Improving Fault Tolerance in 802.11 Wireless Long Distance Rural Networks

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by

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Abstract

Wireless technology is a promising solution for providing communication facilities to rural areas. We consider a network deployment with long-distance wireless links between rural locations. One of the network locations consists of a wired connection/communication, to connect the other locations to the Internet. We call this location the ***central node***. Towers and antennae are used for setting up long-distance wireless links in the network. Directional or sector antennae with high directional gain are used which are fixed and static. The network may be multi-hop. Individual village locations can be a few hops (say 2 or 3 hops) from the central node. One of the major issues with these types of networks is ***fault tolerance***. When an intermediate node fails, a part of the network could get disconnected from the central node.

This thesis work focuses on improving the fault tolerance of the above type of networks. For improving the fault tolerance we propose and explore three solutions. The basic idea in these solutions is to use another node as a ***backup node*** when the ***intermediate node*** fails.

The first solution termed ***replication*** uses multiple directional antennae at the far-away nodes. A programmable RF-Switch is connected between the multiple antennae and the radio, the switch is programmed to select one of the directional antennae for transmission/reception as required. The second solution termed ***rotation*** uses a Stepper Motor to rotate the directional antenna for changing the link of the node from the intermediate node to the backup node. The third solution ***cantenna*** uses a home made sector antenna called cantenna at nodes where the beam width reaches both the intermediate node and the backup node. The link is changed simply by selecting an alternate route at layer-3 of the network stack. We document the cost and performance trade offs of these three solutions.

Acknowledgments

I would like to express my deep sense of gratitude to Dr. Bhaskaran Raman and Dr. A.R. Harish for their invaluable help and guidance during the course of this thesis. I am grateful to them for constantly encouraging me and for giving me new ideas during various phases of this project.

I must take this opportunity to thank all my friends here for their cooperation and company which has made my stay in IIT Kanpur a memorable one. I must also thank the Department of Computer Science and IIT Kanpur for providing me with all the facilities and a very congenial environment. Special mention must be made of the Media Lab Asia people for offering their constant help and equipment for running the experiments.

Last but not the least, I would like to thank my parents for their immense love and continuous support without which this work would not have been possible.

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Chapter 1

Introduction

In the last fifteen years, communication technology has drastically changed the world. Most of this development is confined to cities and urban areas only. But in developing countries like India most percentage of the country is constituted of rural areas both population wise and area wise. Most of them are yet to see the facilities of phone, Internet, etc. The reason for this is that the cost of wired connections in rural areas is non-profitable, as these areas are not densely populated. Thus there is a big digital divide between urban and rural areas. One of the promising solutions to reduce the digital divide is 802.11 wireless technology [40]. 802.11 WiFi can be used with towers and antennae [19] to cover long distances of the order of tens of kilometers. This has been tested in several networks and **Digital Gangetic Plains** [11] at IIT Kanpur is a testbed of such a network. Fig 1.1 shows a pictorial view of the network. The longest link is nearly 40km. In this network, the IITK node is connected to the Internet and thus allows the entire network to be able to connect to the Internet. In terms of service, a telephone booth had been run

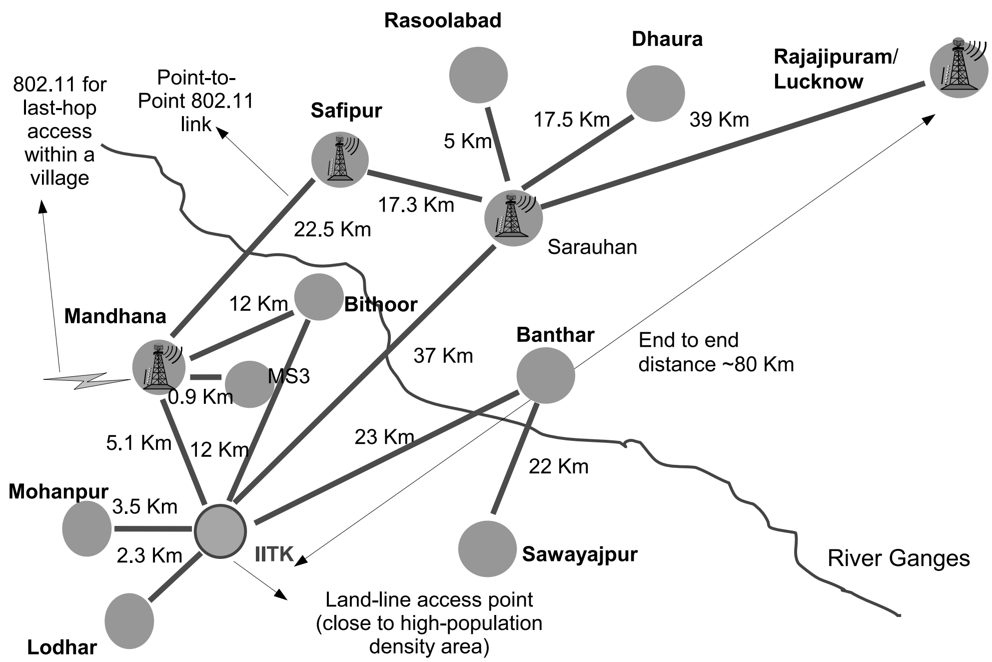


Figure 1.1: Digital Gangetic Plains Testbed

sucessfully at Sarauhan with STD facility from June 2004 to January 2006.

1.1 Network Model

Before going into the problem let us discuss these long distance networks in detail. A typical network consists of rural areas (**nodes**) which are around one particular node (called **central node**) which can be a city or district head quarters. This node has wired connection (e.g. optical fiber [31] dropout) for communication with the rest of the world. All the other nodes use the

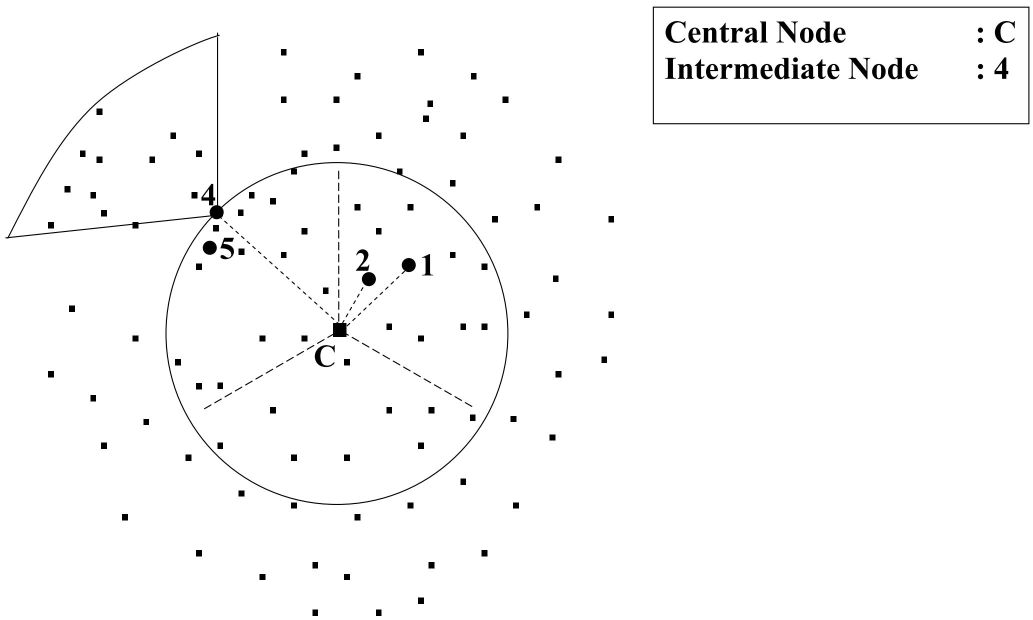
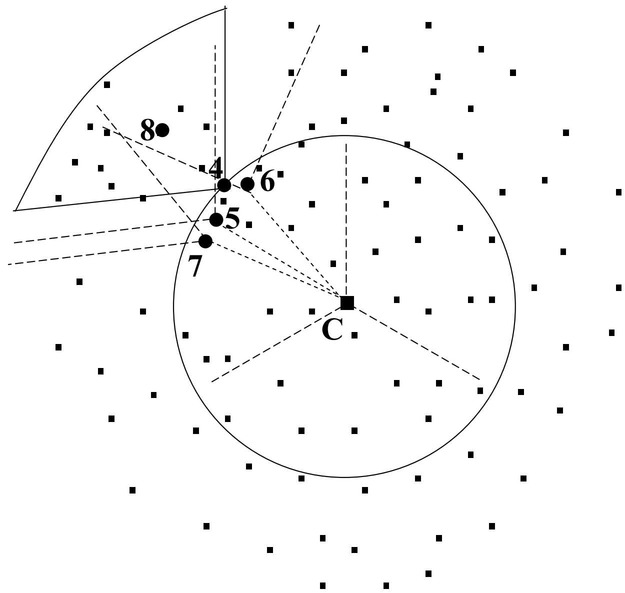


Figure 1.2: Long Distance Network with sector antennae at node C and directional antennae at nodes 1 and 2.

wireless network to connect with the central node. For the long distance connections to be made possible, high gain antennae [23] are used along with tall towers. To reduce the total effective cost, one strategy is to place the towers so that central node tower is very tall (40-50m.) and the rural node towers are as short as possible and that they have enough line of sight [27] for communication. It is common to use sector antennae (generally antennae with beamwidth [13] of less than 15^o are called directional antennae and with more than 30^o are called sector antennae) at the central node to cover as many nodes as much as possible and directional antennae are used at the other nodes. Fig 1.2 is one such network. Due to interference [26] problems and high cost, directional antennae are not used at the central node **C**.



Central Node : **C**
Intermediate Node **:4**
Backup Node:
Option 1:
Node 5
Option 2:
Nodes 6 and 7

Figure 1.3: Long Distance Network with intermediate nodes 5, 6 and 7

Also because it is not possible to mount too many directional antennae on a single antenna tower. In the Fig 1.2, node **C** is the central node and has three sector antennae of 120^o beam width and has range (10-15km.) shown by the circle. The range is calculated from the gain of the antennae used and the maximum transmission power allowed for a radio (which is 100mW). It can have direct communication with all the nodes within the circle. Nodes **1** and **2** use directional antenna for communication with node **C**. The nodes falling under one sector of node **C** time-share the channel (radio frequency). Some of the nodes within the circle are made intermediate nodes for making the nodes outside the circle connect with node **C**. In Fig. 1.2 node **4** is one such node which can be made an intermediate node. Since node **4** is in the same sector as node **5**, it is likely that a directional antenna is used at node

C towards node **4** and a separate channel is used for communication. This makes simultaneous connections of both node **5** and node **4** with node **C** possible. A sector antenna is used at node **4** to cover the sub network and all the nodes in the sub network (e.g. node **8**) use directional antennae for connection with node **4**.

Now node **4** is a point of failure for the sub network. If node **4** goes down then all the nodes in the sub network get disconnected from the network. The immediate solution to overcome this problem is to use another node called the **backup node** as intermediate hop. Thus for each node in the network which is at **2** hops or **3** hops from central node, there should be at least one backup node through which it should be able to reach the central node. Fig 1.3 gives a view of the above network. The selection of backup nodes depends on the topology of the network. For example in Fig 1.3, when node **4** fails, the sub network can be made connected either through a single node **5** or under both nodes **6** and **7**. Suppose node **5** is selected as the intermediate node. It will also have one directional antenna facing towards node **C** and one sector antenna for the sub network. Node **C** also consists of a directional antenna facing towards node **5**. Now node **8** like all the nodes in the sub network is using directional antenna. It has to change the connection from node **4** to node **5** when node **4** goes down.

The above problem can be divided into two parts.

1. Designing optimally the topology such that there is atleast one backup node for all the nodes which are atleast two hops away from the central

node.

2. Given a backup node for an intermediate node, how to change the link from intermediate node to backup node and *vice versa*.

In this thesis, we address the second problem.

An example of such a deployment is the Ashwini network [39] shown in Fig 1.4. The diameter of the network is 45Km which is the distance between the nodes **5** and **7**. In this network, Bhimavaram is a city and also the central node shown by node **C** in Fig 1.4. Two sector antennae are used at the central node ***C*** and two sector antennae are used at nodes **1** and

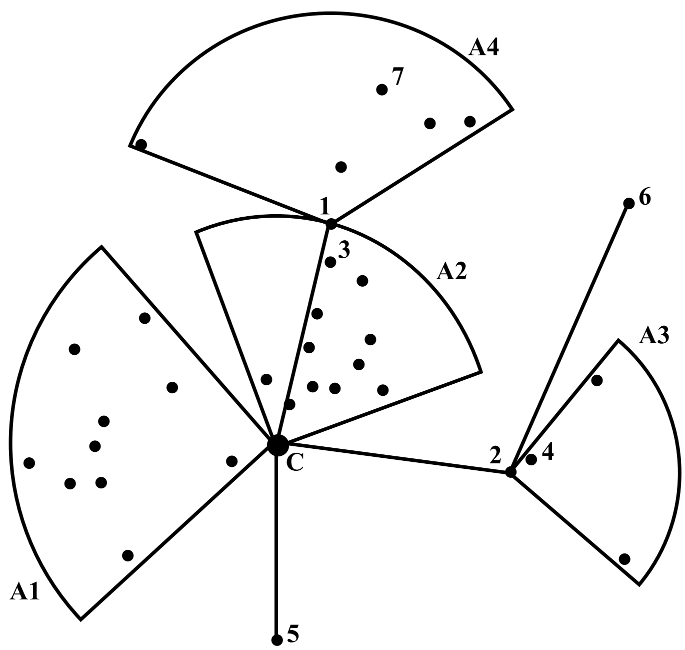


Figure 1.4: Ashwini Network

2 which serve as intermediate nodes. **A1**, **A2**, **A3** and **A4** represent the ranges of these sector antennae. **A1**, **A2**, **A3** are 90^o sectors and **A4** is 120^o sector. As nodes **5** and **6** are not able to be included into any of the sectors, separate directional antennae are used for connecting them. There are three non overlapping channels **1, 6** and **11** in 802.11 which can be used simultaneously in the same region. Thus the nodes present in the sectors **A1**, **A3** and **A4** can be operated in one channel say channel **1**. Channel **6** can be used for the nodes inside the sector **A2** and for nodes **5** and **6**. Thus the third channel, channel **11** can be used for the intermediate nodes **1** and **2**. Now nodes **1** and **2** represent point of failures for the sub network nodes present in the sectors **A4** and **A3** respectively. To improve the fault tolerance node **3** can be made backup node for node **1** and similarly node **4** can be made backup node for node **2**. Now the problem is to change the links of the nodes present in the sectors **A4** and **A3** from nodes **1** and **2** to the backup nodes **3** and **4** respectively.

In this thesis work we propose three solution approaches for changing the link from the main intermediate node to another backup node.

Replication: In this technique multiple directional antennae are used at all the nodes in the sub network. A programmable RF-Switch (Radio Frequency switch) is used and is connected between the directional antennae and the radio/wireless equipment and the switch is controlled through a system to select one of the directional antennae for transmission/reception as required.

Rotation: In this solution a Stepper Motor [33] is used to rotate the directional antenna at the sub network nodes for changing the connection of the node from the intermediate node to the backup node.

Cantenna: In this solution a home made sector antenna called ***cantenna*** [12] is used at nodes in the sub network where the beamwidth reaches both the intermediate node and the backup node. The connection is changed through regular layer-3 routing of OSI [30].

1.2 Methodology

The methodology we follow to explore the above three solutions is to prototype and experiment with the solutions.

Replication: There are three phases in this solution.

1. RF-Switch circuit on a PCB (Printed Circuit Board) [32].
2. Hardware to generate the control signals for switching.
3. Program to detect connection failure and generate the control signals.

Rotation: There are three phases in this solution too.

1. Hardware to generate the control signals for the Stepper Motor.
2. Mounting the directional antenna to the Stepper Motor.

	Replication	**Rotation**	**Cantenna**
Throughput when both Intermediate and Backup node are active	5.8 Mbps	6 Mbps	2.4 Mbps
Cost	$2 * \$50 + (\$33\|\$4)$	$\$50 + \$40$	$10

Table 1.1: Comparison of the three solutions

3. Program to detect the connection failure and sending the control logic to the stepper motor.

Cantenna: Routing module to detect the connection failure and changing the route to the central node C.

1.3 Main Results

We implemented the Replication solution completely and Rotation solution partially, as for cantenna nothing extra has to be in terms of hardware. We experimented the solutions in outdoor setting up two links and recorded the results. Finally we compared all the three solutions and found that the Cantenna case is not good in terms of effective throughtput for the case when both the intermediate node and backup node try to connect the far-end nodes. Table 1.1 gives a brief comparision of the three solutions

1.4 Organization of the report

In the next chapter, we discuss the related work. In Chapter 3 we describe in detail how our solutions are implemented. Subsequently Chapter 4 presents the results of our evaluation of each solution and their comparison. Finally Chapter 5 discusses future work and concludes the thesis.

Chapter 2

Related Work

2.1 MIT Roofnet

MIT Roofnet [9] is a medium range distance network spanning about 2km in diameter. It is an experimental wireless mesh network [37] built to provide Internet connectivity to people in Cambridge, MA, U.S.A. The network consists of more than 50 nodes out of which only 3 nodes have wired connection with the Internet. These 3 nodes are placed on a ten storied building and use Yagi antennae [38]. These nodes are present at the edge of the network instead of at the center. All the other nodes use omnidirectional antennae [29] and connect with the wired nodes for Internet connection. The nodes provide connection to the end users through a local Ethernet LAN. The maximum routing length is 4 hops. Fig 2.1 gives the position of the some of the nodes in the network extracted from [3]. .

Roofnet uses the SrcRR [10] routing protocol. The routes are not fixed to the wired nodes. They are calculated dynamically by broadcasting for the

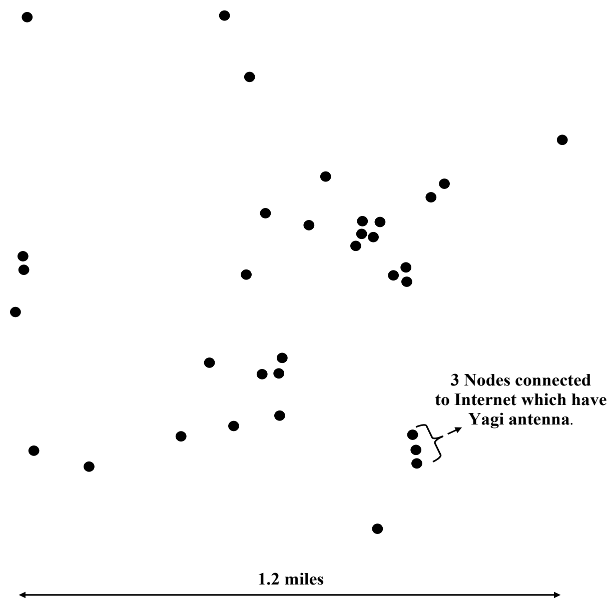


Figure 2.1: MIT Roofnet node positions (Source [3])

destination node and is different from the DSR [41] routing protocol. Since the intermediate nodes are not fixed for routes, intermediate node failures are dealt by the routing protocol.

There are also long distance community networks like **Wireless Leiden** [46] community network which use directional antennae and towers for connections. In Wireless Leiden case, each node has at least three radios, one omni-directional antenna to connect to the end users and at least two directional antenna to connect to the other nodes. So when the intermediate node fails, the far-end nodes change their radio for connection there by changing the link.

There is no mechanism in the literature apart from layer-3 routing to

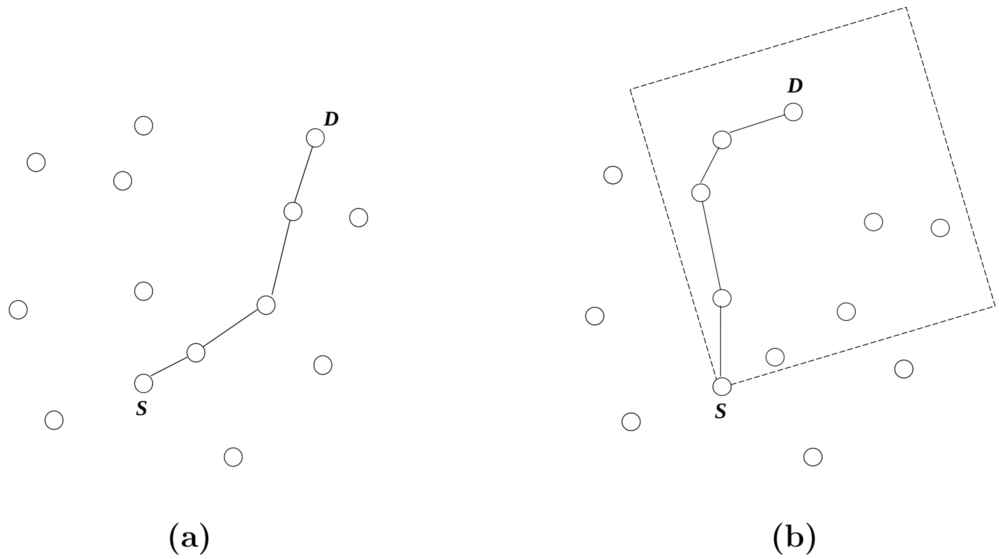


Figure 2.2: Ad-hoc Network with directional antennae

address fault-tolerance.

2.2 Ad-hoc networks with directional antennae

A lot of work has been done in Ad-hoc networks [42, 43] for improving the throughput by using directional antennae. Generally the nodes in the ad-hoc network have omni-directional antenna. All the work is done assuming that the nodes have N directional antennae each with $2\pi/N$ beamwidth. As the nodes move in ad-hoc networks, the routes between nodes are not fixed. DSR [41] is one routing protocol which finds the route from source to destination. Thus when omni-directional antennae are used, it creates a lot of overhead on the network. To reduce the overhead the search space is confined to a specific direction from the source where the destination will be most likely. This can be observed from the following two figures. Fig 2.2(a) shows the initial positions of source node **S** and destination node **D**. Fig 2.2(b) shows the positions of nodes **S** and **D** after the movement of the node **D** and also the search space for finding the route.

In these networks also routing protocols deal with intermediate node failures as the routes are not fixed.

2.3 Off-the-Shelf Components

There are off-the-shelf components available that can be used to improve the fault tolerance. From [14] the cost of off-the-shelf 2.4GHz radio frequency switches are around $100 and from [4, 5, 6] the cost of off-the-shelf Antenna Rotator systems vary from $120 to $1000. These solutions can be implemeted easily for $50 each which are suitable for our application.

2.4 Comparison

Table 2.1 compares all the solutions

	MIT Roofnet	**Ad-hoc**	**Off-the-Shelf**	**Our Approach**
Nodes	Fixed	Mobile	Fixed	Fixed
Range	Hundreds of Meters	Tens of meters	Tens of Kilometers	Tens of Kilometers
Intermediate node failures	Solved by routing protocol	Solved by routing protocol	Solved by routing protocol	Replication and Rotation operate below the routing layer. Cantenna solution operates at routing layer
Cost	-	-	\$100 - \$500	$\approx$ \$50

Table 2.1: Comparison of other solutions and our approach

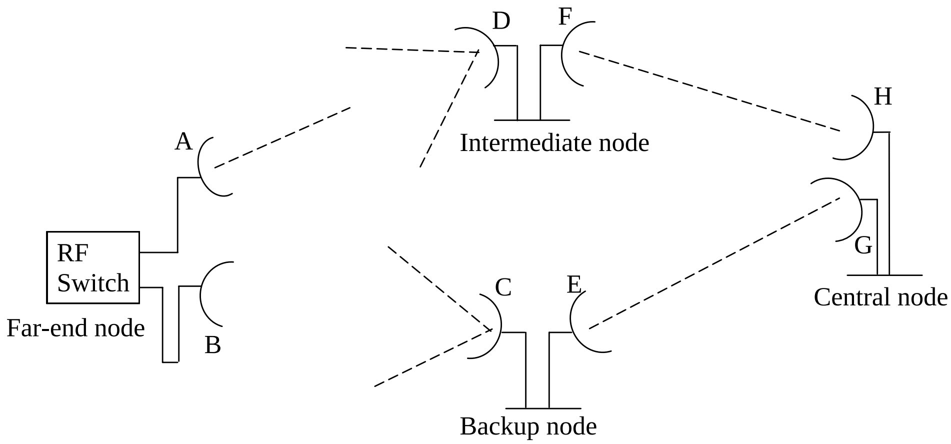
Chapter 3

Design and Implementation

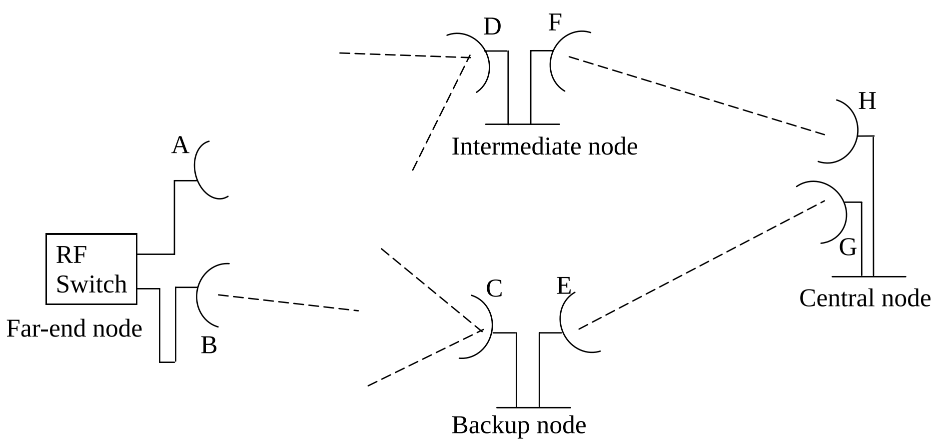
3.1 Replication

The main idea of replication is to use more than one antenna with a single radio. The number of antennae that can be used at a far-end node is equal to the count of intermediate node and backup nodes. We designed and implemented the replication solution with two antennae, one for main intermediate node and another one for backup node. This is illustrated in Fig 3.1.

In Fig 3.1, **A**, **B** are the directional antennae of the far-end node for communication with sector antennae **D** and **C** of the intermediate node and backup node respectively. Similarly **F** and **E** are the directional antennae of the intermediate node and backup node for communication with directional antennae **H** and **G** of the central node respectively. At any point of time, only one of the directional antennae **A**, **B** will be operational for the far-end node. Fig 3.1**(a)** represents the far-end node communication with the intermediate



(a) Far-end node with Intermediate node connection



(b) Far-end node with Backup node connection

Figure 3.1: Replication Solution

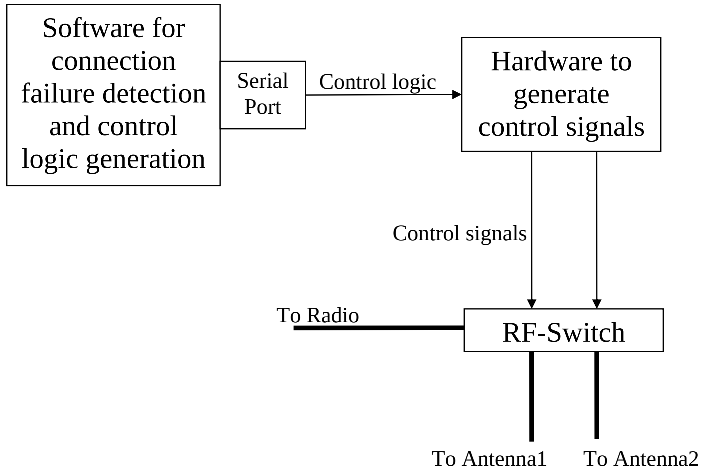


Figure 3.2: Block diagram of Replication solution

node using directional antenna **A**. When the link between the far-end node and the intermediate node fails, immediately the other directional antennae **B** of the far-end node is made operational instead of the directional antenna **A** and link is formed with the backup node. This is shown in Fig 3.1**(b)**

There are three phases in this solution

1. RF-Switch circuit on a PCB.

2. Hardware to generate the control signals to the RF-switch.

3. Program to detect the connection failure and to generate control logic.

Fig 3.2 shows block diagram of the above.

	PSW-1211	RSW-2-25-P
Absorptive	Yes	No
Reflective	No	Yes
Isolation	High	Low
Cost	$33	$4
Type	DIP[22]	Surface mount[34]

Table 3.1: Differences between PSW-1211 and RSW-2-25-P

3.1.1 RF-Switch Design

802.11 WiFi operates in 2.4 GHz radio frequencies. There are off-the-shelf radio frequency switches available in the market. The cost of these switches that operate in 2.4 GHz range is of the order of $100 [14]. There are also off-the-shelf chips available that operate at these frequencies that are very inexpensive. PSW-1211 [15] and RSW-2-25-P [16] are two such chips. The cost of PSW-1211 is $33 and that of RSW-2-25-P is $4. The main differences between the two chips are shown in Table 3.1. We designed PCB layout for the two chips and have them fabricated in the lab. For both the PCBs we used Pig Tails [45] for connections with radio and antennae.

PSW-1211: PSW-1211 [15] is an 8-pin DIP [22] chip. It operates from 10MHz to 2500MHz. This chip does not require power supply for operation. There are two control lines for control signals operating at +5V/0V. The surface of the chip needs to be grounded for operation. So we designed the PCB such that the surface of the chip is on the ground side of the PCB. Three surface mount capacitors each of 33 picofarads are used for the three RF-lines for blocking DC currents if any. The circuit is shown in Fig 3.3.

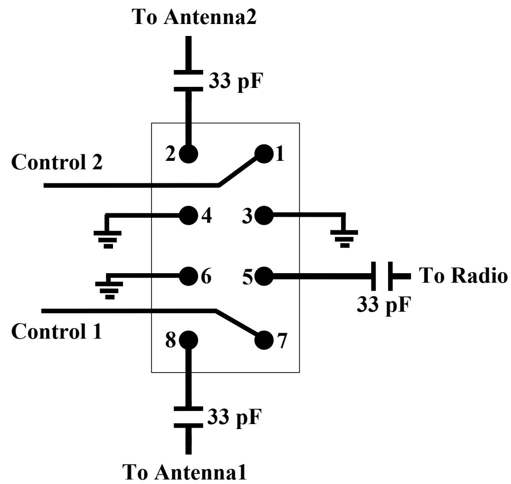


Figure 3.3: RF-Switch with PSW-1211

RSW-2-25-P: RSW-2-25-P [16] is a surface mount [34] 14-pin chip. It operates from DC to 2500MHz. This chip requires +5V power supply for operation. There are also two control lines for control logic and also three 33 picofarads surface mount capacitors are used like in the case of PSW-1211. The circuit is shown in Fig 3.4.

3.1.2 Hardware to generate control signals

For both of the above circuits two control signals are required. For both of the circuits, for the selection of one of the antennae, one control signal has to be kept high while the other has to be kept low. That means the control signals are complementary. Hence one control signal is sufficient from the system. This can be send through serial port easily through a system which has support for both radio/wireless and serial port like Soekris [8]. In serial port, when the baud rate is changed from 0 to any other rate **Data Carrier**

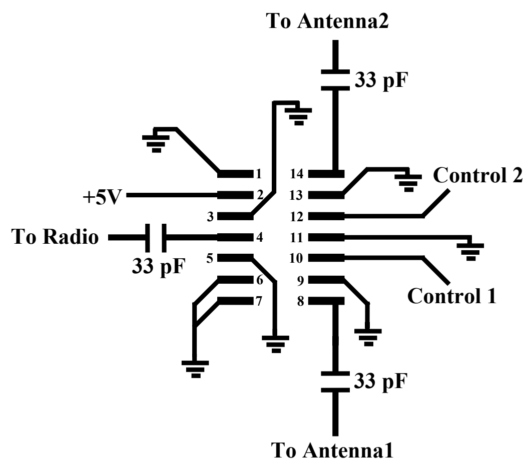


Figure 3.4: RF-Switch with RSW-2-25-P

Detect [44] signal will do a low to high transition and when the baud rate is changed back to 0 the **Data Carrier Detect** signal will become low. Hence this signal line can be used for generating the two control signals.

Generally serial port operates at +13V/-13V for high/low signals. Hence these signals have to be converted to TTL [35] level which is +5V/0V. MAX232 [2] can be used for this conversion. After this, a 7404 NOT gate [17] is used to generate the complementary control signal. The circuit is shown in Fig 3.5.

3.1.3 Software

The link of the far-end node with the intermediate node has to be changed to backup node when the corresponding link fail. Hence this link has to be monitored continuously and when the link fails a control signal has to be sent through the serial port. Thus the software is divided into two parts.

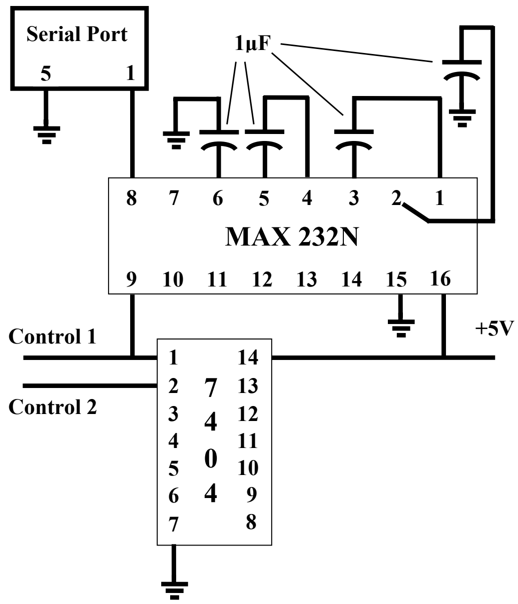


Figure 3.5: Hardware for generating control logic

1. **Connection Failure Detection:** This can be done simply by using a ping command every say 1 sec. If there is no response for 1min. a **flag** is set which represents the connection failure.

2. **Control Signal Generation:** This signal can be generated by changing the baud rate of the serial port as mentioned in the **Hardware** section. By changing the baud rate from 0 to higher rate, **Data Carrier Detect** [44] line becomes logical 1 and changing back the baud rate to 0 makes the **Data Carrier Detect** to logical 0. Hence the above connection failure **flag** is monitored continuously and the baud rate is changed accordingly.

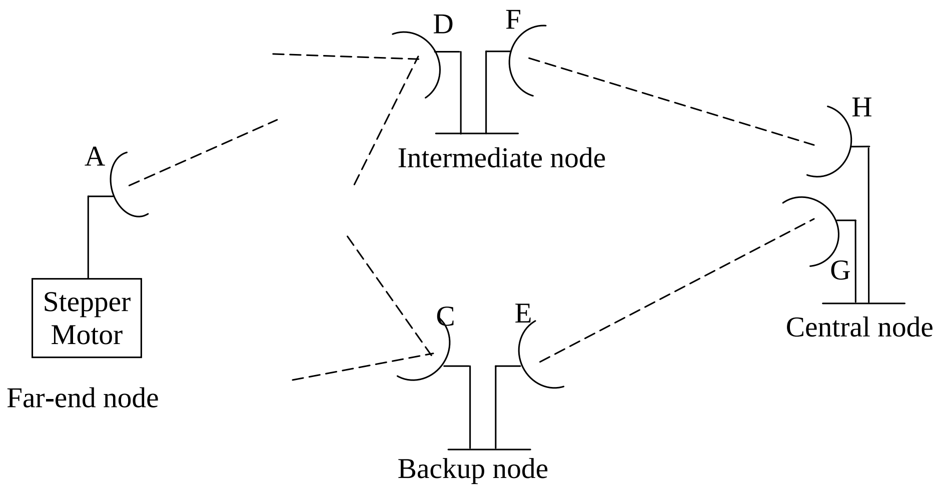
3.2 Rotation

In the antenna rotation based solution, a stepper motor is used to rotate the directional antenna of the far-end node from the direction of the intermediate node toward the direction of the backup node. Fig 3.6 represents this solution.

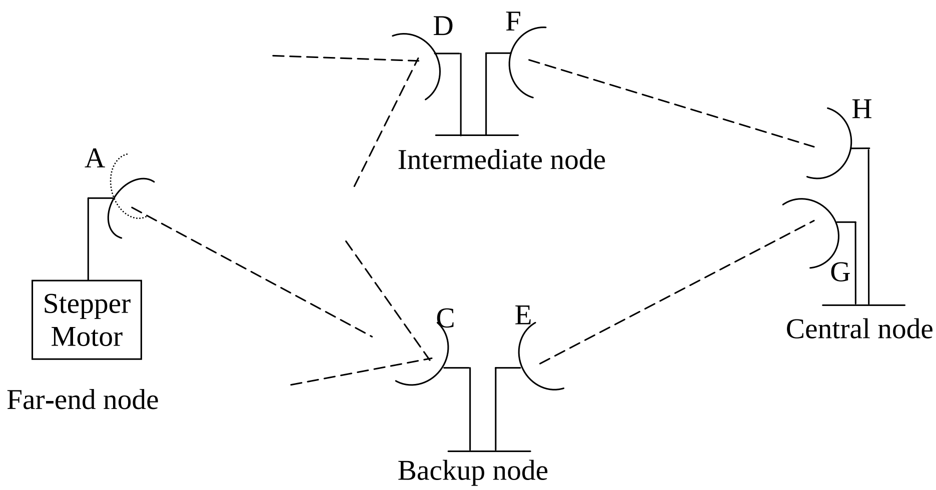
In Fig 3.6, **A** is the directional antennae of the far-end node for communication with either the sector antennae **D** of the intermediate node or **C** of the backup node. Similarly **F** and **E** are the directional antennae of the intermediate node and backup node for communication with directional antennae **H** and **G** of the central node respectively. Fig 3.6**(a)** represents the far-end node communication with the intermediate node using directional antenna **A**. When the link between the far-end node and the intermediate node fails, the directional antennae **A** of the far-end node is rotated by the stepper motor to which it is mounted and the link is changed from the sector antenna **D** of the intermediate node to the sector antenna **C** of the backup node. Fig 3.6**(b)** represents the second case.

Like in Replication there are also three phases in this solution

1. Hardware to generate the control signals for the Stepper Motor.
2. Mounting the directional antenna to the Stepper Motor.
3. Program to detect the connection failure and sending the control logic to the Stepper Motor.



(a) Far-end node with Intermediate node connection



(b) Far-end node with Backup node connection

Figure 3.6: Rotation Solution

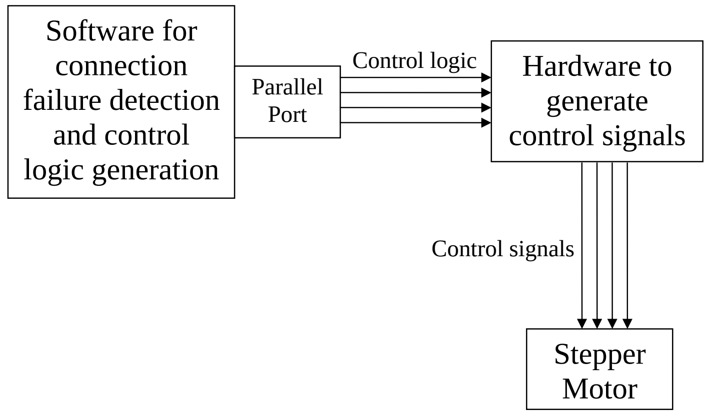


Figure 3.7: Block diagram of Replication solution

Fig 3.7 shows block diagram of the above.

3.2.1 Hardware to generate control signals

Before going into the hardware let us understand about the stepper motor. STM 981 from Srijan Control Drives is a stepper motor rated at 6V DC, 1.4 ampere per phase (total 2 phases), holding torque of 7 Kg-cm and has a step of 1.8^o. This is taken for our implementation as it is easily available for purchase and the stepper motors are easily replaceable. It has six wires coming out of it connected to the windings that are present inside it. These wires are colored Red, Orange, Blue, Green, White and Black. Fig 3.8 shows how the wires are connected internally and also how they are to be connected externally. White and Black are connected to the stepper motor rated voltage. Red, Orange, Blue and Green wires are grounded through switching transistors [36] (or MOSFETs [28]). The transistors are controlled through the control signals so that the wires are grounded as and when required. Ta-

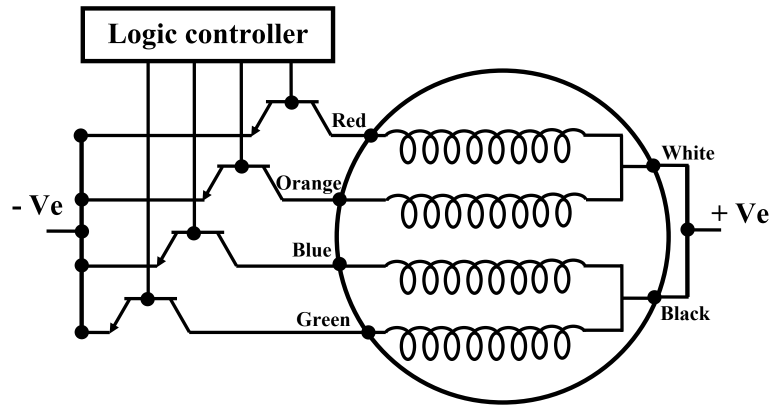


Figure 3.8: Stepper Motor circuit

Red	Orange	Blue	Green
0	1	0	1
0	1	1	0
1	0	1	0
1	0	0	1

Table 3.2: Stepper motor control sequence for full step (1.8^o)

bles 3.2 and 3.3 show the switching logic sequences for the stepper motor for full step and half step rotations. For the opposite direction of rotation, the sequence of the logic is from bottom to top of the sequences in the tables. In the tables, value 1 represents the corresponding wire to be grounded and value 0 represents the same not to be grounded or left open.

Fig 3.9 gives the detailed circuit diagram for generating control signals for the stepper motor. As the control sequences are a group of four, generating the control signals is easier from parallel port than from serial port. We used the lower 4 bits of the parallel port for sending control logic to generate control signals for rotating the motor. A 7407 buffer [1] is used between

Red	Orange	Blue	Green
0	1	0	1
0	0	0	1
1	0	0	1
1	0	0	0
1	0	1	0
0	0	1	0
0	1	1	0
0	1	0	0

Table 3.3: Stepper motor control sequence for half step (0.9^o)

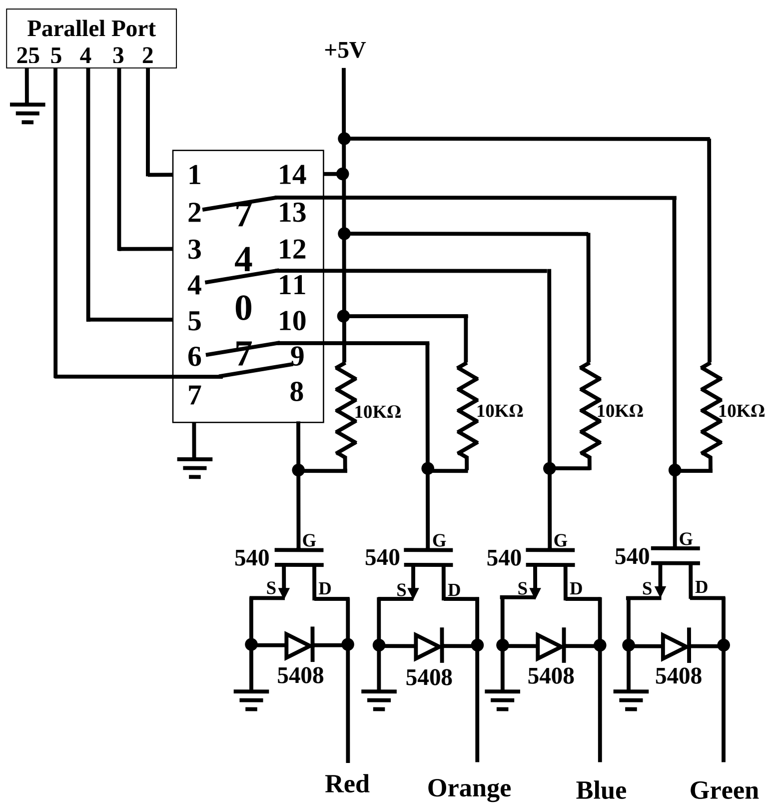


Figure 3.9: Circuit for stepper motor

parallel port and MOSFET to ensure the safety of the parallel port. When logical value 1 (which is +5V) is send through the parallel port which in turn goes to the MOSFET, the MOSFET will be closed making the drain **D** of it to be grounded through source **S**. Thus the colored lines of the stepper motor can be grounded based on the control logic.

3.2.2 Mounting

Fig 3.10 and Fig 3.11 give a prototype of mounting. This has not been implemented however. The directional antenna we considered is a parabolic grid antenna which is of about 6Kg weight, 1m in length and 0.5m in breadth [7]. Spur gear and Worm gear [24] are used for rotation as it is the easiest and simplest method. Spur gear is attached to the pole that holds the antenna and Worm gear is attached to the stepper motor. Two bearings [21] are used for smooth movement and supporting the pole, one at the bottom and the other at the middle of the pole.

3.2.3 Software

The link of the far-end node with the intermediate node has to be changed to backup node when the corresponding link fail. Hence this link has to be monitored continuously and when the link fails the antenna is rotated to change the link to the backup node by sending the logic sequence through the parallel port as explained in the **Hardware** section. Thus the software is divided into two parts

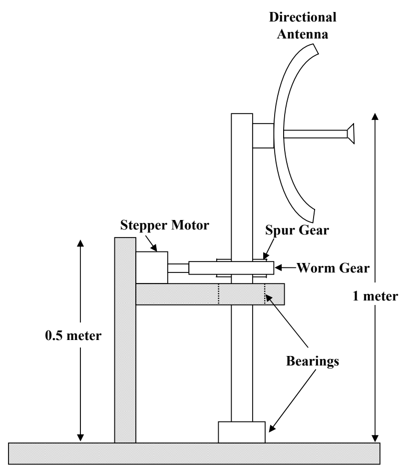


Figure 3.10: Mounting prototype

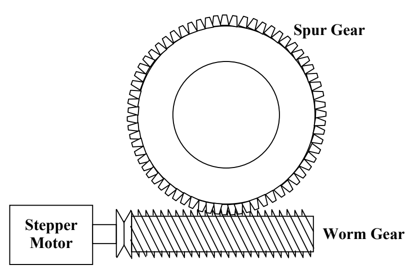
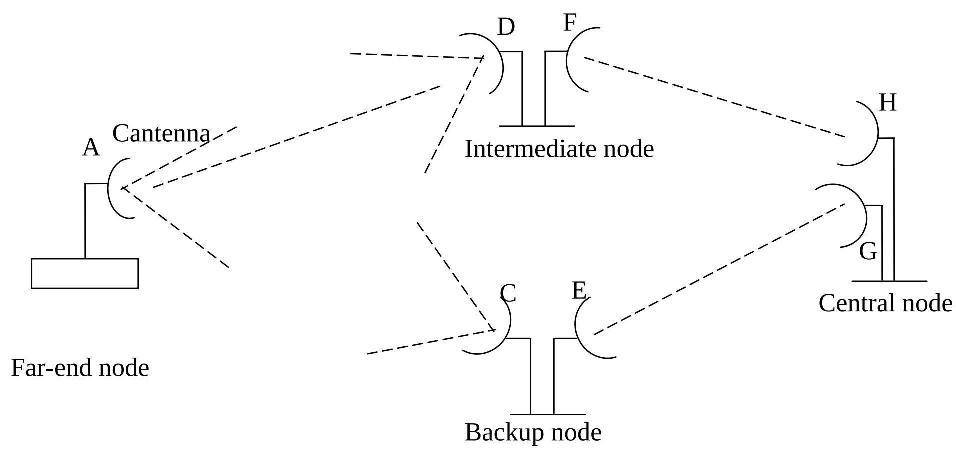
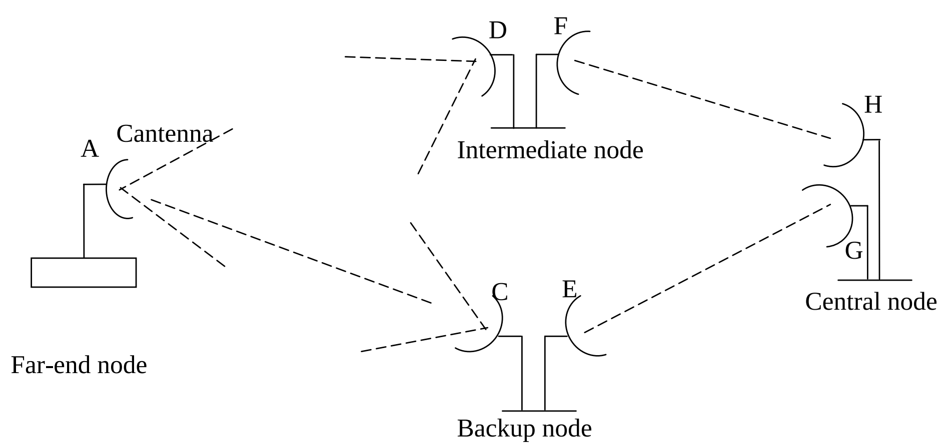


Figure 3.11: Spur Gear and Worm Gear



(a) Far-end node with Intermediate node connection



(b) Far-end node with Backup node connection

Figure 3.12: Far-end node connection with Cantenna

Figure 3.13: Cantenna

1. **Connection Failure Detection:** This can be done simply by using a ping command every say 1 sec. If there is no response for 1min. a **flag** is set which represents the connection failure

2. **Control Logic Generation:** On connection failure (from flag) for rotation the control logic shown in Tables 3.2 and 3.3 is send through the lower order 4 bits of the parallel port.

3.3 Cantenna

Cantenna [12] is a home made antenna. It is very cheap and costs around \$10. Fig 3.13 gives a picture of a cantenna. It has beam width of around 50^o to 60^o and can cover upto 5Km at 100mW transmission power. Thus if both the intermediate node and backup node are within this range, a cantenna can be used at the far-end node. If the intermediate node fails, connection can be changed to the backup node simply by changing the route at layer-3 of OSI [30]. Fig 3.12 gives a view of the links. In 802.11 this can be done easily by changing the "essid"of the far-end node from that of the intermediate node to that of the backup node. If the nodes are used to be in ad-hoc mode [18] with same essid and if the link between the far-end node and intermediate node fails, then the link between the far-end node and backup node will be formed automatically by the ad-hoc network software running over 802.11 hardware.

Chapter 4

Evaluation

In this chapter we show the results of evaluation of the three solutions. By evaluation, we show that the solutions are justifiable and implementable for long-distance links. In evaluation, first we measure the throughput of the two links, far-end node and intermediate node link, and far-end node and backup node link separately. Next we measure the throughput of the two links separately using Replication, Rotation and Cantenna solutions and compare them with the general case. Since we are using one of the solutions at the far-end nodes, we have to compare the throughput with the general case. We also took the throughput measurements of Replication and Cantenna solutions at far-end node when both intermediate node and backup node are sending data at the same time. Both intermediate node and backup node sending data simultaneously represent the case when both intermediate node and backup node try to connect far-end nodes with the central node. Hence in this case when far-end node forms link with the intermediate node, the backup node sending data might cause interference or reduce throughput at the far-end node and *vice versa*. We did not do this for Rotation solution as in this case there is only directional antenna at the far-end node and thus interference is negligible from the other (intermediate or backup) node. For RF-switches we also did calibration which describe the properties of the switches.

For evaluation we setup two outdoor links, one from Faculty Building (FBTOP) to Media Lab Asia (MLA) and other from Faculty Building to Computer Science and Engineering Department (CSE). We used two directional antenna at FBTOP for both the links, one directional antenna at MLA. At CSE we used a sector antenna. The directional antenna at FBTOP facing toward MLA and the directional antenna at MLA facing toward FBTOP have a beamwidth of 13^o and 22.5 dBi gain [23]. The other antenna at FBTOP facing toward CSE has 8^o beamwidth and 24 dBi gain. The sector antenna at CSE facing toward FBTOP has 65^o beamwidth and 12dBi gain. At CSE we used an attenuator [20] so that the signal strengths at all places are of about the same. This can also be done by adjusting the transmission power of the radios. The scenario is shown in brief in Fig 4.1. Now FBTOP represents far-end node, CSE and MLA represent intermediate and backup nodes. We used one laptop, an intersil prism chipset based *Senao* wireless card at each place. We used hostap driver 0.4.7 and hostap utils package 0.3.7 and did all the experiments in ad-hoc mode. We send data using UDP back-to-back traffic pattern at 11Mbps. When one node is sending data the other node of the link will receive the data. For all the experiments we used the sender to broadcast for transmission to avoid Medium Access Layer (MAC) acknowledgments. But when both intermediate node and backup node are transmitting data simultaneously, we made the node causing interference to transmit data to the far-end node directly.

The throughput results obtained for the links are shown in the Fig 4.1 itself. At CSE and FBTOP there are several access points (found three at CSE, five at FBTOP) operating in 802.11. We found that channel 6 (2.426 GHz - 2.448 GHz) is free and used the same. But still because of co-channel interference and other environmental reasons there are variations of about 0.5 Mbps in the results even if the same experiment is repeated. In Fig 4.1 the throughput for the links are taken separately. For FBTOP - CSE link, the signal strength at both the places are -67dBm and **FBTOP → CSE : 5.71 Mbps** means FBTOP is sending data (broadcasting) and CSE is receiving the data and at CSE we get 5.71 Mbps.

4.1 Replication

4.1.1 PSW-1211

PSW-1211 RF-Switch has three ends one for connecting to the radio and two for connecting to the antennae. We name the the radio end to be **I** and the antennae ends to be **A** and **B**.

Calibration:

Calibration represents the properties of the switch. There are three metrics which show the properties of a switch. Transmission, Reflection and

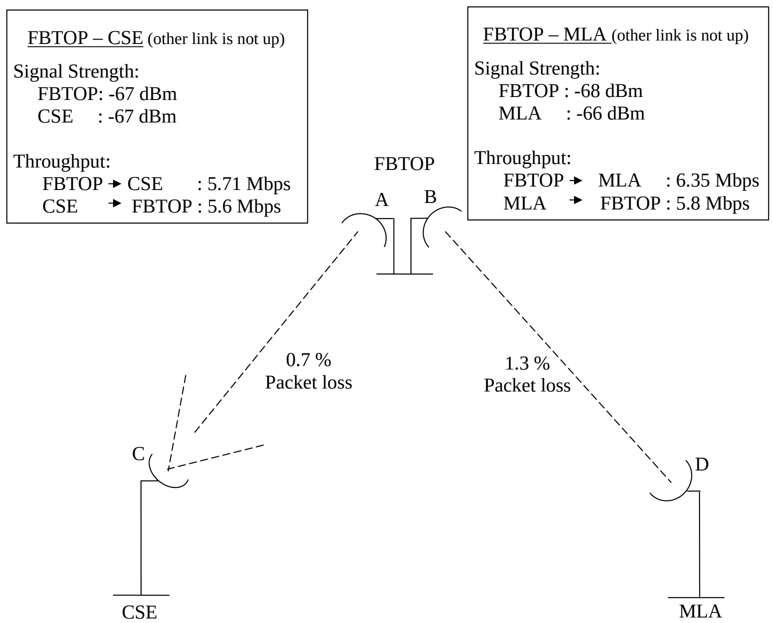


Figure 4.1: Experimental Setup (General Case)

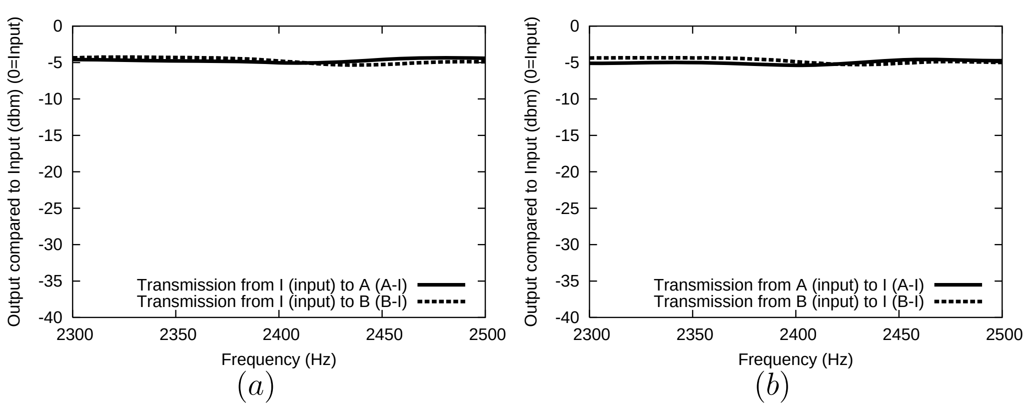


Figure 4.2: PSW-1211:Transmission

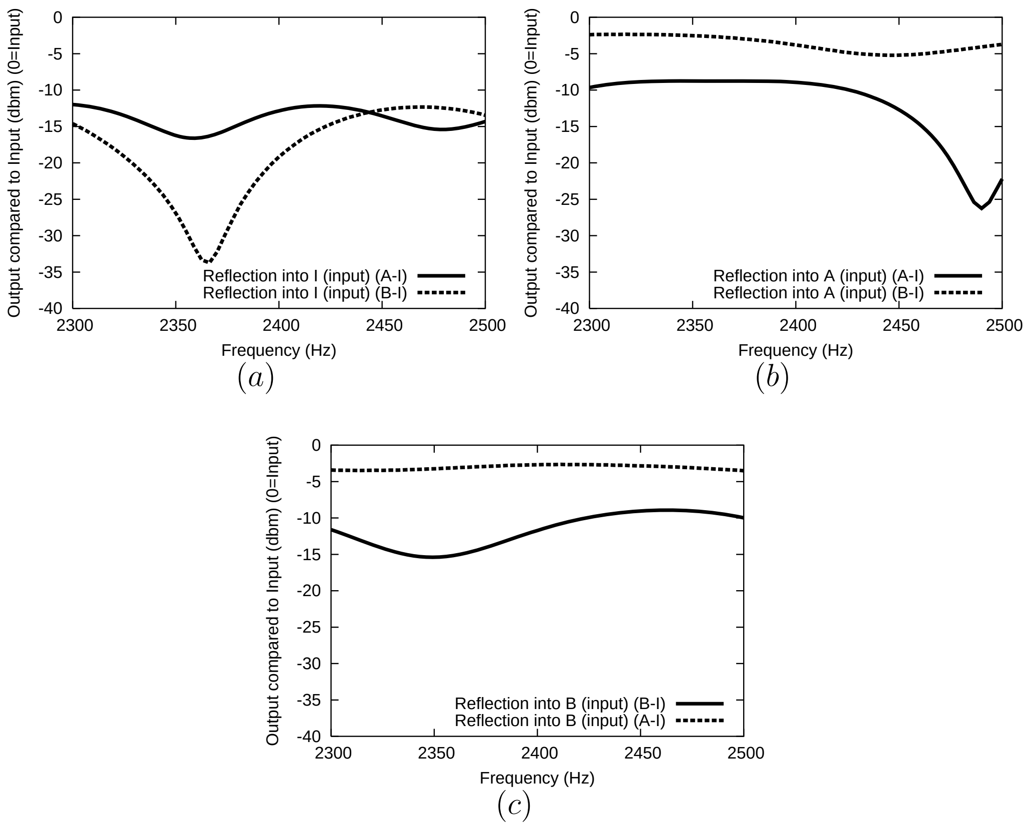


Figure 4.3: PSW-1211:Reflection

Isolation. We used a *Spectrum Analyzer* [25] for calibration.

Transmission: By Transmission means how good the switch is with respect to transmitting the signal from **I** to **A** and *vice versa*, when it is switched for end **A**. Similarly for end **B** also. Fig 4.2 represents Transmission between **I** and **A**, and between **I** and **B**. In Fig 4.2(a), **Transmission from I (input) to A (I - A)** means the graph shows the transmission from **I** to **A** where signal is sent through **I** and received through **A** and **(I - A)** means the control signals are set so that the switch is connected from **I** to **A**. From now on we use this terminology **I - A (or B)**. In this case at 2.4 GHz there is a signal loss of around 5dBm from **I** to **A**. Similarly the other graphs represent the same from **I** to **B**, **A** to **I** and **B** to **I**. Even though 5dBm loss is not good for a switch, it is acceptable for our applications.

Reflection: Reflection means how much signal is bounced back from a line when signal is sent through it. Fig 4.3 shows reflection for **I**, **A** and **B**. For **I** the Reflection is around 12dBm less than what is sent. For **A** and **B** Reflections are around 10dBm less than what is sent when the switch is switched toward them and the Reflections and are 5dBm less than what is sent when the switch is switched toward the other end. These are acceptable for our applications.

Isolation: Isolation represents how much unwanted signal flows through a line. Fig 4.4 shows Isolation among **I**, **A** and **B**. In Fig 4.4(a) **Isolation**

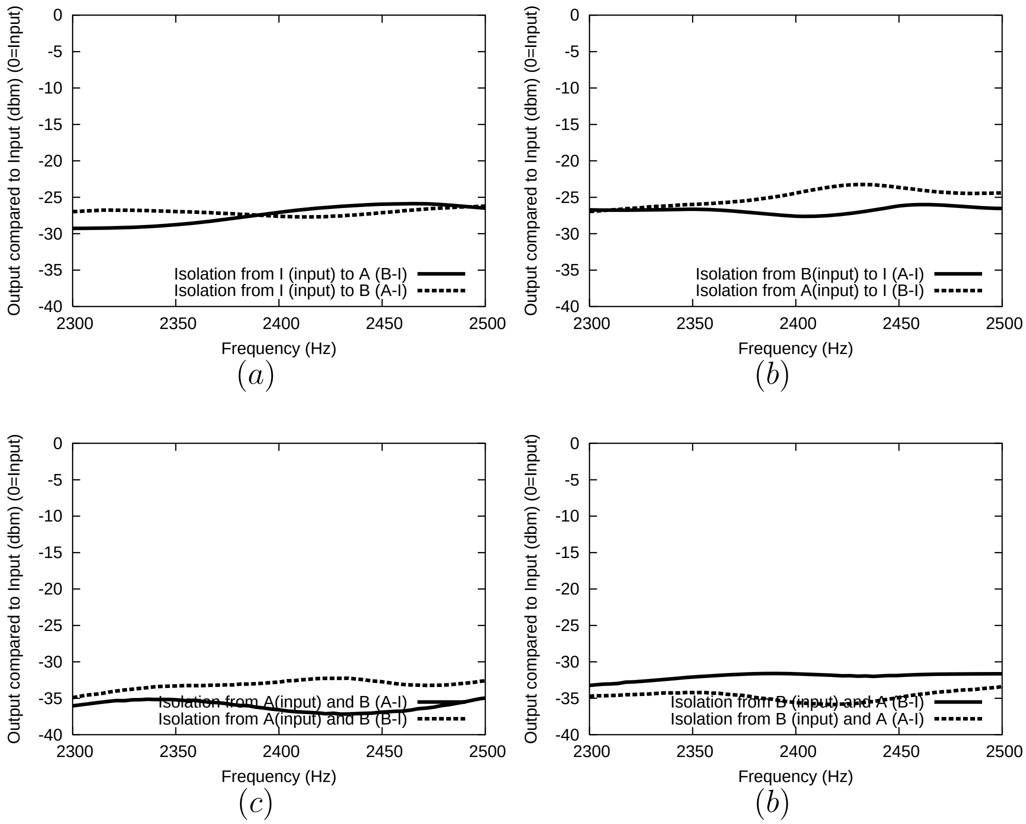


Figure 4.4: PSW-1211:Isolation

from I (input) to A (I-B) shows that at 2.4GHz the signal that is coming through **A** is around 27dbm less than what is sent through **I** when the switch is selected for **I - B**. That means the signal that is sent through **I** not only goes through **B** but also through **A** which is 27dBm less than what is sent through **I**. Similarly the other graphs can be explained.

Outdoor Experiments:

Fig 4.5 shows the outdoor experiment results with the selection of FBTOP and CSE link with PSW-1211 RF-switch. Switch end **I** is connected to the wireless card, **A** is connected to antenna **A** and **B** is connected to antenna **B**. The switch is selected for **I - A**. The signal strengths have reduced by 5 dBm for the FBTOP-CSE link from that of general case which is expected from the calibration results of Fig 4.2. From Fig 4.4(a) the isolation between **I** and **B** when the switch is selected for **I - A** is 27dbm. Hence the signal strength at FBTOP for MLA link should be less than 27dBm of that of the general case. For general case the signal strength is -68dBm, so, at FBTOP the signal strength for MLA link has to be -95dBm. But the observed signal strength is -85 dBm which is not as expected. But even then, for our applications we need only 10dbm difference between two links if one of the links has to dominate the other without having any interference. As signal strength for CSE link is -72dBm and that for MLA link is -85dBm, this makes 13dBm difference between the two links. Hence FBTOP and CSE link dominates over FBTOP and MLA link. The throughput for FBTOP - CSE link is 6.3 Mbps when MLA node is idle. The minimum signal strength required for 802.11 to be operational is -85 dBm. FBTOP - MLA link has a lot of variation in throughput, varying from 1.8 to 4.5 Mbps. This is expected as the signal strength is at the border mark. When both CSE and MLA are sending data in the same channel at the same time, for which MLA is causing interference, the throughput for FBTOP-CSE link is 5.8 Mbps which is very promising. As mentioned earlier this reduction of 0.5 Mbps throughput can be either because of environmental reasons or interference of the access points

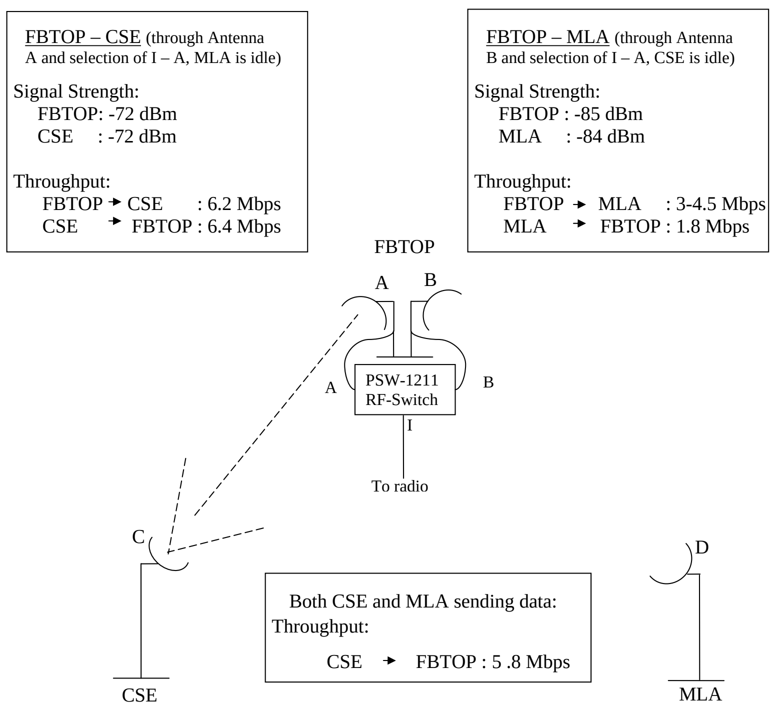


Figure 4.5: PSW-1211: FBTOP - CSE link

present at CSE and FBTOP or interference from MLA. Finally the cost of applying this solution is 2*$50 [7], for each directional antenna and $33 [15] for the switch.

Fig 4.6 shows the results with the selection of FBTOP and MLA link with PSW-1211 RF-switch. The setup is same as above except that the switch is selected for **I - B**. The signal strength for FBTOP-MLA link now is -70dBm which is only 3dBm less than that of general case. As explained above the signal strength for FBTOP-CSE link has to be -95dBm, but the observed signal strength is -89 dBm making a difference of 19dbm between the two links. Hence FBTOP and MLA link dominates over FBTOP and CSE link.

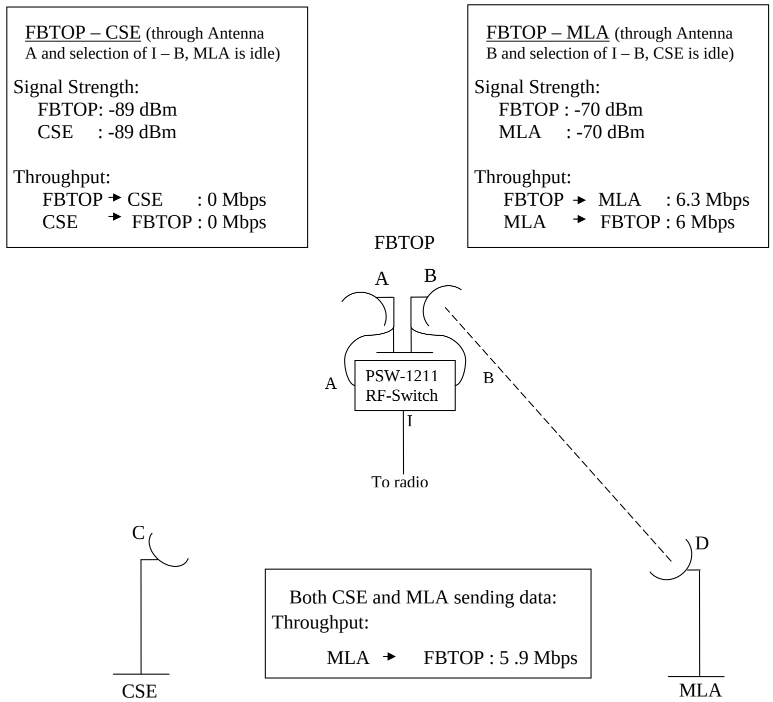


Figure 4.6: PSW-1211: FBTOP - MLA link

The throughput for FBTOP - MLA link is 6.3 Mbps when CSE node is idle. The minimum signal strength required for 802.11 to be operational is -85 dBm. But FBTOP - CSE link has only -89dBm. So the throughput for FBTOP-CSE link even if MLA node is idle is null.When both CSE and MLA are sending data in the same channel at the same time, for which CSE is causing interference, the throughput for FBTOP-MLA link is 5.9 Mbps.

4.1.2 RSW-2-25-P

As PSW-1211, RSW-2-25-P RF-Switch also has three ends, one for connecting to the radio and two for connecting to the antennae. We name the radio end to be **I** and the antennae ends to be **A** and **B**.

Calibration:

Transmission: Fig 4.7 represents Transmission between **I** and **A**, and between **I** and **B**. For RSW-2-25-P, at 2.4 GHz there is a signal loss of around 3dBm from **I** to **A**. Similarly the other graphs represent the same from **I** to **B**, **A** to **I** and **B** to **I**.

Reflection: Fig 4.8 shows reflection for **I**, **A** and **B**. For **I** the Reflection is around 11dBm less than what is sent. For **A** and **B** Reflections are around 11dBm less than what is sent when the switch is switched toward them and the Reflections and are only 3dBm less than what is sent when the switch is switched toward the other end.

Isolation: Fig 4.9 shows Isolation among **I**, **A** and **B**. In Fig 4.9(a) **Isolation from I (input) to A (I-B)** shows that at 2.4GHz the signal that is coming through **A** is around 20dbm less than what is sent through **I** when the switch is selected for **I - B**. That means the signal that is sent through **I** not only goes through **B** but also through **A** which is 20dBm less than what is sent through **I**. The other graphs can be explained like wise.

Fig 4.8 shows reflection which represents the signal that is bounced back. Fig 4.9 shows Isolation among **I**, **A** and **B**.

Fig 4.10 shows the outdoor experiment results with the selection of FBTOP

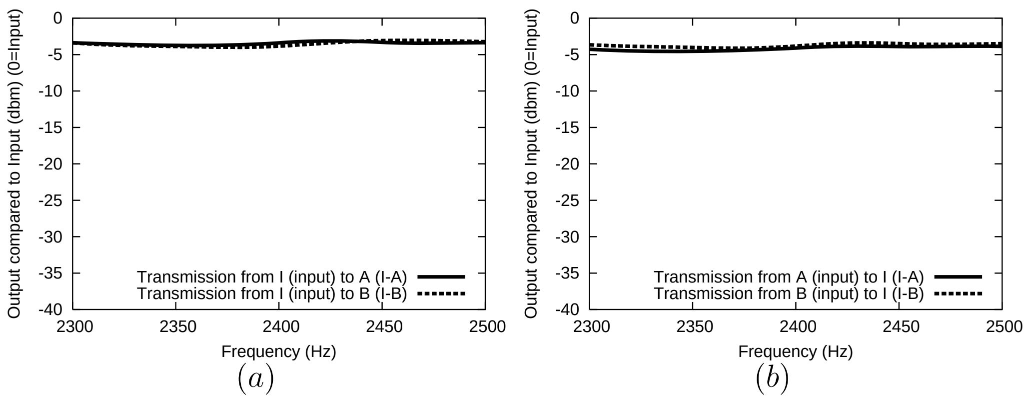


Figure 4.7: RSW-2-25-P:Transmission

and CSE link with RSW-2-25-P RF-switch. The setup is same as mentioned in the PSW-1211 case. The switch is selected for **I - A**. The signal strengths are reduced by 4 dBm for the FBTOP-CSE link from that of general case which is expected from the calibration results of Fig 4.7. From Fig 4.9(a) the isolation between **I** and **B** when the switch is selected for **I - A** is 23dbm. As the signal strength is in general case is -68dBm, so at FBTOP the signal strength for MLA link has to be -91dBm. But the observed signal strength is -85 dBm. Signal strength for CSE link is -72dBm and that for MLA link is -85dBm which has 13dBm difference. Hence FBTOP and CSE link dominates over FBTOP and MLA link. The throughput for FBTOP - CSE link is 6 Mbps when MLA node is idle. FBTOP - MLA link has a lot of variation in throughput, varying from 0.5 to 3 Mbps since the signal strength is just equal to the required level. But for the case, when both CSE and MLA are sending data in the same channel at the same time, the circuit started malfunctioning and hence the experiments cannot be done for the simultaneous

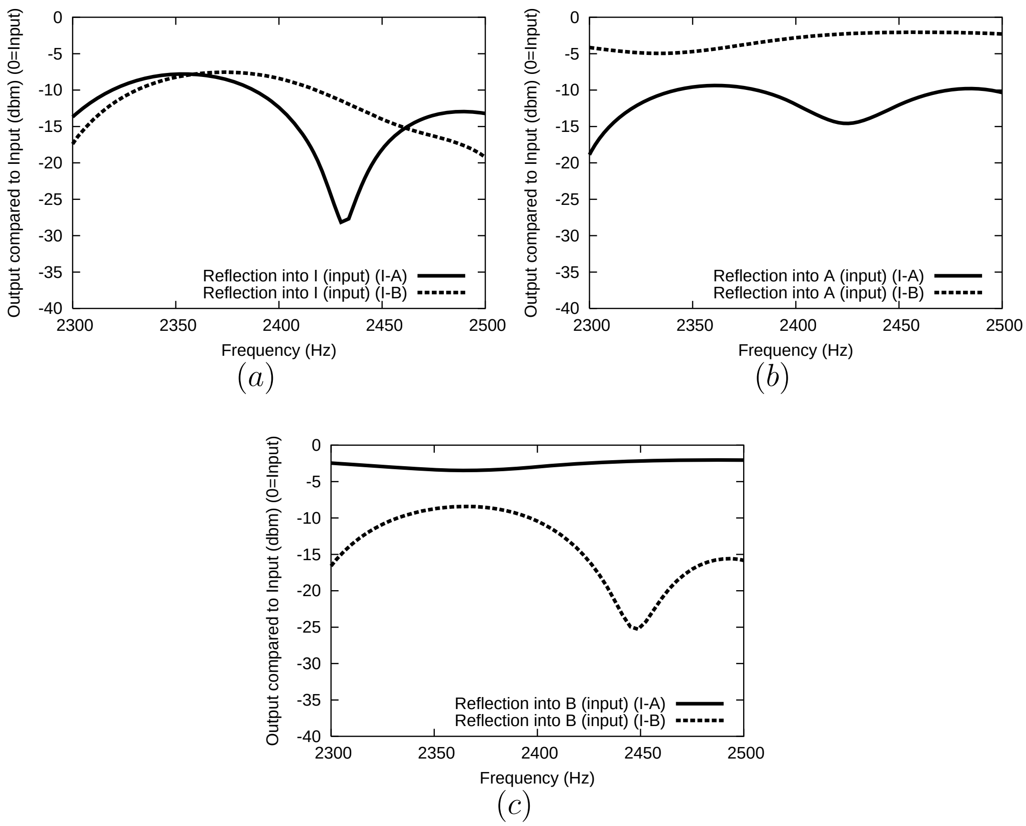


Figure 4.8: RSW-2-25-P:Reflection

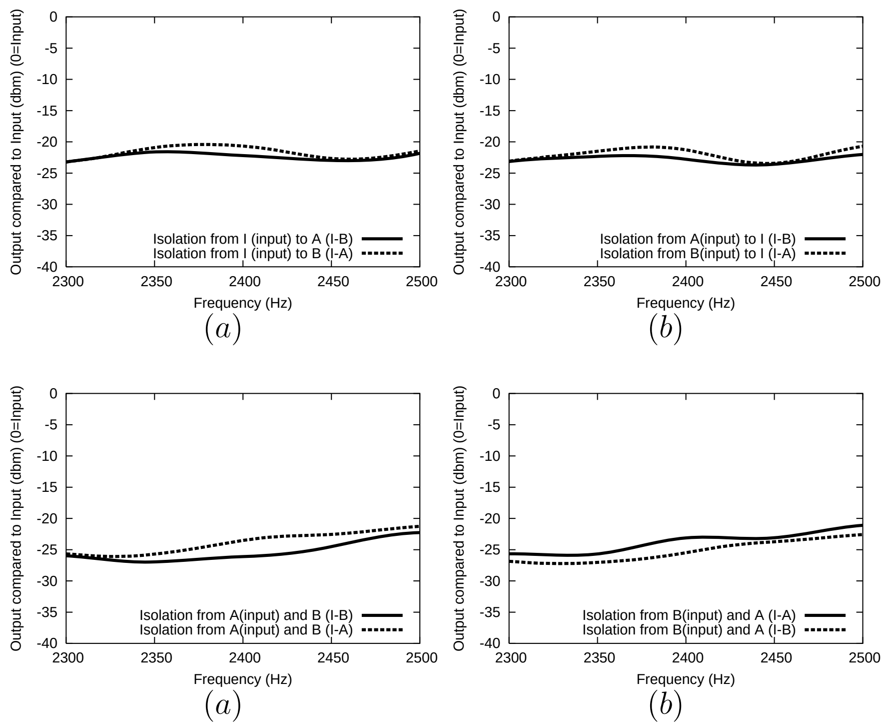


Figure 4.9: RSW-2-25-P:Isolation

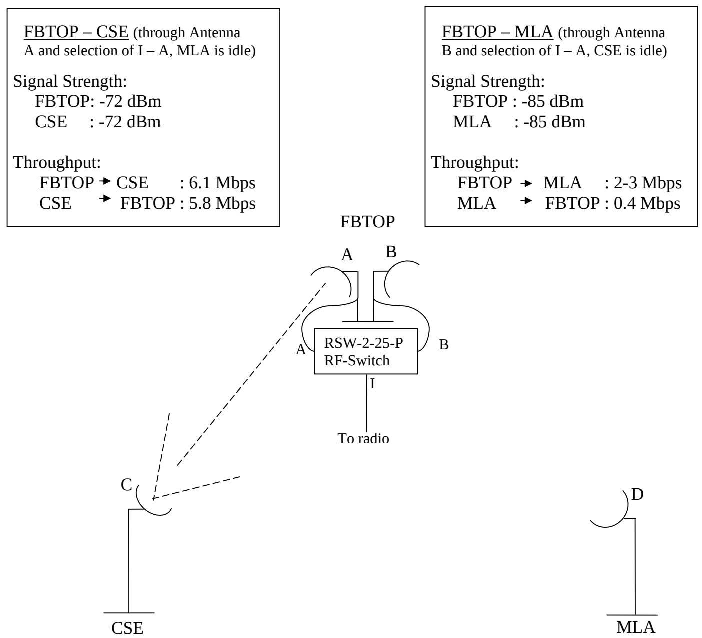


Figure 4.10: RSW-2-25-P: FBTOP - CSE link

cases. As all the results are same as of PSW-1211 cases, we can say this case will also have the same result of around 5.8 Mbps.

Fig 4.11 shows the results with the selection of FBTOP and MLA link with RSW-2-25-P RF-switch. The setup is same as above except that the switch is selected for **I - B**. The signal strength for FBTOP-MLA link now is -70dBm which is only 3dBm less than that of general case. As explained above the signal strength for FBTOP-CSE link has to be -95dBm, but the observed signal strength is -88 dBm making a difference of 18dbm between the two links. Hence FBTOP and MLA link dominates over FBTOP and CSE link. The throughput for FBTOP - MLA link is 6 Mbps when CSE node is idle. The minimum signal strength required for 802.11 to be operational is -85 dBm. But FBTOP - CSE link has only -88dBm. So the throughput for FBTOP-CSE link even if MLA node is idle is null.Finally the cost of applying this solution is 2*$50 [7], for each directional antenna and $4 [16] for the switch.

4.2 Rotation

As antenna mounting to the stepper motor is not done, the results for rotation are not taken using the stepper motor. Since only one link is possible at any time, the results will be the same as explained in Fig 4.1. The cost for this solution is $50+$59 $50 for one directional antenna and $59 for the motor ($30), gears ($15), bearings ($4), and stand ($10). The motor we bought has very high torque (7kg-cm) than required and thus it's cost can be reduced by choosing lower torque (2kg-cm) motors which can be obtained for about $10.

4.3 Cantenna

For this case the results are not taken using a Cantenna. We used a splitter to connect the radio to both the antenna which sends the signals from the radio to both the antenna and *vice versa*. This is the same as the Cantenna case as for both splitter and Cantenna both intermediate node and backup node are within line of sight. The only difference will be with signal strengths as the gain of the antennae are different. As switches, splitter also has three ends, we name the ends the same as in case of switch. **I** is the end for radio,

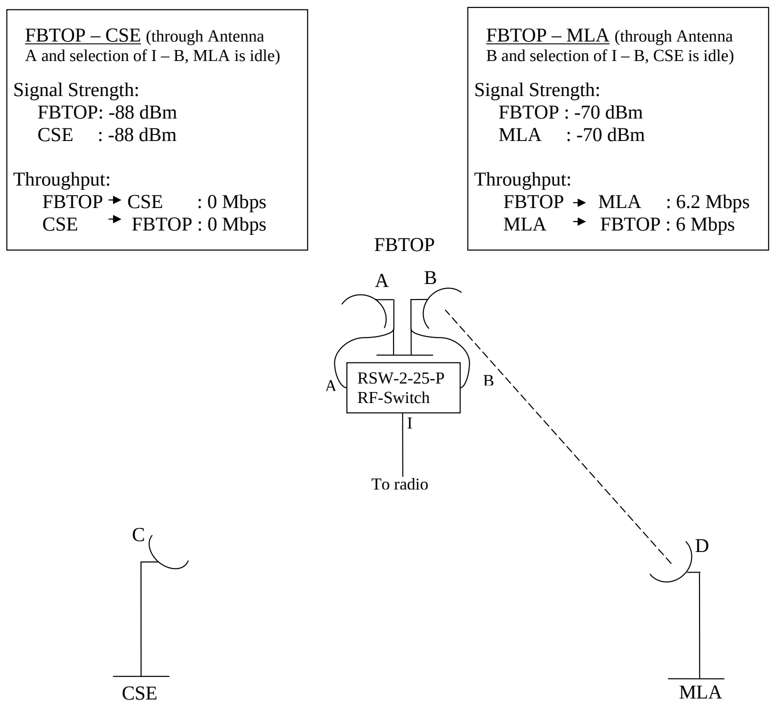


Figure 4.11: RSW-2-25-P: FBTOP - MLA link

A and **B** are the ends for antennae. Unlike for switch there is no control on transmissions from **I - A** and **I - B**. When some signal is sent through **I**, it will go through both **A** and **B**.

Fig 4.12 shows the outdoor experiment results. The setup is same as mentioned in the switch case except that we use splitter instead of switch. The signal strengths are reduced by 4 dBm for both the links. The throughput for FBTOP - CSE link is 6 Mbps when MLA node is idle. FBTOP - MLA link also has throughput of 6 Mbps when CSE is idle. But for the case, when both CSE and MLA are sending data in the same channel at the same time, the throughput drastically reduced to around 2.3 Mbps. This means this solution is not good for the case when both intermediate node and backup node try to service the far-end nodes simultaneously. The cost for this solution is very cheap and is $10.

4.4 Comparison

Table 4.1 gives a comparison of the solutions

	General	Replication		Rotation	Cantenna
		PSW-1211	RSW-2-25-P		
No. of Antennae	N/A	2		1	1
Switching Time	N/A	Order of micro seconds		Order of minutes	Order of micro seconds
Interference	N/A	13dB less than normal link signal strength	13dB less than normal link signal strength	No Interference or negligible	same as normal link signal strength
Throughput for FBTOP-CSE link	5.7 Mbps	6.2 Mbps	6.1 Mbps	5.7 Mbps	6 Mbps
Throughput for FBTOP-MLA link	6.2 Mbps	6.3 Mbps	6.2 Mbps	6.2 Mbps	6 Mbps
Throughput at FBTOP when both CSE and MLA nodes are active	N/A	5.8 Mbps	Will be same as PSW-1211	6Mbps	2.4Mbps
Cost	N/A	2*$50+$33	2*$50+$4	$50+$59	$10

Table 4.1: Comparision of the solutions with general case

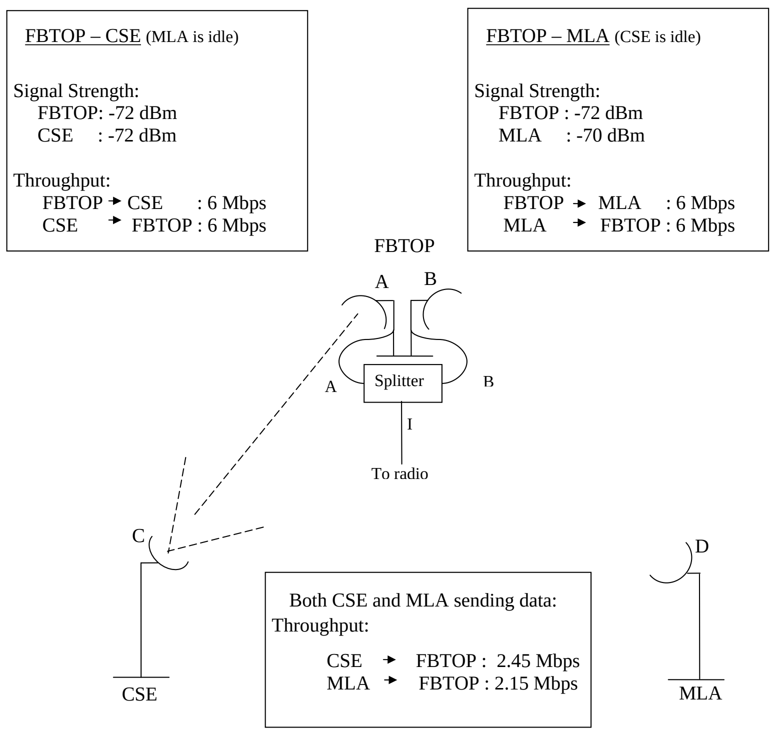


Figure 4.12: Cantenna

Chapter 5

Future Work and Conclusion

Currently for the rural networks there are no cost-effective solutions for improving the fault tolerance. We presented, implemented three solutions Replication, Rotation and Cantenna and tested the same in outdoor links. We found that Replication and Rotation solutions are very effective in all cases and Cantenna case is not suitable when both intermediate node and backup node are trying to make the far-end nodes be connected with the central node. Coming to maintainability, for Replication keeping the switches in weather proof boxes will make them last long and nothing extra care has to be done for Cantenna. For Rotation, as mechanical work is involved with gears and bearings, special care has to be taken checking them at regular intervals.

In this work we assumed that intermediate nodes and backup nodes for the rural network are given. This is not trivial. There are times when both intermediate nodes and backup nodes are up, thus if both of them are made active for connecting the far-end nodes, then the overall throughput increases. Finding intermediate nodes and backup nodes for the network cost-effectively with high overall throughput is another problem. In our work we implemented Rotation solution partially. Further work has to be done and also the cost can be reduced by choosing the components wisely.

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