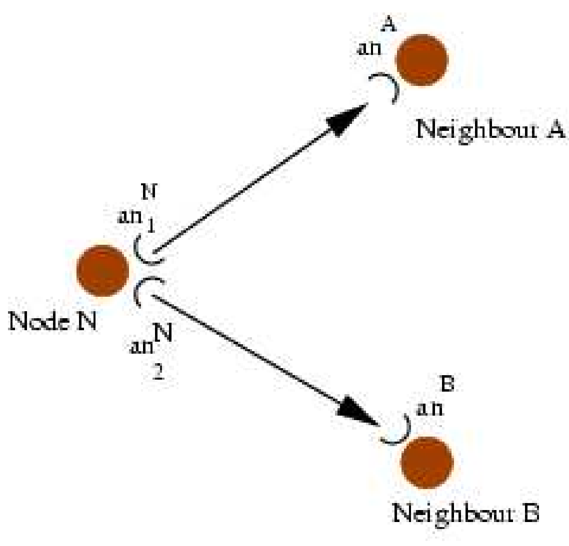

Figure 6.1: Simultaneous Transmission

Consider the simultaneous transmission situation in Fig 6.1. At node N, an_1^N is transmitting to an^A and at the same time, an_2^N is transmitting to an^B. an^B will see the interference from an_1^N because of the side-lobes. Similarly an^A will see the interference from an_2^N. These two traffics are independent of each other. Now in our experiment, we verify this operation on the testbed. We vary the transmission powers at an_1^N and an_2^N and measure the throughput achieved at an^A and an^B.

6.1 Experiment Setup

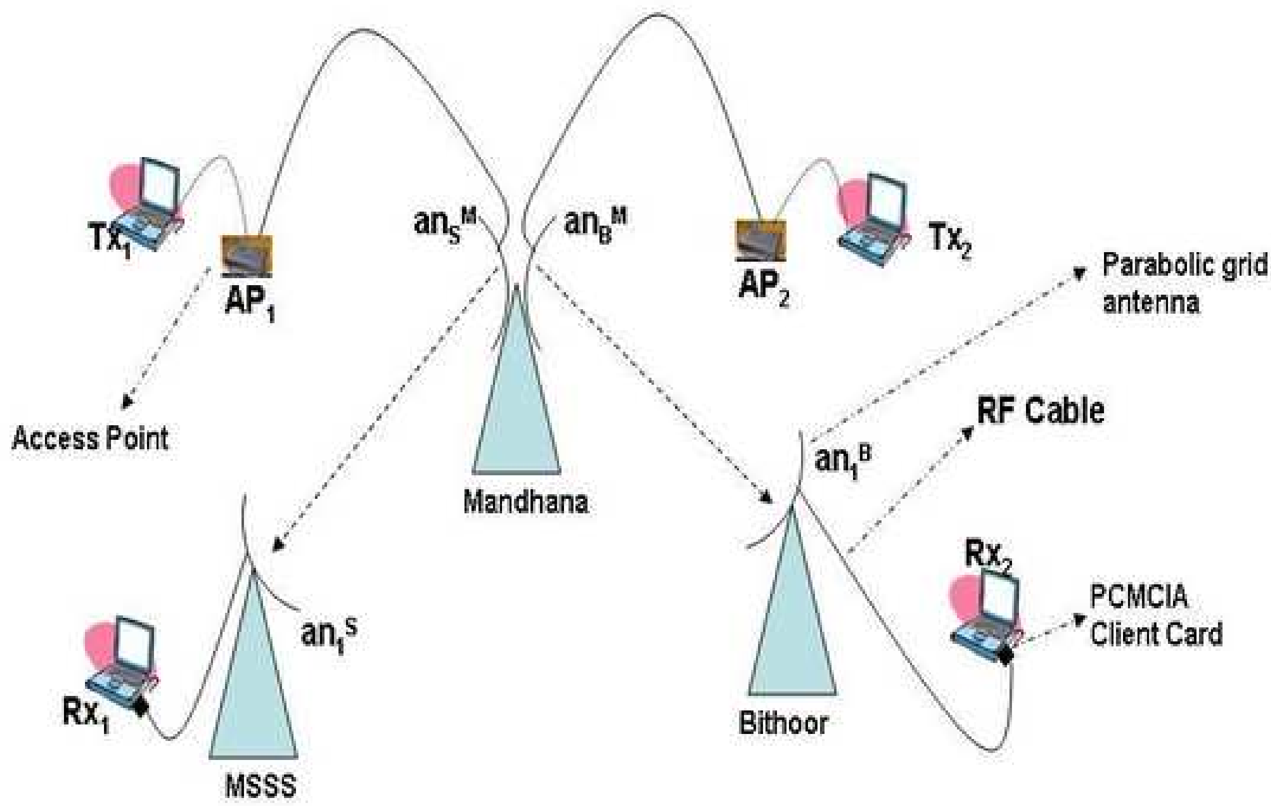

Figure 6.2: Simultaneous Transmission Experiment on the DGP testbed

We perform the experiment at three villages which are part of DGP project testbed. The experiment setup is as shown in the Fig 6.2. The three villages are Mandhana, MSSS and Bithoor. The distance between Mandhana and MSSS is 0.9 Km. and between Mandhana and Bithoor is 12 Km. At Mandhana, we have two parabolic grid antennae mounted on a tower among which an_S^M is aligned towards an_1^S which is at MSSS and an_B^M aligned towards an_1^B which is at Bithoor. At Mandhana, we have two access points AP_1 and AP_2. Access point's transmitting slot is connected to the antenna using RF cable. AP_1's transmitter is connected to an_S^M and AP_2's transmitter is connected to an_B^M. Each access point is connected to a laptop which acts as the sender (Tx) of traffic. AP_1 is connected to Tx_1 and AP_2 is connected to Tx_2. At MSSS and Bithoor , a laptop which is having a PCMCIA client card acts as the receiver(Rx) of the traffic. The PCMCIA card which is having external connector is connected to the Antenna using RF cable. At MSSS, Rx_1 is connected to an_1^S and at Bithoor, Rx_2 is connected to an_1^B.

6.2 Motivation for the setup

The motivation for this setup is as follows. Our objective is to produce the situation in Fig 6.1. Mandhana node acts as node N. MSSS node acts as node A and Bithoor node acts node B. The antennae already mounted at the locations serve the purpose of antennae in Fig 6.1. Now we connect the AP to the antenna with RF cable at the transmitter and we connect the PCMCIA card in the laptop to the antenna with RF cable at the receiver.

6.3 Experiment Run

Since the three nodes are at different locations, once the links have been setup, we stay at Mandhana and operate the other nodes using remote shell application. The transmission power is controlled by adjusting the transmission power level of AP since we have no other way(like attenuators we used indoor) of controlling the power on the testbed. Now we transmit UDP broadcast traffic from Tx_1 and Tx_2 while varying the transmission power and measure the throughput at Rx_1 an Rx_2. Here, we faced problem of "back-off" of APs at the transmitting node. Since one AP can hear the signal from the other AP because of the side-lobe of the antennae, it will back-off based on CSMA/CA MAC protocol. We have to avoid this because if

Transmission power at AP_1 (dB)	Transmission power at AP_2 (dB)	Received power at Rx_1 (dB)	Received power at Rx_2 (dB)	Throughput at Rx_1 (Mbps)	Throughput at Rx_2 (Mbps)
20	20	-55	-77	6.9	5.1
17	17	-58	-80	6.9	6.2
15	15	-60	-82	6.9	7.3
13	13	-62	-84	6.9	7.3
7	7	-71	-93	6.9	0

Table 6.1: Signal levels vs Throughput in Simultaneous Transmission

one AP does not transmit while the other is transmitting, it will not be considered as simultaneous transmission. To avoid this, we played a trick based on the hardware of AP. AP has two slots called “left” and “right”. We can configure the AP such that any slot can be used for transmission or reception. We connect only transmitting slot to the antennae so that it will not hear the signal from the other AP.

6.4 Results

Table 6.1 shows the result of our experiment. We vary the power levels in steps at both APs and measure the throughput. The received power is less at the receivers because of the RF cable loss, path loss and also leakages in the equipment. The received power at Rx_2 is less than that of Rx_1 because of greater distance. The throughput at Rx_2 is less when the transmission powers at the APs are 20dB and 10dB. This is because of the “back-off” of the APs. At these power levels, APs sense each other and back-off according to the CSMA/CA protocol of 802.11. This drop is there even if we connected only the transmitting slot of AP to antenna because of the high power level of transmission. In other power levels, the throughput is maximum on both the links which proves that *Simultaneous Transmission* is possible. At a transmission power level of 7 dB, Mandhana-Bithoor link went down giving a throughput of 0 because the received power at Bithoor node is less than the receive-sensitivity of the client card.

Chapter 7

Conclusions and Future Work

The aim of the DGP project is to provide voice and data communications in rural areas at a low cost. As part of the DGP project, an extensive testbed has been built. This testbed covers several tens of kilometers of sparsely populated rural areas connected by long distance 802.11 point-to-point links spanning up to 80 kms at its longest forming a multi-hop wireless access network. Since 802.11 was designed for indoor use only, trying to use it in the outdoor setting poses many challenges. In this thesis, we address the problem of Medium access. We showed how to maximize spatial reuse of the spectrum using the flexibility of simultaneous operation.

We have successfully verified *Simultaneous Operation* in the 802.11 multi-hop mesh network which maximizes the spatial re-usability of the spectrum. We calculated the Signal-to-Interference ratio that should be provided for correct operation of the links. 2-phase scheduling protocol to address the problem of medium access works based on this flexibility of simultaneous operation in the same channel. This protocol achieves maximum link utilization proving that this approach is efficient.

In proving *simultaneous operation*, we initially experimented indoor and later we successfully validated on the testbed. Our approach can be applied to any 802.11 point-to-point network satisfying the following conditions

- All the links are point-to-point
- All nodes have directional antennae towards each of its neighbours.

- Sufficient side-lobe rejection level (such that it provides SIR_{reqd}) is provided between the antennae at a node.

We conclude that we addressed the problem of spectral efficiency by maximizing the spatial reuse of the spectrum and also it is effective in terms of link utilization.

Simultaneous operation can be put to widespread by implementing the 2-phase scheduling protocol in the access point. This requires further investigation about whether CSMA/CA altogether has to be replaced or can be implemented with broadcasting messages itself.

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