# The Feasibility And Usefulness Of Link Abstraction In Wireless Networks

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# The Feasibility And Usefulness Of Link Abstraction In Wireless Networks

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*under the guidance of*

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## CERTIFICATE

It is certified that the work contained in the thesis entitled "*The Feasibility And Usefulness Of Link Abstraction In Wireless Networks*" by *Dattatraya Y Gokhale* has been carried out under our supervision and that this work has not been submitted elsewhere for a degree.

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# Abstract

*Most recent measurement work in wireless networks has found that the concept of* link abstraction *does not hold for a wireless link. Research work has thus focussed on working around the absence of a link abstraction by doing intelligent things at the higher layers. Our measurement work in this thesis, has focussed on studying the feasibility and usefulness of a* link abstraction *especially in the two domains of wireless sensor networks and WiFi-based wireless mesh networks. We used Tmote Sky motes equipped with 2.4 GHz radios for our wireless sensor network measurements. The WiFi-based wireless measurements were carried out using 802.11b based Senao PCMCIA cards fitted in laptops and connected to external antennas.*

*Our experimental data suggests that in the absence of external interference, it is indeed possible, to achieve* link abstraction *in case of a wireless link. We find that there exists a* threshold *value of RSSI above which the error rates on the link are stable and negligible i.e. the wireless link becomes a close approximation of a wired link – a situation in which the* link abstraction *holds.*

*A link operating close to the* RSSI threshold *experiences variable error rates. This variability in error rate means that routing metrics proposed for Wireless Mesh Networks (WMNs), like ETX that rely on the Packet Success Rate will be inherently unstable. Imposing an* RSSI threshold *also implies that the maximum link range reduces, effecting a trade-off between link range and predictable performance. However, there are ways to increase the link range. We explore one of them – use of external antennas. The results, from our experiments carried out with wireless sensor nodes suggest that the use of external antennas can substantially increase the maximum communication range over which predictable performance is achievable up to 500m in case of a clear Line-of-Sight (LoS) being available. This range is more than sufficient for a wide range of sensor network applications. In addition, in some cases, it may also help to reduce the network to a single-hop network thereby simplifying the design of routing protocols and reducing the increased losses during multi-hop data transfer.*

*Finally, the feasibility of* link abstraction*, has a number of implications. It can help to plan predictable links with low, stable error rates in new networks and also help to decide the transmit powers to achieve stable, low error links in existing networks.* Link abstraction *can also be used to classify existing links in a network. By classifying an existing link with a stable, low error rate as* ‘up’ *and one with an intermediate error rate as* ‘down’, *we can restrict a network to use only those links with stable, low error rates so that predictable performance can be achieved. In wireless sensor networks,* link abstraction *can also simplify routing, which may eventually help to reduce the overhead of routing messages and thus increase the longevity of the network.*

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At the outset are due
Many thanks to *'you'*
For taking off some precious time
To stop here and read this rhyme

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I must dedicate this work to my '**Father**', who is the reason I am what I am today and who is no longer around to see me graduate from one of the finest academic institutions of this country...

Lastly but not in the least the following lines are dedicated to the omnipotent, omniscient and omnipresent...

My debt to You is immeasurable...
My words try to say so
And in the bargain accept
Their complete inadequacy to do so...

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# Chapter 1

# Introduction

Over the last few years, wireless networks operating in the ISM bands have grown tremendously in popularity on account of the mobility and the convenience they offer. The Industrial , Scientific and Medical (ISM) radio bands, are sets of frequencies that have been reserved for use by the industrial, scientific and medical communities. The delicensing of the ISM bands has also contributed in a big way to the multifold growth in the popularity of these networks. As the devices in these networks operate in the de-licensed region of the spectrum, they have to comply with regulations that govern the maximum power that can be radiated by these devices.

Wireless LANs are a type of wireless networks based on the 802.11 family of standards that were initially formalised by the working group 11 of the IEEE LAN/MAN Standards Committee [3]. The standards are available at [10]. A number of standards now govern the multiple over-the-air modulation schemes that are being used and which use the same basic 802.11 protocol to communicate. The 802.11b standard [12], was ratified in 1999 and that helped to increase the popularity of wireless LANs. It promised a maximum raw data rate of up to 11Mbps. The 802.11b standard uses Complimentary Code Keying (CCK) as the modulation scheme at the physical layer. The quantum of increase in throughput that 802.11b offered compared to the older 802.11-Legacy standard coupled with the simultaneous price reductions ensured that 802.11b became very the most popular Wireless LAN technology. It has eventually given way to 802.11g [8] and now the 802.11a standards [9] which offer much larger data rates. However, 802.11b still remains a favourite, especially for outdoor networks. People have also been able to tweak the original 802.11 standard to allow it to operate over long distances by making modifications at the driver level ([14], [35], [27]).

Wireless Sensor Networks (WSNs), on the other hand, consist of groups of small, low cost, resource constrained devices that carry sensors and a radio and are able to sense physical phenomena of interest (such as temperature, sound, vibration, pressure etc.). The devices can communicate with one another using the radio and transfer their data over the wireless medium to a base or a gateway node, from where it can be forwarded onward to a regular network. The concept of wireless sensor networks was motivated initially by military applications such as surveillance. However, with the development and availability of commercially manufactured nodes and a stable operating system like *TinyOS*, WSNs have gained popularity and found a number of applications in areas like environment monitoring ([37], [26]], habitat monitoring [36], structural monitoring of bridges [23]) etc.

However, as their names imply, both these type of networks rely on the wireless medium for data transfer. In the absence of a wired medium to connect two nodes in a network, there exists a possibility that the relationship between Signal-to-Noise Ratio (SNR) and Bit Error Rate (BER) will not have a rapid transition from a very low value to a value high enough that the two nodes are unable to communicate. This in essence is the concept of link abstraction, which is explained again in the following chapter.

This thesis explores the feasibility of achieving link abstraction in a wireless medium. It also comments on the usefulness of achieving link abstraction.

In particular, the thesis looks for answers to the following questions:

- Is it possible to achieve link abstraction in Wireless Networks, specifically in
  - Wireless Sensor Networks (WSNs)
  - Wireless Mesh Networks (WMNs) based on 802.11 (over intermediate distances, $< 500m$)
- If it is possible to achieve link abstraction, how does one engineer links that achieve link abstraction?
- If link abstraction is feasible, is it possible to classify links in an existing network based on the whether the *link abstraction* holds or not, such that predictable performance may be achieved in an existing network?
- What is the main factor that destroys the correlation between RSSI and error rates such that link abstraction cannot be achieved? Is it multi-path or interference?

Prior work by Woo et al. [39], uses *Mica* motes operating at 916 MHz, to bring out their observation that the wireless medium is dynamic and lossy. They mention the existence of a *transitional region*, where the delivery probability varies. Zhao and Govindan, in [40] have used *Mica* motes operating at a frequency of 433 MHz, to study the packet delivery performance in a dense sensor network deployment. In line with Woo, they also point out the presence of a *gray region*, where the error rate is unpredictable and also varies with time. They, in fact, go on to say that the *gray region* extends as much as 30% of the total communication range for an indoor environment and upto 20% in their outdoor setting. They also observe that high signal strength is a necessary but not a sufficient condition for a good packet delivery probability.

Sensor network deployments like the Redwood deployment [37], have tried to work around this uncertainty by using Multi-hop LQI (Link Quality Indication) as a routing metric to choose the best path to the final destination. In [39], the authors suggest the use of metrics like $1/PSR$ (Packet Success Rate) which are used by wired internet protocols like IGRP and EIGRP to evaluate the quality of a link. A metric like ETX [17], proposed in the WMN domain, can also be used to choose the better links amongst links with intermediate delivery probabilities. Protocols like RMST [33] proposed by Stann et al try to overcome this unpredictability in the lower layer at the transport layer. RMST uses directed diffusion and provides reliable delivery, fragmentation/reassembly. Our experimental data however, suggests that it may actually be possible to achieve link abstraction.

In the domain of community wireless sensor networks, the Roofnet study [13] that was carried analysed the causes for intermediate packet delivery ratios over the links of a community network in Cambridge, MA, USA. They concluded that in their setting, there was no correlation between Signal-to-Noise Ratio (SNR) and error rate. Their experiments also lead them to believe that *interference* is not the main cause of intermediate delivery probabilities. Their controlled multi-path experiments then lead them to conclude that it is actually multi-path that is the real culprit.

In an effort to work around links with such intermediate delivery probabilities, De Couto et al. proposed the ETX metric [17] for routing packets. The ETX metric tries to minimise the expected number of transmissions (including retransmissions) required to successfully deliver a packet to its final destination. In [21], Draves et al. propose a metric called ETT (Expected Transmission Time) that tries to improve upon ETX by considering the differences in link transmission time. The Weighted Cumulative ETT (WCETT) metric [21] in turn exploits channel diversity along a path in a network in an effort to reduce the effect of interference. However, we reiterate that all these complex routing protocols work under the assumption that link abstraction is not possible in a WMN.

In our work, we thus perform a number of experiments at various locations to test and answer the questions we have posed above. We used *Tmote Sky* motes [7] to perform the WSN experiments. The motes are equipped with a IEEE 802.15.4 compliant Zigbee® radio that operates in the 2.4 GHz ISM band. To test the maximum communication ranges attainable, we connected external antennas to the motes. The external antennas were mounted on masts. On the other hand, the WMN experiments were carried out using 802.11b based Senao PCMCIA card fitted in laptops. The cards were connected to external antennas using RF cables. The external antennas, as earlier, were mounted on masts.

Our experimental results and their implications are as mentioned under:

**WSNs:**
Our results indicate that:

- There exists a threshold value of RSSI, such that operating a link at an RSSI above that will ensure that the error rates remain stable and low and the concept of link abstraction holds.
- There exists a *steep region* close to the receive sensitivity of the receiver where

the error rate becomes unpredictable and rises very sharply for a small fall in the RSSI. The width of the *steep region* varies depending on the environment in which the link is operating.

- We observed variability in the RSSI values over time scales as small as 2 seconds to as large as 24 hours. This has important implications which we mention hereafter.

Our results have important implications. They are listed below:

- The feasibility of the link abstraction has important implications for routing, and network design in WSNs - link abstraction makes it possible to design very simple routing algorithms that do not have to continually track the state of a metric and thereby the quality of the link. This also helps to reduce the traffic overhead that may be generated in case of unstable links viz. links where the link abstraction does not hold and thus eventually also helps to to increase the overall network lifetime.
- The limitation on range imposed by opting to operate away from the *steep region* can be overcome by using external antenna. With the use of external antennas it is possible to extend the communication range of a device especially in Line-of-Sight environments. Thus link abstraction now holds for a larger number of links. This simplifies network design and also increases the number of nodes that are closer to the gateway. Simplified routing can thus be used to eventually increase the lifetime of the network.
- The variability in RSSI over long and small time durations means that when operating very close to the steep region, there will times when the RSSI overlaps with the *steep region*. During this time the error rate would become unstable and routing metrics that try to predict the link using metrics like 'packet success rate' will be unstable. This has implications while planning links as well – we need to allow a headroom equal to the maximum variability in RSSI while calculating the mean RSSI at which to operate the link.

**Wireless Mesh networks:**
In the context of Wireless Mesh Networks (WMNs) we make the following observations from our experiments:

- *External Interference*, not multipath is the primary cause of unpredictable link quality and the lack of dependence on SNR / RSSI
- In the absence of *external interference*, the link error rate has a strong correlation with RSSI / SNR. There is a clear RSSI threshold where the error rate rises steeply. A link experiences stable, low error rates if the RSSI values do not overlap with the *steep region*
- In the absence of interference, RSSI values observed are stable and lie within a band of 3 - 4 *dB*

These observations have implications some of which we enumerate below:

- To ensure that *link abstraction* holds for a given link, we need to ensure that the RSSI at the receiver is above the *RSSI threshold*. Considering a variation of 3–4 *dB* in the long term variation of RSSI, we need to account for this while designing the link.

- As error rates are unstable and vary in the *steep region*, metrics like ETX [17] which try to select one link over another by looking at the loss rates, will be unstable.
- As it is difficult to guage the amount of interference on available hardware, it may be better to avoid interference all together. The difficulty in guaging the amount of interference present accurately, implies using the value of interference to make intelligent decisions about the network link may thus not be very accurate.

The remainder of the thesis report is organised as follows. Chapter 2 outlines the related work in the areas of sensor networks and wireless mesh networks. Chapter 3 explains our experimental setup and the choice of locations and the parameters we used for the purpose of our experiments. Chapters 4 and 5 lay out our experiments, results and their implications for WSNs and WMNs. Finally, Chapter 6 reiterates our important results and identifies areas for future work.

# Chapter 2

# Related Work and Background

## 2.1 Introduction

A lot of literature related to the wireless domain, both in the area of wireless mesh networks and Wireless Sensor Networks (WSNs), has focussed on overcoming the unpredictable vagaries of the wireless medium by doing intelligent things at the link layer or higher ([17], [21], [33]). The implicit assumption in all this work is that a wireless link has unstable and varying error rates, which in other words means that the '*link abstraction*' is not valid.

The next section explains the concept of a *link abstraction*. Section 2.3 discusses the related work in the field of WSNs. Section 2.4 lays out related work in 802.11 and also motivates the idea of FRACTEL, which influences our further experimental setup and methodology for experiments in the 802.11 domain.

## 2.2 Link Abstraction

*Abstraction* is a mechanism and practice to reduce and factor out details so that one can focus on a few concepts at a time. The concept of link abstraction is derived from the world of wired networks. In the wired world if two points in a network are connected directly then it can be safely assumed that the link between them has a very low error rate. In effect the link has only two states viz. it exists and allows communication at its full capacity with a negligible error rate (0%) or it does not exist at all and the error rate may be assumed to be 100%.

This assumption about the the error rate, when applied to wireless links means that there will be very few links where the error rate will not be nearly 0 or nearly 100%. In effect, it means that in a given network, nodes will either be able to communicate with each other with very small or no errors or will not be able to talk to each other at all.

With this in background in place we now take a look at some related work in the fields of wireless sensor networks and 802.11 based networks.

## 2.3 Wireless Sensor Networks (WSNs)

Wireless sensor networks have been deployed in various environments such as a redwood tree in a forest [37], on the slopes of an active volcano [38], inside bird burrows to monitor birds [36] and so on. Others have proposed deploying such networks to monitor and warn about imminent landslides [30] and to monitor structures like railway bridges [23].

One of the main considerations while deploying these networks is to maximise the longevity of the network while at the same time ensuring that there is no loss of data collected by the individual nodes, especially while transmitting the data from one node to another. Constrained by the scant resources at the disposal of each node, various papers in literature have proposed varied mechanisms to overcome the unreliability and temporal instability of the wireless medium.

The authors in [37] deployed a network of *Mica2Dot* nodes on a redwood tree for a period of nearly 44 days. The motes were placed at a distance of 2 meters from each other from 15 to 70m along the trunk of a redwood tree. The deployment used TASK a sensor network framework used for collecting data. In addition the deployment also used Multi-Hop LQI as a metric for their routing. The CC2420 chip, in addition to RSSI, provides another value called the Link Quality Indicator (LQI) [1]. The LQI is characterised by the strength and/or quality of a received packet. The LQI is expressed as number between 0 - 255. The LQI uses the *chip error* rate which denotes the average correlation value of the the first 8 symbols for an incoming packet. The LQI is used to determine the quality of a link and decide on the best links on which to route packets.

However, in [32], Sreenivasan and Levis find that LQI for a link shows a larger variance than RSSI and the LQI values need to be averaged out over a considerably longer duration to obtain a more accurate estimate of link quality. This, however, makes the routing algorithm less agile in adapting to changes and increases the estimation time.

In [39] the authors state that the wireless medium is dynamic and lossy. Their experiments were carried out using *Berkeley Mica* motes operating at 916MHz. The motes carry an RF Monolithic Amplitude Shift-Keyed (ASK) radio capable of a data rate of 40 Kbps and a power of 1 mW. The non-ideal characteristics of the medium that they observe, raises issues that must be addressed by routing protocols. The authors show that in their setting the mean link quality and the variance in the link quality is a function of distance. The measurements carried out by them point to the existence of an *effective region* (a distance within which all nodes essentially have good connectivity, a *transitional region* (wherein the link quality falls of smoothly with distance), and points beyond the transitional region where all nodes have poor connectivity. In the *transitional region*, intermediate loss rates and asymmetric links can be observed. The authors propose that the use of a simple time averaged EWMA link estimator, frequency based neighbourhood table management and cost-based routing provides an effective solution to overcome these problems.

The authors in [40] have studied the packet delivery performance in a dense wireless sensor network in three different environments viz. an indoor office building, a habitat with moderate foliage and an open parking lot. The authors use *Mica* motes with an ASK radio operating at 433 MHz. The mote is connected to an external omni-directional whip antenna instead of using the internal trace antenna. The authors place over 60 nodes in a linear topology, about 0.5m to 0.25m apart. During the course of the experiment one node at the end, sends out packets that are received and logged by all the other nodes. The authors then analyse the logs. The authors make the following important observations:

- There exists a gray area in the complete communication range where the error rate is unpredictable and also varies with time.
- The gray area extends to about *one-third* the overall communication range for an indoor environment and to about *one-fifth* for the habitat environment.
- High signal strength is a necessary but not a sufficient condition for a good packet reception ratio.
- At the MAC layer, nearly 50% to 80% of the energy is spent in repairing lost transmissions.

In contrast to the above findings we find that in an environment where there is LoS available, the RSSI band over which the error rates become unpredictable is about $3 - 4$ $dB$. The width of this band increases especially in environments with dense foliage.

In the absence of *link abstraction*, work on routing metrics has focussed on finding appropriate metrics that are able to choose the best link among various links exhibiting intermediate delivery probabilities. To be able to function/work in conditions where most links have varying error rates anywhere between 0% and 100%, routing metrics like $1/PSR$ [39] and multi-hop LQI [37] have been proposed.

The $1/PSR$ metric differentiates between links by estimating the delivery probability on the link. Links with larger delivery probabilities will have a lower value of $1/PSR$ and will be favoured. The multi-hop LQI metric uses $1/LQI$ as the measure of the link quality. The LQI value is a per-packet value supplied by radios like CC2420 [1] that is an estimate of the quality of the link. A metric like ETX [17], proposed in the WMN domain, is quite similar to the $1/PSR$ metric and can also be used to decide the best hop along a path in a multi-hop scenario. Our experimental data however suggests that it may be feasible to achieve *link abstraction* over a wireless link.

We now take a look at some of the related work in the wireless Mesh Networks.

## 2.4 Wireless Mesh Networks (WMNs)

The availability of cheap 802.11 devices has led to an increase in the number of outdoor community networks based on 802.11. Typically a 802.11 community network consists of a number of users who use 802.11 hardware to connect to each other to form a wireless mesh network. Such a network may be used to share internet bandwidth that may be available to a sub-section of users of the community network. Such networks, however, have typically not been known to provide predictable performance.

Roofnet is a typical example of a community network established in the Cambridge area.

> "Roofnet is an experimental 802.11b/g mesh network in development at MIT CSAIL which provides broadband Internet access to users in Cambridge... Roofnet is part of our research, which includes link-level measurements of 802.11, finding high-throughput routes in the face of lossy links, adaptive bit-rate selection, and developing new protocols which take advantage of radios unique properties." [4]

The authors in [13] conducted a study to analyze the packet loss in a 38-node urban multi-hop network. The authors start the with the observation that most links in the Roofnet network have intermediate loss rates i.e. *link abstraction* does not hold in their scenario. They then go on to analyse the main causes of packet loss in their network and the predominance of links with intermediate loss rates. The main relevant conclusions that they draw are:

- Signal-to-Noise ratio has little predictive value for loss rate
- The large number of links with intermediate loss rate is due to multipath fading rather than attenuation or interference.

These conclusions from the Roofnet study are in stark contrast however, to the measurement study carried out on the DGP network [16]. The DGP study observes that:

- The correlation between SNR and error rate is close to the theory
- External interference on a link is detrimental to the performance of the link

The FRACTEL (wi**F**i-based **R**egional/Rural data **AC**cess and **TEL**ephony) project is our motivation for measurements in the Wireless Mesh Network domain. In Table 2.1 we compare the settings for FRACTEL and existing networks like DGP and Roofnet.

In many ways FRACTEL, our motivation, is closer to Roofnet than to long distance mesh networks like DGP. Most links in our setting are expected to be shorter than 500m and most antennas would be placed on rooftops and not high towers/masts like in DGP. In our setting, we expect buildings up to 1-2 storeys tall.

| | **WMNs**<br>**Eg: Roofnet** | **Long Distance Wi-Fi Links**<br>**Eg: DGP** | **FRACTEL**<br>***Presently*** |
|---|---|---|---|
| **External Connectivity** | Multiple Points | Single Point | **Single** |
| **Link Distance** | Mostly $< 500m$ | Up to few tens of kms | **Mostly** $< 500m$ |
| **Network Architecture** | Omni Antennas on Rooftops | High Gain Directional Antennas on tall towers | **Avoid use of tall towers** |
| **Environment** | Dense Urban | Rural Setting | **Rural / Campus** |
| **Multipath effects** | Susceptible | Less Susceptible | *To be determined* |
| **Link Abstraction** | Invalid | Valid | *To be determined* |
| **SNR/RSSI and Link Quality** | Not useful in predicting link quality | Has Strong correlation with link quality | *To be determined* |

**Table 2.1. Comparison: Roofnet, DGP and FRACTEL**

However, unlike Roofnet, which operates in a dense urban environment, FRACTEL would operate primarily in a rural environment. Considering the contrasting results that Roofnet and DGP have obtained especially with regard to *link abstraction*, it is important for us to study the link characteristics that we would obtain in our setting.

In particular we verify the feasibility of forming links that exhibit link abstraction over intermediate distances and typically with antennas placed at rooftop height. During the course of our experiments we have found that our results are in contrast to those obtained in the Roofnet measurement study.

Results from the Roofnet measurement study have led people to propose metrics like ETX and WCETT that try to function/work in conditions where most links have error rates varying anywhere between 0% and 100%. The Expected Transmission Count (ETX) metric tries to find paths with the highest throughput through a network. The metric minimises the expected total number of transmissions (including retransmissions) required to successfully deliver a packet to its final destination. The ETX metric accounts for the losses on a link, unequal losses in either direction i.e. asymmetry in the loss rates between the two directions on a link and interference among successive links on a path.

The Weighted Cumulative Expected Transmission Time (WCETT) metric proposed by Draves et al., accounts for the effect of interference between links. The

WCETT metric calculates an Expected Transmission Time (ETT) for each link. The sum of all ETTs along a path to the final destination gives an estimate of the total delay a packet will face while traveling along the path. In addition, the metric takes a weighted average of the ETT and the sum of transmission times of hops on the common channel. The metric thus tries to achieve a trade-off between throughput on a link and the the total delay a packet experiences.

# Chapter 3

# Experimental Setup and Methodology

## 3.1 Introduction

We now take a look at the experimental setup we used to run our experiments. This chapter also explains the methodology we adopted while running our experiments and the reasoning behind our choice of locations for the experiments.

Section 3.2 covers the experimental setup and methodology used for the experiments conducted with wireless sensor nodes *(WSNs)*, while Section 3.3 covers the experimental setup and methodology used for the WiFi experiments. Each section is further divided into suitable sub-sections that outline the hardware and software used, the experimental setup and the methodology used while running the experiment. In addition, where applicable, we also mention the motivation for the various choices made.

## 3.2 Experimental setup using Wireless Sensor Nodes

Our experiments using wireless sensor nodes were done with commercially available hardware, details of which are mentioned below. Later we outline our experimental setup and the methodology used to carry out the experiments.

### Hardware

We used the commercially available Moteiv *Tmote Sky motes* [7] for our experiments. The *Tmote* carries a Chipcon CC2420 radio [1] that operates in the 2.4 GHz ISM band and complies with the 802.15.4 standard.

The *Tmote* is equipped with a 3 *dBi* internal antenna [7], which we have used during our experiments. In addition to the internal antenna, we also used external antennas in our experiments. In order to use the external antenna, a SMA (Sub-Miniature ver-A) connector was soldered onto the *Tmote*. An *adapter* was then used to connect an external antenna to the mote using this connector.

We used the following external antennas during our experiment runs:

- **Parabolic Grid Antenna** – 24 *dBi*, 8° beamwidth
- **Sector Antenna** – 17 *dBi*, 90° beamwidth
- **Omni-directional Antenna** – 8 *dBi*

Henceforth we will refer to these antennas as *grid*, *sector* and *omni* respectively.

The antennas were used in the following combinations during the experiments:

- internal – internal
- omni – internal
- sector – internal
- grid – internal
- omni – omni
- sector – omni, and
- grid – omni

**Software**

> TinyOS is an open source operating system designed for wireless embedded sensor networks. It features a component-based architecture which enables rapid innovation and implementation while minimizing code size as required by the severe memory constraints inherent in sensor networks. [5]

We have used *TinyOS* ver 1.1.15 [6] for writing the packet generation and transmission program that was used at the transmitter end and the *TOSBase* program, supplied as part of the *TinyOS* distribution, which was used at the receiver end. The laptops that were connected to the motes at either end, had the TinyOS distribution installed in *Cygwin*. The underlying OS on the laptop was Windows XP®.

At the receiver, the received packets were transmitted by the mote over the USB interface to the laptop, where they were logged in a file. A *Ruby* script was used to analyse the generated log-file. It extracted the fields of interest, converted them into the proper format and then wrote them to another log-file. This log-file was analysed using MATLAB® programs to generate the required statistics and plots.

### Experimental Methodology

Each experiment used two *motes* – one transmitter and one receiver. In case of an external antenna, the mote was connected to the antenna using the SMA connector. The antenna itself was clamped onto a mast, the height of which is furnished in Chapter 4, along with other details where relevant. The motes were connected using an USB cable to a laptop. The USB cable powers the mote and also allows one to collect data received by the mote and reprogram the mote as and when required.

The transmitter was programmed to send a configurable number of packets with an inter-packet gap of 20ms. All the packets were sent as a broadcast by the transmitter. There is no link level recovery mechanism enabled by default in *TinyOS*. We also did not enable any link level acks as we felt that it would have given us a wrong picture about the quality of the link as some losses would have been recovered by link level retransmissions. The transmission power of the transmitter was set to 0 *dBm*, which is the maximum allowed by the CC2420 radio. Each packet that was transmitted contains a 10-byte header and 14-bytes of data. The data includes a sequence number that is used to keep track of the packet losses.

The receiver, as mentioned earlier, also consists of a mote that is mounted on a tripod at a height of about 1.5 to 1.7m above the ground. The receiver mote was programmed with the *TOSBase* application running in the listening mode. The receiver receives packets over the radio and fills up the RSSI and LQI (Link Quality Indicator) values in the packet before forwarding the packet over the USB interface to a connected laptop.

### Experiment Locations:

Our experiments were carried out at the undermentioned locations:

- The IIT-Kanpur airstrip – referred to hereon as *airstrip*
- A narrow road with foliage some distance away on either side of the road – referred to hereon as *road*
- Dense foliage – referred to hereon as *foliage*
- Structures lab – referred to hereon as *lab*
- Hall 8 corridor – referred to hereon as *corridor*

The above environments were chosen so as to resemble the environments of sensor network deployments in literature. In addition, we felt that the above environments would also experience varying degrees of multi-path.

The *airstrip* is situated inside the campus and is an environment with no foliage around it. The airstrip is nearly 1 km long and provided ample clear space to carry out our measurements. This environment is primarily characterised by the availability of a clear Line-of-Sight (LoS) and the complete absence of any foliage in the vicinity.

The *road* is a nearly 500m long stretch of narrow road inside the campus. It is relatively unused especially in the mornings and late evenings. It provided a clear LoS. There was foliage some distance away from the road side.

The *foliage* environment is situated in the campus and consists of a area densely covered with trees, shrub and tall grass. The foliage environment was chosen as it was close to the environment that the Redwood study [37] must have experienced. The foliage was so dense that we had to use cell phones beyond 30m to coordinate our experiments.

The *lab* is the Structures Laboratory in the Civil Engineering Department of the Institute. The laboratory is situated in a large enclosed hall and has a large number of machinery and equipment. Being an enclosed space the environment was expected to exhibit a significant amount of multi-path. In addition it was a highly dynamic environment as well, with a lot of movement of people and equipment during our experiment runs.

The *corridor* is about 70m long and is covered on the top, and has pillars lining it on either side. In addition, there are also a number of buildings in the vicinity. We chose this environment as we expected the close-by structures to generate significant amount of multipath.

Figure 3.1 shows views of the foliage environment and the narrow road environment with an *omni* and *grid* antenna respectively. Figures 3.2 and 3.3 show the *lab* and the *corridor* environments.

**Figure 3.1. Dense Foliage and Narrow Road Environments**

The link quality measurements were carried out in the *airstrip*, *road*, *foliage*, *lab*, and *corridor* environments while the link range measurements were carried

**Figure 3.2. Structures Lab, Dept. of Civil Engineering, IIT, Kanpur**

**Figure 3.3. Hostel Corridor, Hall of Residence, IIT, Kanpur**

out in the *foliage* and *road* environments. The dense foliage environment was chosen as it is close to the environment in which the Redwood study [37] was carried out. The narrow road environment mimics the environments in which the Volcano monitoring and BriMon deployments would be carried out. The primary characteristic of such an environment is the availability of some degree of Line-of-Sight (LoS).

We marked out the transmitter and receiver positions during each experiment so as to reduce/minimise the change in the experimental setup across days. The link quality experiments on the *airstrip* and the *road* were conducted using omni antennas at both ends while the ones in the *foliage* environment were conducted using different antenna combinations. The measurements were carried out in the *foliage* and *road* environments. However, while using the *sector* and *grid* antennas, we had to shift out measurements to the airstrip as we could the length of the road was limiting the maximum range at which we could receive packets.

## 3.3 Experimental setup using WiFi radios

This section presents the experimental setup, equipment and the methodology we used to conduct the WiFi experiments. We the report the hardware and software that was used to carry out the experiments. We also explain the methodology we used to plan and carry out the experiments, while also listing out the locations at which the experiments were carried out. We also explain our rationale for choosing those locations.

### Hardware

We used the Senao 2511CD plus ext2 PCMCIA cards inserted into laptops (1.7 GHz Pentium Centrino, 512MB RAM) for our experiments. The cards had connectors to which we could connect external antenna using RF cables. The transmitter was connected to a 8-*dBi* omni antenna and a 17 *dBi* sector antenna in turns. The receiver end was always connected to an 8 *dBi* omni antenna. The antennas were mounted on a small tripod stand about 1.5m tall. In some cases we also used a variable attenuator at the transmitter end to attenuate the value of the received signal strength. The experimental setup is shown in Figure 3.4.

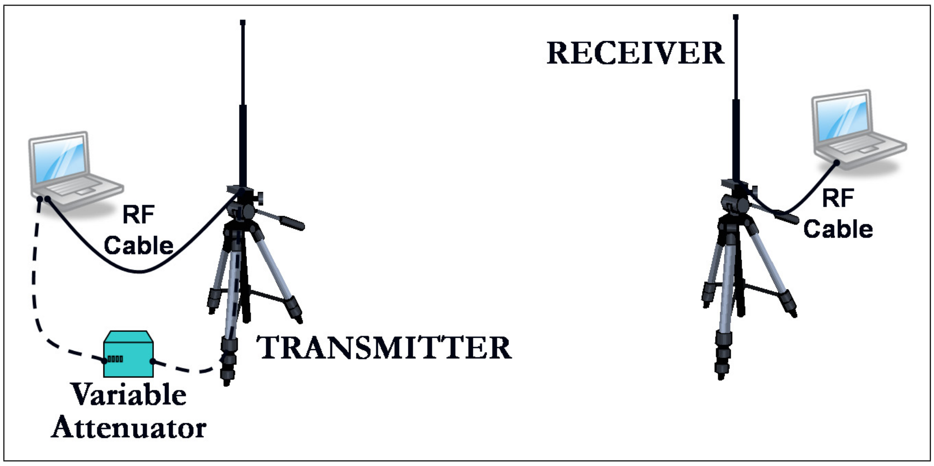


**Figure 3.4. Experimental Setup used for the WiFi experiments** *(Note: The tripods were placed atop buildings or on the ground as per the experimental location)*

### Software

The laptops used a Linux 2.6.11, and HostAP driver version 0.4.9. We instrumented the driver to pass the following per-packet information to the user level at the receiver:

- RSSI

- Noise (silence) level
- rate (1, 2, 5.5 or 11)
- MAC header details
- Result of CRC check

The receiver was set in monitor mode for all the experiments. The transmitter sent packets at a fixed transmit power and a fixed transmit rate in Pseudo-IBSS mode with an inter-packet arrival gap of 20ms. In each experiment, the transmitter sent a total of 6000 packets over a period of 2 minutes. The inter-packet gap is kept at 20 ms and we do not send packets back-to-back as in [13]. This allows us to observe the effect of interfering packets more directly.

In addition to the 2-min experiments, the long-duration experiments that we carried out were carried out over a period of 24 and 48 hours respectively. During these experiments too, the transmitter transmitted packets at 11Mbps with an inter-packet gap of 20 ms.

**Environment/Experiment Locations:**

For the purpose of our measurements we chose two kinds of *environments*: a university campus and a rural village. We chose 5 *locations* within the campus and one location in a village. For each location, we fixed one transmitter *position.* We varied the receiver *position* over up to six places at each *location.* The link lengths in our setting were between 150 – 400m. These distances are similar to the link lengths in the Roofnet study [13]. Roofnet however has a number of links that are also more than 500m in length. Our choice of the transmitter and receiver positions has been motivated by the deployments that we envision for FRACTEL in a campus or a rural area.

Figures 3.5(a), 3.5(b), 3.5(d) and 3.5(c) shows the locations used for the 2-min, 24-hour and 48-hour measurements inside the campus. Each set of transmitter and receiver positions used for an experiment are enclosed inside a circle/ellipse. We now present a brief description of each location below:

- *ACES Type II (Apt):* This location consisted of several rows of two-storeyed houses on campus. There are a number of trees in the vicinity of the houses that are much taller than the houses. This location is visible enclosed in the circle in Figure 3.5(a). We performed our 2-min experiments at this location in addition to running a 48-hour experiment.
- *Staff Ground (Gnd):* Near the *Apt* area we had a playground with an adjoining area covered with dense foliage. The WSN experiments in the dense foliage environment were also performed in this area. This is visible in the ellipse in Figure 3.5(a)
- *Student Hall of Residence (Dorm):* This location, visible inside the circle in Figure 3.5(b), is a student residential location. There were four rows of three-storey tall buildings, along with few very short trees in the vicinity.

We also conducted a long duration (24-hour experiment) at this location (ellipse in Figure 3.5(b)). The transmitter was placed some distance away on a rooftop, in the new SBRA building on the third floor. Two of the receiver positions (the lower two) were on the third floor, while the topmost position was atop the guard cabin situated near the Hall 8 gate.

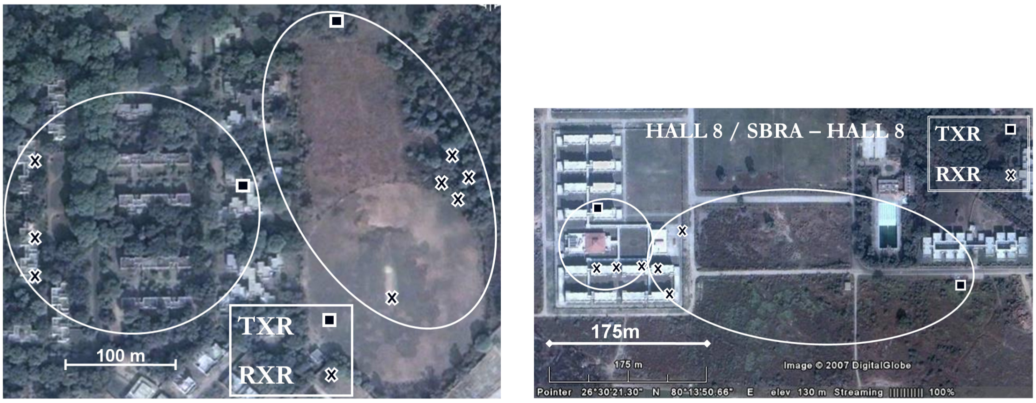
- *Academic Area Corridor (Acad):* This location is located inside the academic area on campus. It has several academic buildings in the vicinity. The corridor where we carried out our measurements is flanked by walls on either side, for the initial 100m. The corridor is about 3m wide. The remaining portion of the corridor is open. It is also pertinent to mention that inside the academic area there a number of active wireless access points, which are a cause of interference – a fact which was very evident when we inspected the logs obtained at this location.
- *Amaur Village (Vill):* The village location is situated in a village called Amaur, which is a two hour drive from the campus. The region as seen in Figure 3.5(c) consists of roughly 400m $*$ 400m area, which is densely packed with one or two-storeyed houses. A few scattered trees were also present in this location.

**Choice of transmitter and receiver positions:**
At every *location* we first chose a convenient transmitter *position.* The transmitter was placed at an elevation from the ground in all *locations* except in the *Gnd.* At the *Gnd* location, the transmitter was placed on a clearing in the ground.

The receiver position was classified based on its location with respect to the transmitter as well as on the average RSSI value that was calculated over an initial test set of 1000 packets sent by the transmitter. We defined three types of receiver positions as below:

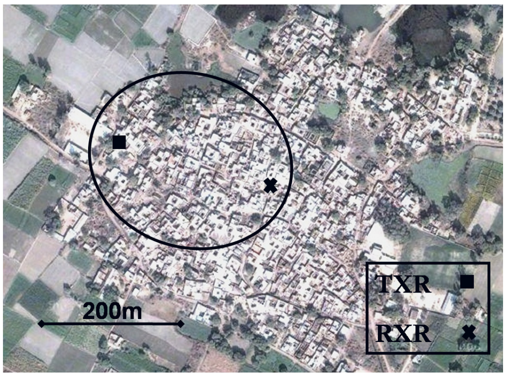
- ***good*:** There existed a clear Line-of-Sight (LoS) between the transmitter and the receiver and the mean RSSI was about -70 *dBm*
- ***medium*:** There was some foliage/obstruction in between the transmitter and the receiver and the mean RSSI was about -75dBm
- ***bad*:** No clear LoS was available between the transmitter and the receiver and the mean RSSI measured was about -80 *dBm.*

At each location we chose a combination of good, medium and bad positions to conduct the experiment runs.

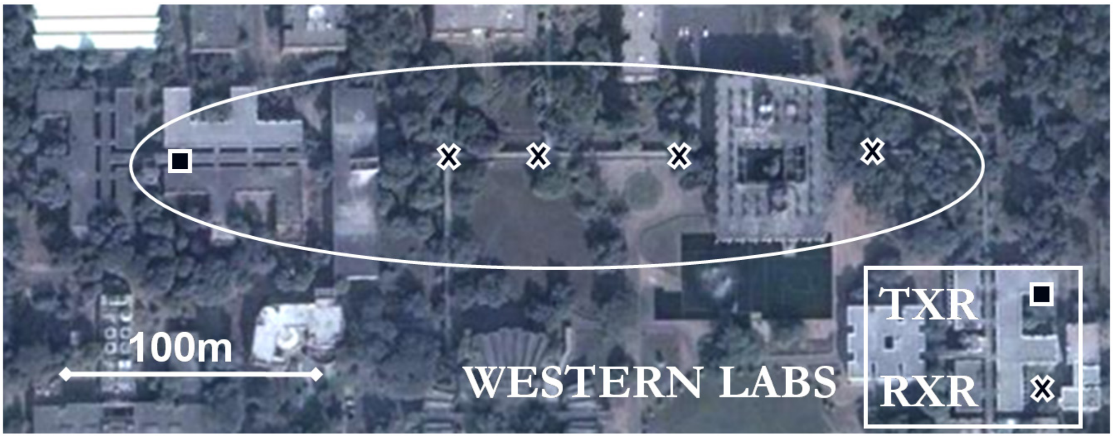


(a) ACES Type II *(Apt)*and Staff ground *(Gnd)*: 2-min and 48-hour experiment locations (Source: `http://earth.google.com`)

(b) Hall 8 *(Dorm)* and SBRA: 2-min and 24-hour experiment locations (Source: `http://earth.google.com`)



(c) Amaur *(Vill)*: 2-min experiment locations (Source: `http://earth.google.com`)



(d) Western Labs *(Acad)*: 2-min experiment location (Source: `http://earth.google.com`)

**Figure 3.5. WMN experiment locations**

# Chapter 4

# Results and Implications: Wireless Sensor Networks

## 4.1 Introduction

In order to examine the feasibility of link abstraction over a link it is important to assess the behaviour of a link over a period of time. Knowledge of the behaviour of a link over time will also aid in protocol development and help improve network performance. It is thus important to assess the stability of the link-quality of a link over small and long periods of time.

We thus conducted a set of experiments to study the stability of link quality in a wireless sensor network. The vagaries of the wireless medium and the number of factors that may influence the quality of a wireless link are large. Hence it is necessary to evaluate the experimental setup in a controlled environment that reduces the number of factors that may affect our experiments. Before carrying out experiments in realistic environments, we conducted a controlled experiment to separate the behaviour of the radio from the effect of the environment.

The remaining chapter is laid out as follows: Section 4.2 describes the controlled calibration experiment we did. Section 4.3 talks about the experiments we performed in different environments to study the relationship between error rate and RSSI. Section 4.4 outlines the temporal variability we observed in RSSI and error rate. Section 4.5 explains the link range measurements that we carried out using external antennas to check the maximum communication range that we could attain. Section 4.6 summarises our observations and the implications of those observations.

## 4.2 Calibration Experiment

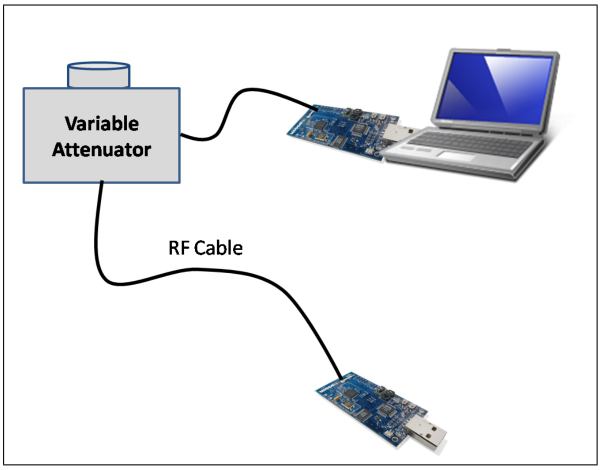


**Figure 4.1. Error rate versus RSSI: using RF cable**

We used the setup shown in Fig 4.1 to calibrate the radios of the *motes*. A 50-ft RF cable with a variable step-attenuator was used to connect the transmitter to the receiver. The variable step attenuator allows fine control over the attenuation of the transmitted signal and thus allows one to measure the required parameters over a large range of received signal strengths. The RF-cable allows physical separation of the transmitter as well as the receiver, while factoring out the effects that the environment would have. The physical separation prevents radiation, that may leak out through the connectors and the transmitting mote, from bypassing the cable and being received by the receiver through the air.

The received signal strength of a packet (RSSI) that is received by the receiver is given by

$$P_R = P_T - P_{PL} - P_{Att} \tag{4.1}$$

where $P_R$ is the RSSI/power received at the receiver, $P_T$ is the transmitted power, $P_{PL}$ is the path loss in the RF cable and $P_{Att}$ is the amount of attenuation introduced by the variable step-attenuator, all in *dB*. During each experiment run the transmitter transmitted a sequence of 5000 packets to the receiver. The sequence of transmitted packets is separated into bins of 100 transmitted packets and the average RSSI as well as the average packet error rate is calculated for each bin. In case no packets were received in a particular bin, then that bin is neglected.

Figure 4.2 is a scatter plot of RSSI vs the error rate for each bin. It can be seen that the error rate rises from 0% to 100% within the space of 5 – 6 *dB*. This is called the '*the steep region*'. This behaviour is close to what is expected theoretically.

We select a point in the steep region in the above graph such that the average RSSI at that point is close to -90 *dBm*. Figure 4.3 plots the temporal variation of RSSI for such a point (time period of 2 seconds – 100 packets sent with an inter-packet gap of 20 ms). The average RSSI over all the received packets is -94

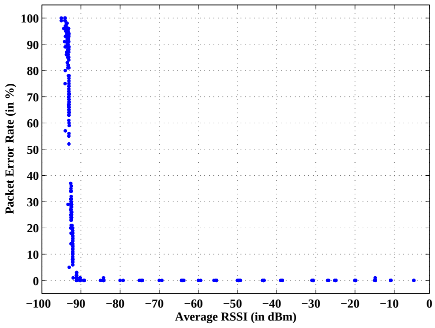


**Figure 4.2. Error rate versus RSSI: using RF cable**

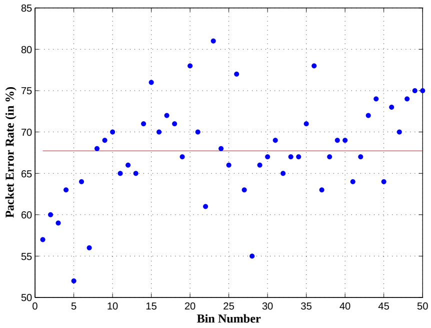


**Figure 4.3. Calibration Experiment: Error Rate Variation**

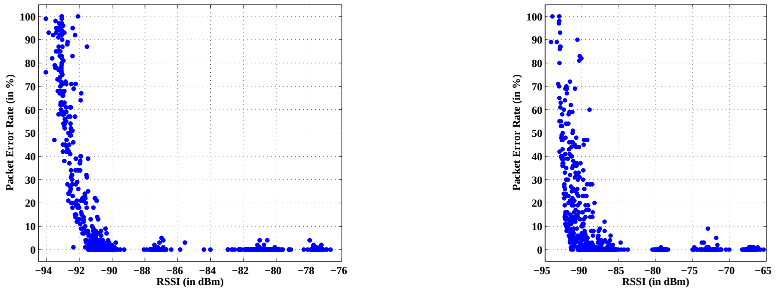
*dBm*. We see that there is a large variation in the error rate over this small time period. Given that the environment we are working in is controlled, the large variation in the losses may be attributed to the fact that we are operating very close to the receive sensitivity of the radio [7]. Similar variations in error rate are also noticeable at other points in the steep region which experience intermediate data rates.

## 4.3 RSSI and Error Rate in Other Environments

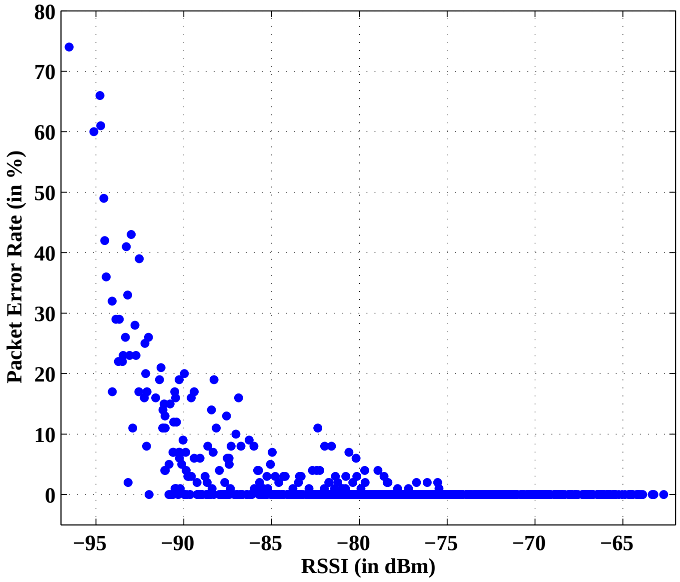
We then performed experiments in real life environments to study the stability of a link. The experiments were performed in the *airstrip*, *road*, and *foliage* environments. The environments were chosen as we expected that the amount of multi-path we would experience would be least in the *airstrip*, intermediate in the *road* and maximum in the *foliage* environments. The experiments in the *road* and the *airstrip* environments were repeated over a period of three days and care was taken to mark out the transmitter and receiver position so that the experimental setup would not change much on successive days thereby introducing additional variability in our observations. Each of the experiments used a mote connected to an external omni-directional antenna at each end. The experiments in the foliage environment were done on a single day with different combinations of antennas at the transmitter and receiver.

The experimental setup consisted of two motes which acted as the transmitter and the receiver. Each mote was connected to a 8-*dBi* omni antenna that was mounted on a tripod at a height of about 1.5m - 1.7m above the ground. As earlier the transmitter transmitted packets 6000 packets with an inter-packet duration of 20ms.

Figure 4.4 presents plots of the average error rate per bin against the average RSSI for each bin in each of the three environments. Similar to the previous figures the error rate and RSSI values are average values over 100 packet bins.



(a) Airstrip (b) Road



(c) Foliage

Figure 4.4. Error Rate vs RSSI

Figure 4.4(a) shows the error rate plotted against the RSSI value for experiments on the airstrip. It can be seen that below -85 *dBm* the error rates are stable and low. Similar observations can also be made for the foliage (-75 *dBm*) and narrow road environment (-85 *dBm*). **It is evident from the figures that when the RSSI is above a certain '*threshold*', the error rates are stable and low.** In such cases the link abstraction can be said to hold. This is similar to the conclusions drawn in [32]. However, unlike [32], in the multi-path environment we also see an increase in the 'spread' of points that experience intermediate loss rates.

## 4.4 Temporal Variability in RSSI and Error Rate

Considering that RSSI and error rate have a good correlation, it would be instructive to study the the temporal variability in RSSI and error rate. The variability can be used to decide if RSSI/error rate can be used as metrics for designing networks / stable routing protocols.

In [32], the authors point out that as the temporal variability in RSSI that they observed is not very large across a small time interval (200 packet bin as considered by them), the instantaneous value of RSSI can be used as a close approximation to the short term average RSSI. We now first look at the per packet and long term variability of RSSI.

### 4.4.1 Temporal Variability in RSSI

We consider a specific experiment to illustrate the variability in RSSI. This experiment refers to the Omni-50m case in the foliage environment in Table 4.2. We choose this case as it has an intermediate packet error rate of 7.2% i.e. neither 0% nor 100%. Figure 4.5 is a CDF plot of the individual RSSI values of the 6000 packets sent during the experiment. The width of the 5 - 95 percentile band between which most of the packets were received is about 15 *dB*. This large a band suggests that the RSSI values vary over a wide range and the RSSI value in a single packet may not be a good indicator of the short term average RSSI that may exist at that point of time..

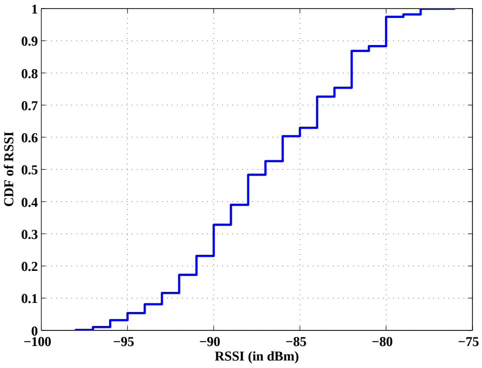


**Figure 4.5. CDF of RSSI: Omni-50m case of Table 4.2**

We also plot the observed RSSI values against the received sequence number of the packet in Figure 4.6. We then bin the 6000 packets into bins of 100 packets each and plot the average RSSI values for each bin to see if the observed variability at the per-packet level is accounted for by averaging over a 100 packet time interval. Figure 4.7 shows the average RSSI per 100 packets plotted against the bin number (effectively time). Fig 4.8 plots similar values for a bin size of 1000 packets.

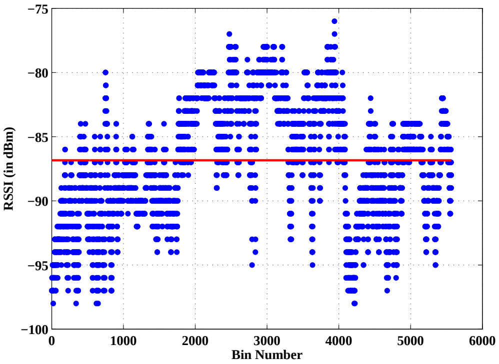


Figure 4.6. RSSI variation with time: Environment – foliage, Omni-50m, bin size 1

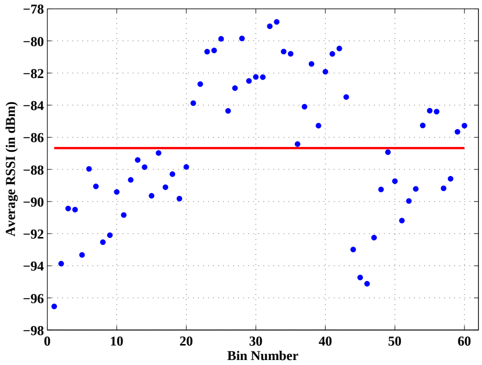


Figure 4.7. RSSI variation with time: Environment – foliage, Omni-50m, bin size 100

It is evident from the figures that variability in RSSI is visible over the short (100 packets or 2 seconds) and long term (1000 packets or 20 seconds) as well. It is thus not possible to predict the value of RSSI over some future time period by measuring a small sample in the present.

Such variability in RSSI is also visible in our other experiment runs in different

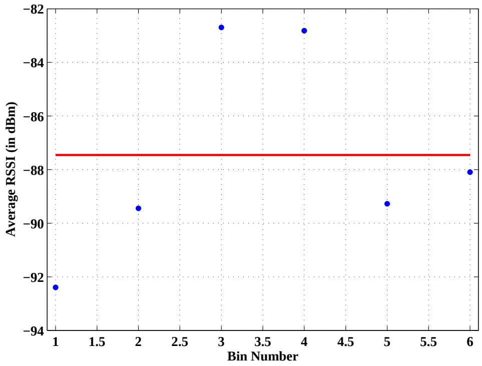


Figure 4.8. RSSI variation with time: Environment – foliage, Omni-50m, bin size 1000

locations where we observed intermediate error rates. We ran experiment runs at different times and different days at the airstrip and on the road. A $4-5$ *dB* variability in RSSI was observed when experiments were repeated at the same place at different times of the day and across different days.

### 4.4.2 Temporal variability in Error Rate

The variability in RSSI means that during the course of time there would be periods when the RSSI would drop. At such time it may happen that the RSSI values fall in the 'steep region' observed in Figure 4.3. This region inherently exhibits variability in error rate. We may thus have a case where the error rate may vary even though the average RSSI value is above the threshold value (in our example the average RSSI value is -87 *dBm*). Putting together both the above statements we may conclude that we would experience variability in the error rate as well. Figures 4.9, and 4.10 depict the variability in error rate.

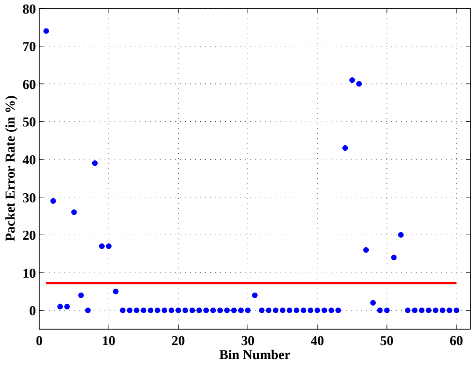


**Figure 4.9. Error rate variation with time: Environment – foliage, Omni-50m, bin size 100**

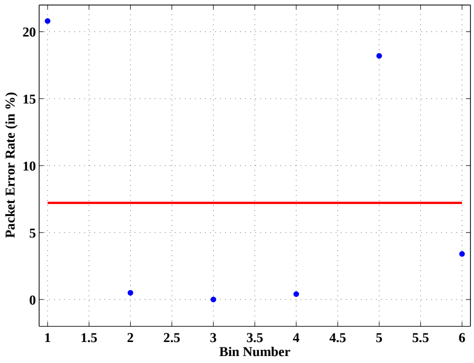


**Figure 4.10. Error rate variation with time: Environment – foliage, Omni-50m, bin size 1000**

In case the overlap of the RSSI values over the steep region is higher, the variation in error rate is more pronounced. In Figure 4.11, the error rate can be seen to vary from 0% to almost 90%. This experiment was run on the road and had a mean RSSI of about -89 *dBm*. In the rest of our dataset too, experiments that had intermediate error rates over the duration of the experiment also exhibited variability in error rates over short (2 second) and longer (about 20 second) time scales.

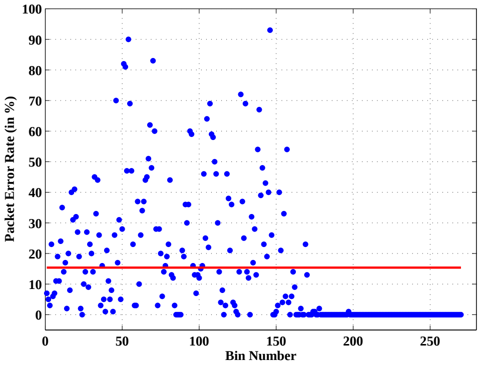


**Figure 4.11. Error rate variation with time: Environment – Road, bin size 100**

This observation essentially implies that routing metrics that rely on the number of lost packets / Packet success rates [39], would be unstable. By the time the routing protocol would finish measuring the packet error rate over a link the rate would have already changed. The present measurement would thus not give a true picture about the state of the link.

### 4.4.3 RSSI variability in other environments

In addition to measurement environments chosen earlier, we also carried out measurements in two additional environments i.e. the *corridor* and the *lab* environments.

Table 4.1 shows the RSSI variability, we observed, in these environments in terms of the difference between the $5^{th}$ and $95^{th}$ percentile of observed RSSI values. This way of showing the differences, factors out the effect of outliers. The table is a small sample of our complete data. Distances between the transmitter and the receiver are indicated in the first column. In case of the Structures Lab (StrLab), the measurements were carried out at 4 locations in the lab. The distances between the transmitter and the receiver at these locations were 10.3m, 14.8m, 21,5m and 18.4m respectively. It can be seen in the table that the difference between the $5^{th}$ and the $95^{th}$ percentile of the RSSI values can be as high as 11 *dBm* in many cases. Also RSSI variability can be seen to exist between different times in a day (for e.g. StrLab Locations 1 and 2 at 15:45 and 23:30) and also across days (Corridor-60m day 1 and day 3). Our results thus comprehensively indicate RSSI variability at all time scales - 2 sec, 20 sec, several hours to even across days.

| **Location** | **Tx Ant** | **Rx Ant** | **Day / Time** | **$5^{th}$ perc** (dBm) | **$95^{th}$ perc** (dBm) | **Diff** (dBm) |
|---|---|---|---|---|---|---|
| Airstrip-90m | Omni | Omni | Day 3 | -84 | -80 | 4 |
| Foliage-40m | Internal | Internal | Day 1 | -81 | -70 | 11 |
| Foliage-40m | Omni | Internal | Day 1 | -86 | -76 | 10 |
| Foliage-40m | Sector | Internal | Day 1 | -76 | -66 | 10 |
| Road-210m | Grid | Internal | Day 4 | -80 | -70 | 10 |
| Corridor-60m | Internal | Internal | Day 1 | -71 | -68 | 3 |
| Corridor-60m | Internal | Internal | Day 3 | -76 | -70 | 6 |
| Corridor-60m | Internal | Internal | Day 5 | -76 | -67 | 9 |
| Road-55m | Omni | Omni | Day 2 | -69 | -66 | 3 |
| Road-90m | Omni | Omni | Day 3 | -82 | -79 | 3 |
| StrLab Location 1 | Internal | Internal | Day 1 15:45 | -76 | -66 | 10 |
| StrLab Location 1 | Internal | Internal | Day 1 23:30 | -71 | -66 | 5 |
| StrLab Location 2 | Internal | Internal | Day 1 15:45 | -87 | -78 | 9 |
| StrLab Location 2 | Internal | Internal | Day 1 23:30 | -78 | -74 | 4 |
| StrLab Location 3 | Internal | Internal | Day 1 15:45 | -80 | -73 | 7 |
| StrLab Location 3 | Internal | Internal | Day 1 23:30 | -78 | -76 | 2 |
| StrLab Location 3 | Internal | Internal | Day 2 11:15 | -84 | -76 | 8 |
| StrLab Location 4 | Internal | Internal | Day 1 23:30 | -89 | -82 | 7 |
| StrLab Location 4 | Internal | Internal | Day 2 11:15 | -88 | -78 | 10 |

**Table 4.1. RSSI Variation ($95^{th}$ percentile to $5^{th}$percentile)**

### 4.4.4 Implications

In light of this variability in RSSI and consequently the error rate, it seems a daunting task to operate in a region such that the link abstraction holds. However, simple design choices at the time of planning the network can ensure that we operate links which have a stable error rate. By providing sufficient leeway such that the link operates away from the steep region, it is possible to obtain links that have low and stable error rates i.e. in effect obtain links where the *link abstraction* holds. The way to do this would be:

- Take a set of sample measurements, each for a certain duration, at the required location and obtain the RSSI and error rates at that place

- Given sufficient measurements, the maximum value of the measured RSSI would fall beyond the $95^{th}$ percentile of all possible values for that given location. If we assume a worst case safety margin of 11 $dB$ for RSSI variability and subtract it from the earlier value then the RSSI variability window will have a very small overlap with the steep region.
- If the overlap is small, then the link would have stable, low error rates making link abstraction feasible.

The sample measurements could be taken before planning the network or also in the background on a running network. Using the above criteria if we only decide to use the links with low and stable error rates, we would be acting conservatively and as result we may lose out on some links that could have been possible to form otherwise. However, the advantage of only using links with low, stable error rates is simplicity in further design.

In addition to planning links in new networks such that the *link abstraction* holds, the concept of *link abstraction* can also be used to classify links in an already existing network. For example, if we choose to classify only those links with a stable low error rate as '*up*', then in effect, it means that for the sake of predictability we are choosing not to use links with an intermediate error rate as the error rate on those links will keep varying. Operating on the unstable links, exposes us to the variability of error rates and tackling that requires other mechanisms like routing. In such cases the routing metric is required to dynamically track the status of links and choose the best link based on some parameters/statistics that are available to it at that instant of time. If we choose to operate away from the threshold in a stable region, then in some cases even if the error rate is comparatively higher, it will still be stable. This in effect means that inspite of losses, the routes in the network will be more or less stable.

The variability of RSSI that we have observed at smaller time scales also has important implications for routing metrics that rely on the averaged value of RSSI over a time duration. In such cases we would observe unstable behaviour as the averaged value will not be a true indicator of the state of the link.

The variability in RSSI over longer durations has implications for sensor network applications like BriMon / Industrial Monitoring where nodes wake up only for a short period of time in a day, sense the environment and transfer their readings to a base node. In such cases, it may not be possible to use a system where the nodes measure the RSSI values during one wake-up time and use it to route packets during the next time that they wake up as such measurements would no longer be valid.

## 4.5 Link Range Measurements

Considering what we observed in the last section, if we choose to operate a link away from the *steep region*/the *RSSI threshold* then we can obtain stable low error rates. However, as the received signal strength at a receiver is inversely proportional to the fourth power of its distance from the transmitter, the predictability comes at the price of reduced communication range. In this section, we explore the idea of using an external antenna to help increase the communication range of a mote while still allowing the mote to establish a link where the *link abstraction* holds. Our results below, indicate that substantial increase in communication range can be achieved by the use of external antenna.

The use of external antenna also has the added advantage of reducing the network in many cases to a single hop network (for e.g: In the redwood deployment [37] the use of a single directional antenna placed at the base of the redwood tree looking upward, would have put most nodes on the tree one hop away from the gateway at the base of the tree). The improved communication range thus has the benefit of simplifying the network architecture and can help to eventually improve network lifetime and performance.

The link range measurements we carried out, were carried out in the *foliage* and *road environments*. The environments were chosen to be in line/close to those found in [37], [38], [23].

However, the increase in range possible through the use of an external antenna is at the expense of increased cost and form factor / size of a deployed mote. The increase in cost and size is quite marked for motes that operate at lower frequencies (*Mica 2s* operate at 433, 868 and 916MHz compared to the 2.4GHz of a *Tmote*) as lower frequencies require antennae of larger dimensions. This work focuses on use of external antenna at 2.4GHz.

### 4.5.1 Dense Foliage Environment

Experiments in this environment were done using *tmotes* at both ends. Refer to Sub-section 3.2 for the experimental setup used. The receiver used was the internal antenna available on a *tmote* while the antenna at the transmitter was varied from the internal antenna of the *tmote* to an 8-*dBi* omni-directional antenna, to a 60° sector antenna and a parabolic grid antenna. The receiver was placed at multiple positions at different distances from the transmitter and multiple readings were taken at each receiver position. The omni-directional antennas were placed at a height of 1.5 – 1.7m above the ground. In case of the sector and the parabolic grid antennas, the antennas were mounted at a height of nearly 3.8m above the ground as we found that ground reflections were causing an increase in the error rate. We took readings up to a distance where the received signal strength fell below *-85 dBm*.

Table 4.2 shows statistics for the data we collected in the dense foliage environment. The transmitter transmitted a sequence of 6000 packets during the course

| **Tx-Rx Dist. (m)** | **Average Pkt Error (%) (Std. Dev.)** | **Average RSSI ($dBm$) (Std. Dev.)** |
|---|---|---|
| Internal-20m | 0.03 (0.26) | -74.98 (2.37) |
| Internal-25m | 0.15 (0.63) | -74.41 (3.64) |
| Internal-30m | 0.08 (0.53) | -79.44 (2.35) |
| **Internal-35m** | **0.3 (1.25)** | **-78.79 (3.43)** |
| Omni-20m | 0.2 (1.1) | -72.97 (3.43) |
| Omni-30m | 0.18 (0.81) | -76.75 (3.94) |
| **Omni-40m** | **0.0 (0)** | **-79.42 (2.35)** |
| Omni-50m | 7.22 (1.65) | -86.88 (4.57) |
| Sector-30m | 0.03 (0.26) | -67.76 (3.15) |
| Sector-40m | 0.07 (0.52) | -69.33 (2.92) |
| Sector-50m | 2.27 (4.55) | -82.76 (3.7) |
| **Sector-30m** | **0.53 (2.6)** | **-80.77 (3.55)** |
| Sector-30m | 13.01 (14.37) | -90.01 (3.91) |
| Grid-70m | 1.5 (3.61) | -79.79 (5.03) |
| Grid-70m | 0.28 (0.99) | -77.07 (3.11) |
| **Grid-70m** | **1.6 (4.08)** | **-85.05 (4.19)** |

**Table 4.2. Range measurements in dense foliage environment**

of run of each experiment. The 6000 packets are divided into bins of 100 packets each. Error rate and average RSSI is calculated within each bin of 100 packets. Mean and standard deviation of the values from the 60 bins are used to calculate the statistics mentioned in the table. If no packet was received during the course of a bin, the bin is ignored as the calculation of average RSSI within such a bin is meaningless.

The rows marked in bold in the table represent the maximum ranges at which the error rates were negligible and thus represent the maximum distance that was achieved in the dense foliage environment with the corresponding antenna at the transmitter end. Using the internal antennas of the *tmote* at both ends, we achieved a range of about 35m. Using the internal antennas no packets were received beyond a distance of 40m. The internal antenna at the transmitter was then replaced by an 8 dBi omni-directional antenna. This allowed a marginal improvement in the range (up to 40m). The next two set of antennas used were the sector antenna (17 dBi) and the parabolic grid antenna (24 dBi). The sector and grid antennas gave ranges of 60m and 90m respectively. It is pertinent to note that the foliage in the location was very dense and that we had absolutely no visual contact beyond 35m. We used cell phones to coordinate and run the experiment.

### 4.5.2 Narrow Road Environment

The narrow road environment was chosen to emulate deployments like BriMon and the Volcano Monitoring deployment which essentially enjoy line-of-sight between nodes. The road where the experiment was carried out was about 4m wide and about 500m long. The initial experiment runs were carried out using an internal antennas at the transmitter and receiver followed by 8 dBi omni-directional antennas at the both ends. While using sector and parabolic grid antennas at the transmitter we realised that the length of the road was limiting our measurements. Hence measurements with the sector and parabolic grid antenna were repeated at the nearby airstrip, whose length is about 1km. Measurements over 500m indicated in Table 4.3 refer to measurements carried out on the airstrip. The high gain antennas were mounted at a height of about 3.8m above the ground as we observed that ground reflections were introducing losses in our measurements.

It is evident from Table 4.3 that far greater communication ranges are achievable. For example while using a parabolic grid antenna at the transmitter and the internal antenna of the *tmote* an increase in range of over 430m was achieved. If the internal antenna at the receiver was replaced by an 8 dBi omni-directional antenna a further increase in range of 300m was achieved.

### 4.5.3 Implications

Even though the increased range available (60 - 90m) in the dense foliage environment with the use of high gain antenna, is small it is still quite useful. For e.g. in the Redwood study [37] a sector or grid antenna pointing upwards could have been used at the base of the tree such that all the nodes (installed up to a height of 70m) could have been reached in a single hop.

The Volcano monitoring deployment [38], uses a linear deployment of nodes on a mountain-side. They report ranges of 200 - 400m using 8 *dBi* omni antennas and their network uses multiple hops to reach the base node. However, by placing a parabolic grid antenna (beam width of 8°) at the base it could have been possible to thus allow all nodes to directly communicate with the base node. Similar possibilities are also possible with BriMon, where the node can also be expected to lie in a more or less linear configuration. As majority of the railway bridges are not over 800m in length, similar configurations can be used to deploy a one hop network for bridge monitoring as well.

A significant number of deployments, such as SenSlide [30] and Habitat Monitoring [36], however do not use a linear topology and are spread out over a small area. The use of a sector antenna in such cases can allow nodes even up to 500m (using an omni antenna at the remote node) to reach the base station over a single hop.

The numbers achieved as part of our experiments must be considered as guides as the actual distances achievable will also depend on the exact environment in which a network is being deployed.

## 4.6 Implications

To reiterate our observations and their implications: –

- If we operate away from the 'steep region' error rates over a link are stable and low. The link abstraction holds in such a scenario.
- *How does one know that one is operating away from the steep region?* Sufficient sample measurements spread over a few days provide a fair idea of the maximum RSSI that can be obtained at that place. Plan links such that their average RSSI minus the safety margin is still above the steep region.
- If links are planned to operate/are operated away from the 'steep region' they experience stable, low error rates. The existence of the link abstraction makes it possible to design simpler routing metrics and other higher layer protocols. Stable, low error links with simpler routing protocols can also help reduce the number of routing and maintenance messages that are sent thereby increasing the longevity of the network.
- The variability in RSSI and consequently error rates, when operating close to the 'steep region' makes metrics that rely on packet losses/packet success rates inherently unstable.
- Use of external antennas allows a larger number of stable, low error links to be set up that eventually helps to increase the lifetime of the sensor network.

| **Tx-Rx Dist. (m)** | **Average Pkt Error (%) (Std. Dev.)** | **Average RSSI (*dBm*) (Std. Dev.)** |
|---|---|---|
| **Internal Antenna at Receiver** | | |
| Internal-60m | 0.18 (1.03) | -81.11 (2.97) |
| **Internal-75m** | **1.37 (4.34)** | **-83.74 (3.61)** |
| Omni-60m | 0 (0) | -81.92 (0.49) |
| **Omni-75m** | **0 (0)** | **-80.64 (2.47)** |
| Omni-90m | 35.92 (33.42) | -94.91 (1.6) |
| **Sector-210m** | **0 (0)** | **-81.92 (0.49)** |
| Sector-310m | 1.02 (4.3) | -91.85 (0.81) |
| Sector-400m | 0.62 (2.24) | -92.33 (1.03) |
| Sector-500m | 0 (0) | -90.12 (0.5) |
| Grid-90m | 0 (0) | -75.35 (1.36) |
| Grid-210m | 0.03 (0.18) | -75.825 (2.37) |
| Grid-300m | 0 (0) | -80.42 (1) |
| Grid-400m | 0 (0) | -82.21 (0.9) |
| **Grid-500m** | **0 (0)** | **-85.67 (0.94)** |
| Omni Antenna at the Receiver | | |
| **Omni-90m** | **0.04 (0.33)** | **-80.92 (0.88)** |
| Omni-150m | 7.63 (12.46) | -90.86 (0.64) |
| **Sector-500m** | **0.13 (0.68)** | **-80.92 (0.88)** |
| Sector-600m | 0.07 (0.25) | -89.48 (0.35) |
| Sector-700m | 0.5 (1.05) | -91.22 (0.34) |
| Sector-800m | 3.42 (4.83) | -91.58 (0.41) |
| Sector-30m | 13.01 (14.37) | -90.01 (3.91) |
| Grid-500m | 0.12 (0.49) | -75.25 (0.07) |
| Grid-600m | 0.07 (0.25) | -79.85 (0.24) |
| Grid-700m | 0.15 (0.61) | -82.07 (0.2) |
| **Grid-800m** | **0.13 (0.39)** | **-85.76 (0.31)** |

**Table 4.3. Range measurements on Narrow road / airstrip (Line-of-sight environment)**

# Chapter 5

# Results and Implications: FRACTEL - 802.11 networks

## 5.1 Introduction

The Roofnet community wireless network measurement study [13] claims that the concept of link abstraction does not hold in their setting. They point out that the main culprit for links with intermediate delivery probabilities is multipath.

In contrast to the Roofnet study, the measurement work carried out on the Digital Gangetic Plain (DGP) network reports that the link abstraction holds in most cases [16]. The setting in which DGP operates is different from Roofnet in many ways. The primary ones being the nature of the network (adhoc in Roofnet, planned in DGP), height of antennas (omni-directional rooftop antennas in Roofnet, high gain antennas placed on towers/masts in DGP) and the link distances (few kms on an average in DGP, up to a km in Roofnet).

FRACTEL, our motivation, is more akin to Roofnet in terms of link distances and height of antennas, while it is closer to DGP in terms of the environment in which the network will operate. We thus study how links will behave in our setting - whether the link abstraction will hold as in the case of DGP or whether we will have a large number of links with intermediate error probabilities.

The outline of the remaining chapter is as follows – Section 5.2 examines the relation between error rate and RSSI. In Section 5.3 we re-analyse the Roofnet data available on the Internet [2] and provide alternate explanations to the observations made in [13]. Section 5.4 describes the controlled experiments we conducted to study interference and the effect of interference on the noise floor values reported by the hardware. Section 5.5 describes the experiments and our results while examining the temporal variability in RSSI. Finally, Section 5.6 summarises the results and examines the implications of these results on issues such as routing metrics, opportunistic routing, interference-aware routing and MAC mechanisms.

## 5.2 Error Rate and RSSI

### 5.2.1 Introduction

As earlier we seek to characterise the wireless links in our setting in terms of error rate and RSSI. We carried out experiments in all the five chosen *locations* on campus and on one *location* in a rural environment (Amaur village). The experimental setup used for these experiments is shown in Figure 3.4. The tripods on which the transmitter and receiver antenna was mounted were placed at an elevation from the ground (typically the rooftop of a double storeyed building) in all places except in the *Gnd*, where it was placed on the ground. During each experiment run, the transmitter transmitted 6000, 1400-byte packets with an inter-packet gap of 20ms. The packets were sent as broadcast packets. The receiver was put into monitor mode for the duration of the experiment, while the transmitter operated in the Pseudo-IBSS mode. The receiver logged the received packets, which were later analysed using a combination of Perl and MATLAB® scripts.

Considering that we observed variation in RSSI over small time scales on these links we decided to work with average values obtained over bins of 100 packets. So essentially we divided the 6000 packets that a transmitter sent to a receiver into 60 bins of 100 packets each. The average RSSI and error rate were calculated for each of these bins. In case in a bin if we did not receive any packet the average RSSI of the bin was taken to be -100 *dBm*.

In addition, we also observed that the noise level reported by the card in our setting was -94 to -95 *dBm*. Thus the graphs we plot in terms of RSSI are also valid if we plot them against SNR instead of RSSI.

While analysing our logs we found cases where the error rate was high in spite of the high RSSI. This led us to examine our logs more closely and we found that a number of foreign packets (packets not sent by the transmitter) had been received. The *Acad* environment had many WiFi access points operating in the vicinity, while the *Gnd* environment had a long distance link working in the vicinity.

Using this criteria we separated out the experiments we had run into two sets viz. *interference-free* and *interference-prone* cases. The interference varied from 500 foreign packets over a 2 minute interval to over 90,000 foreign packets in some cases.

### 5.2.2 Experimental Data

At the outset we perform a controlled experiment to determine the effect of the receiver on the cards we used. As earlier, we used a long RF-cable via a variable attenuator to connect the two card fitted in two laptops. In these controlled conditions, we observed the noise floor values to be the same as observed in the real life experiments. The 'threshold' RSSI values, for which the observed error rate was below 1% are -88 *dBm*, -86 *dBm*, -82 *dBm* and -81 *dBm*.

We now plot the error rate against the RSSI, for both the categories of locations viz *interference-free* and *interference-prone* at all the four data rates, for all the experiments done at all the outdoor locations. In Figures 5.1, 5.2, 5.3, and 5.4 each point represents a bin of 100 transmitted packets.

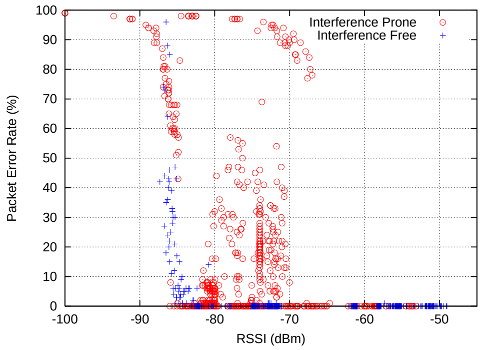


**Figure 5.1. Error Rate vs RSSI (1Mbps)**

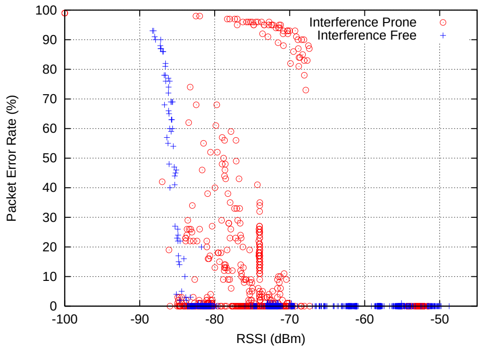


**Figure 5.2. Error Rate vs RSSI (2Mbps)**

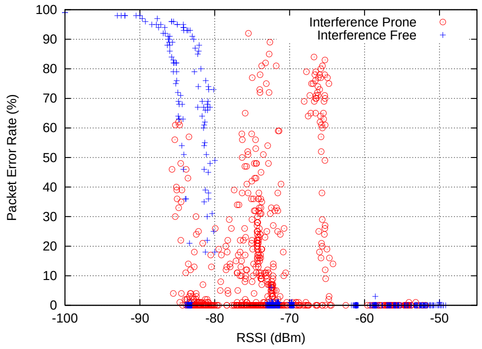


**Figure 5.3. Error Rate vs RSSI (5.5Mbps)**

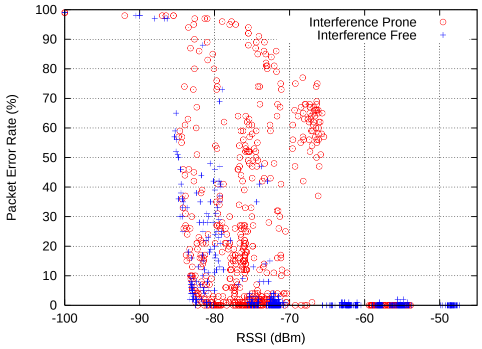


**Figure 5.4. Error Rate vs RSSI (11Mbps)**

It can be clearly seen from the figures that there is little correlation between the error rate and RSSI in the *interference-prone* cases. There are ample instances where the error rate is high in spite of the RSSI being high. It is possible to visually identify clusters of points in the plots. The clusters of points correspond to the different locations at which the experiments were done.

In case of the *interference-free* cases we can see that there exists a 'threshold' RSSI. If RSSI is above this value, the error rates are low and stable. The threshold values appear to be -86 *dBm*, -85 *dBm*, -80 *dBm* and -79 *dBm* for the rates of 1, 2, 5.5 and 11 Mbps respectively. These values are very close to the values observed during the controlled experiment conducted earlier. If the RSSI falls below this threshold it goes into the '*steep region*', where the error rates become unpredictable. Above the threshold the link abstraction is seen to hold.

In Figure 5.4, we find some points which show a high error rate at a high RSSI at the *interference-free* locations. Examination of the log files shows us significant RSSI variation in the first 15-20 seconds of the experiment. This may be attributable to some experimental error or human movement very close to the antenna.

## 5.3 Roofnet Data: A Relook

### 5.3.1 Introduction

Figures 5.1, 5.2, 5.3, and 5.4 indicate that the main reason/cause of intermediate error rates is interference. This is in contrast to what was observed in the Roofnet study [13]. The Roofnet study made the following observations:

- Packet loss cannot always be attributed to a low SNR value - there are a number of cases with high RSSI where the error rates are also high.
- There is no correlation between the number of foreign packets received and the number of packets lost.
- If an environment experiences multi-path, loss rates increase.
- Previous studies ([18] and [31] cite delay spreads in the excess of $1\mu s$, which is in excess of the limits of the 802.11b receiver [11].

Based on the above observations, the Roofnet study claims that multi-path is the main cause of low correlation between RSSI and error rates. Prima facie it may seem that the difference in our observation vis-à-vis the observation in Roofnet is due to the fact that we did not observe significant multi-path, while they did. When we had a closer look at the data reported by them, which is available in [2], we found that the noise levels reported in their case showed a large variation. Such a large variation is bound to affect the SNR at the received card. The noise level reported by the card is an average of the energy levels measured by the card for some time before the actual packet was received. So irrespective of whether there is multi-path or not this value should not fluctuate unless there is some other source that radiates energy in the same spectrum/channel. In our observations we find that the silence values remain more or less constant.

### 5.3.2 Results

We then decided to plot the silence values and their variation for the Roofnet data. We chose a subset of the complete Roofnet data – the experiment runs included in this data set are experiment runs which had been conducted at a data rate of 11Mbps, an average RSSI above -77 *dBm* and had error rates between 20% and 80%. These runs represent points with high RSSI and a high error rate. We obtained 26 such points which were then sorted in in the increasing order of the

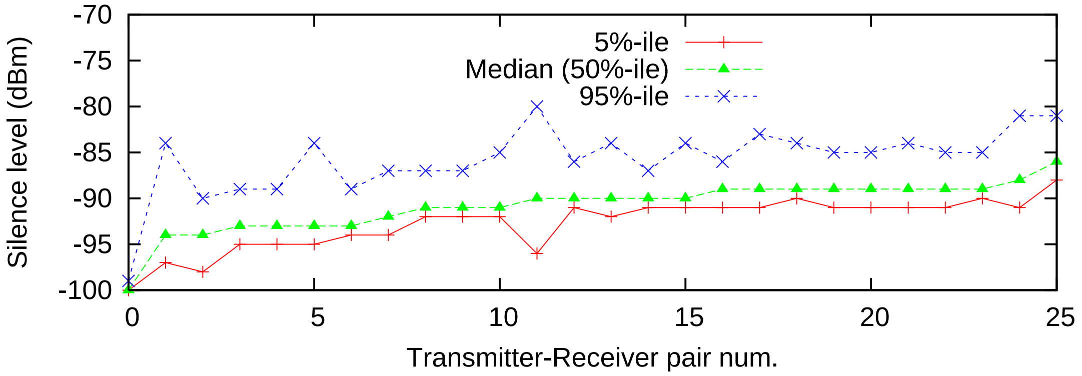


**Figure 5.5. Noise levels in Roofnet data (11 Mbps)**

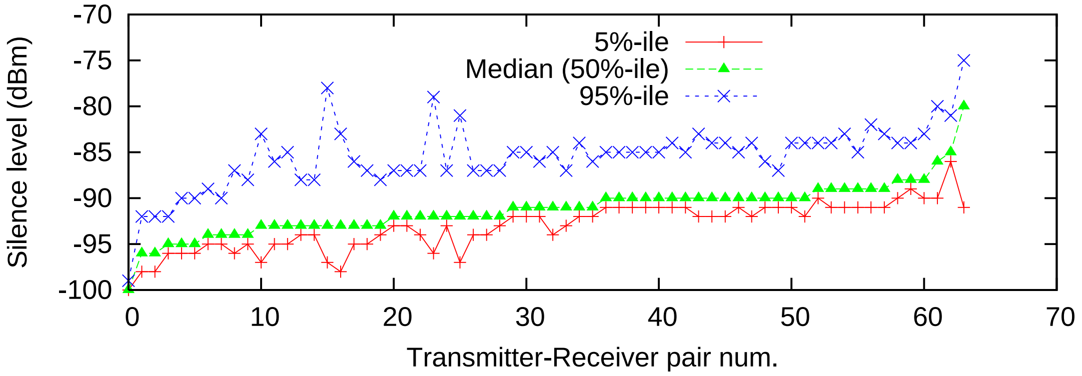


**Figure 5.6. Noise levels in Roofnet data (1 Mbps)**

median noise level. Figure 5.5 plots the $5^{th}$ percentile, the median and the $95^{th}$ percentile for the points. It is evident from the graph that the variation in the noise level is large. The silence value / noise level is as high as -86 $dBm$ at places and even several median values are higher than -90 $dBm$. The 95 %-ile minus 5 %-ile band is as large as 16 $dB$.

We plot a similar graph for a data rate of 1Mbps. The points plotted in Figure 5.6 include experiment runs which had an average RSSI above -80 $dBm$ and an error rate between 20% and 80%. We find that our earlier observations hold true in this case as well.

The large noise band is also visible when one plots the RSSI and noise values in an experiment run against the packet number. Figure 5.7 plots these values for point 13 in Figure 5.5 (points are numbered from 0 to 25 in the ascending order in the figure. To guage the distribution of the noise level values, we plot a cumulative distribution function (CDF) of the noise values observed in the above-mentioned experiment run. It can be seen from Figure 5.8 that over 50% of the points have a noise value greater than -90 $dBm$.

In light of the above variation in noise level, it becomes pertinent to determine the following:

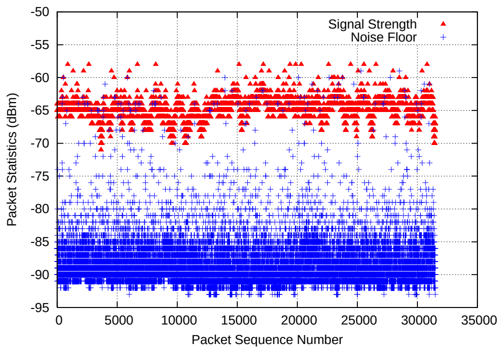


**Figure 5.7. Roofnet: Per Packet Variation of RSSI and noise floor**

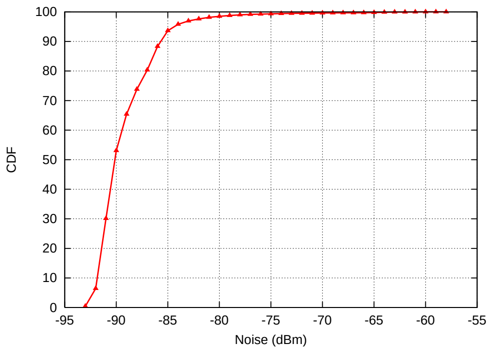


**Figure 5.8. Roofnet: CDF of noise level**

- Is interference the reason why Roofnet does not observe a correlation between the packet error rate and RSSI?
- Does interference cause an increase in the observed noise level?
- Can the value of noise level then be used to make an inference about the amount of interference?

## 5.4 Interference and its effects

### 5.4.1 Introduction

To answer the above questions we performed a controlled experiment. The experimental setup for the controlled experiment is depicted in Figure 5.4.1. We have two transmitters $A$ and $B$. The transmitters are basically PCMCIA cards that are fitted into laptops. $A$ is connected to a variable step-attenuator, while $B$ is connected to a fixed attenuator by RF-cables. The attenuators are in turn connected to $R$. $R$ is a PCMCIA card which has two antenna connectors and thus accommodates both the RF cables from $A$ and $B$. The setup is such that $A$ and $B$ cannot hear each other's transmissions, while $R$ can hear transmissions from both (this is a case of hidden nodes). $R$ logs all packets that it hears.

$A$ and $B$ both transmit at a fixed inter-packet interval of 2ms. $A$ transmits UDP packets of length 1400 bytes while $B$ transmits UDP packets of length 1300 bytes. The different lengths are used to merely facilitate easy recognition of the source of a received packet in the log file generated at $R$.

Since $A$ and $B$ both are transmitting, they act as sources of interference for each other. The RSSI of packets from $B$ was fixed at -75 $dBm$ by adjusting the value of the fixed attenuator and the transmit power of $B$. At the same time, the RSSI of $A$ was adjusted in turn to -75 $dBm$, -80 $dBm$, -85 $dBm$ and -90 $dBm$ by adjusting the value of the variable attenuator.

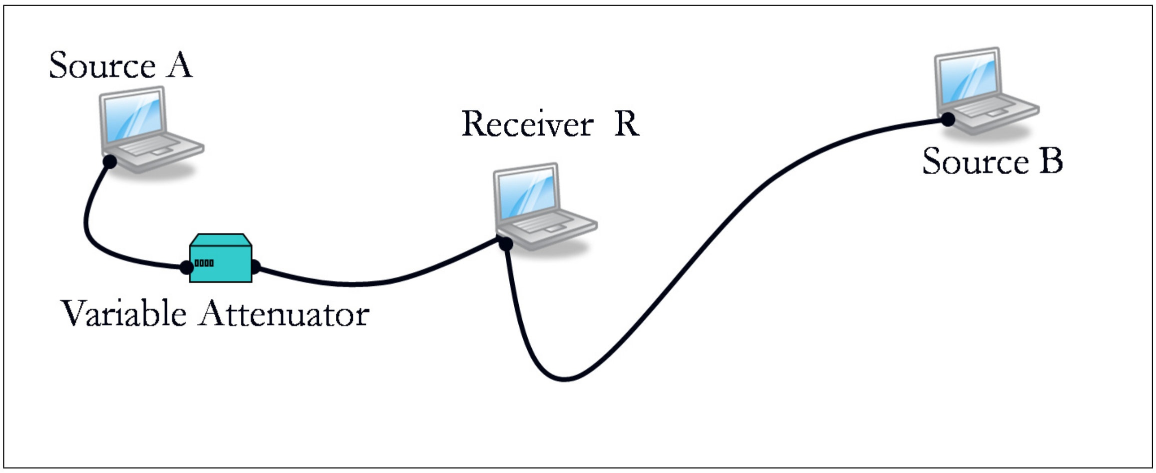


Figure 5.9. Setup for controlled interference experiment

We analyse the log files generated by $R$ to collect various statistics about the experiment runs. These are displayed in Table 5.1. The obvious conclusion that can be drawn from the table is that the loss rate experienced by $A$ drops as the RSSI value of *A's* packets increases, while that of $B$ drops (Col-3 and Col-4 in the table).

We now try to answer the questions we posed earlier with the help of data from the table.

### 5.4.2 Inferences

***Does interference cause the level of noise reported by a card to increase?*** Firstly it can be seen from Col-5 and Col-8 in the table that the mean noise level and the noise band (95%-ile minus 5%-ile) are high. These values are similar to the ones observed in the Roofnet data that we have analysed. If we plot the noise and RSSI values for packets from B received during experiment run 2 in the table, the difference between the noise bands becomes apparent. Note, Figure 5.10 shows that the noise values are well below the -85 *dBm* mark, while those in Figure 5.7 stretch well upto the -75 *dBm* mark and even well above it. Hence, we may conclude that **interference does increase value of the noise reported by the card.**

***Can packet loss rate be related to the level of interference observed?*** Is it possible to guage the amount of interference by the the the number of foreign packets that a node receives? If it is and if the loss rate and interference are directly correlated, then as the number of packets received from the interference source increase, the number of packets that are received from the intended transmitter should decrease.

| **Col-1** Expt No. | **Col-2** Source | **Col-3 Mean RSSI (dBm)** | **Col-4 Loss % from source** | **Col-5 Mean Noise (dBm)** | **Col-6 5%-ile Noise (dBm)** | **Col-7 95%-ile Noise (dBm)** | **Col-8 Noise Band (dB)** | **Col-9 Max Noise (dBm)** |
|---|---|---|---|---|---|---|---|---|
| 1 | A | -89.74 | 100.0% | -93.26 | -94 | -90 | 4 | -88 |
| 1 | B | -75.59 | 0.5% | -92.1 | -94 | -88 | 6 | -88 |
| 2 | A | -85.23 | 99.2% | -92.53 | -94 | -85 | 9 | -85 |
| 2 | B | -74.68 | 18.3% | -89.34 | -94 | -85 | 9 | -84 |
| 3 | A | -80.69 | 63.2% | -90.85 | -94 | -80 | 14 | -80 |
| 3 | B | -75.73 | 37.2 | -85.16 | -94 | -80 | 14 | -80 |
| 4 | A | -75.25 | 39.8% | -93.06 | -94 | -92 | 2 | -74 |
| 4 | B | -75.11 | 61.3% | -90.18 | -94 | -75 | 19 | -74 |

**Table 5.1. Controlled Interference Experiment: Results**

However if we look at row 2 in Table 5.1 we find that *B* has a loss rate of 18.3% (Col-4). The number of packets of *A* that were received at this point of time is very low - 99.2% loss rate. *A* is sending packets at a rate of 500 pkts/sec and in the present scenario it translates to only 4 packets being received per second. However, at this stage when we completely stopped *B's* transmissions, the number of packets received from *A* still remains low (99% loss rate). This is because the average RSSI of packets received from *A* is about -85 *dBm*. This is much below the receive sensitivity / threshold of -81 *dBm* mentioned earlier. Thus **the loss rate can be very high even if the number of foreign packets received is low**.

In case two transmitters are near each other and can hear each other transmit, one of them will back-off if it hears the other one transmit. This can explain how **the packet loss rate can be low even if the number of foreign/interference packets received is high**.

If we consider both of the above statements in conjunction with each other we can conjecture as to why the Roofnet study did not find any correlation between the loss rate and the rate of reception of foreign packets.

***Can the noise level reported by the card be used to guage the amount of interference?*** It would be of interest to determine if we could use the noise level reported by the card for predicting the amount of interference. If it was possible to do so, then the presence or absence of interference on a link could be guaged by maintaining a tab on the noise levels that the card reports. Figure 5.10 indicates that there is a large amount of variability in the reported noise level

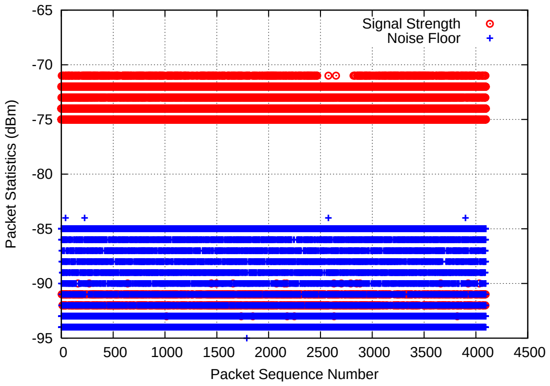


**Figure 5.10. Per Packet variation of RSSI and noise in the controlled interference experiment**

even when the signal level of the interference is fixed. Let us now compare the card-reported noise values from Table 5.1 (Col-5 to Col-8) with what we know to be the level of the interference (Col-3). In case of $B$, we see that the maximum noise value reported by the card is equal to the signal level of $A$, however, in case of $A$, the maximum noise level that the card reports (-85 $dBm$) is much lower than the signal level of $B$ (-75 $dBm$).

The variability in noise floor arises due to the way the noise level is reported by the card. The noise level reported by the Prism2 card hardware is an average of 256 samples [11]. Thus the noise level reported by the card depends strongly on the exact time at which a packet was received vis-à-vis a transmission by a source of interference. This implies that **it is difficult to predict the level of interference based upon the noise values reported by the hardware of the card**. This holds true at least for cards with the Prism2 chipset.

***Can one estimate the link performance based on the average noise floor/level measured by the card hardware for the received packets*** We plot a scatter plot of the observed error rate against the reported noise floor. Each point in Figure 5.11 represents the average packet error rate for the corresponding average RSSI calculated over a bin of 100 packets. We can see that for a reported value of noise floor, there can be a large number of error rates possible. This means that **it is not possible to estimate the error rate accurately based on the noise floor level reported by the card hardware.** Effectively combining the last two statements that it means that it is difficult to use the noise floor level reported by the card to estimate the behaviour of a link.

## 5.5 Temporal Variability in RSSI

In the past two sections we have seen how the presence of interference makes link behaviour unpredictable. The question now is, in the absence of interference, whether it is possible to build links with stable, low error rates viz. links where

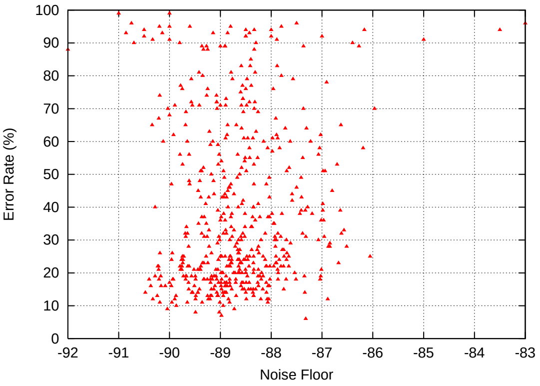


**Figure 5.11. Avg. Noise: Error Rate vs Noise Floor, 100 packet bins**

the abstraction holds. The stability of RSSI affects the error rate i.e if the RSSI is unstable then the error rate will also tend to vary. Stability of RSSI thus needs to be examined over short and long time scales.

The stability of RSSI over shorter time scales has direct implications on routing protocols that use RSSI / error rate a s a metric for choosing the best link. On the other hand the long term stability of RSSI is of importance while planning a network link or while deciding on improvements to existing links.

### 5.5.1 Short Term RSSI Variability

The data from the 2-minute experiments conducted by us can be used to study the stability of RSSI over a short period of time. Figure 5.12 plots the $5^{th}$-percentile, mean, median ($50^{th}$-percentile) and the $95^{th}$ percentile values for the 2-minute experiment runs carried out at the interference free locations. The difference between the $5^{th}$-percentile and the $95^{th}$-percentile represents the band in which 90% of the RSSI values of the received packets lie. The figure depicts data from 14 different positions and all 4 data rates. The points are sorted in the increasing order of the median RSSI.

The '*RSSI band*' is plotted separately in Figure 5.13. It is seen that nearly all the values we observed lie below 3-4 *dB* . In case of node pairs 16, 19 and 36 in the figure, the band is 6-7 *dB*. We did not have a clear Line-of-Sight (LoS) in these cases between the transmitter and the receiver. In the three cases, when we plot the variation in RSSI against packet number/time, we find that there are periods of a few seconds when we see a sharp marked drop in the RSSI, which seems to indicate that there was some human movement / obstacle in between the transmitter and the receiver during that duration.

In the case of pairs 42, 43 and 44, the band is 18, 23 and 24 *dB* respectively. These large bands are a result of a hardware quirk that we have observed at times, with the cards that we have used. The cards suddenly show a drop of close to 20 *dB* while operating. This quirk has also been reported in [16]. These hardware

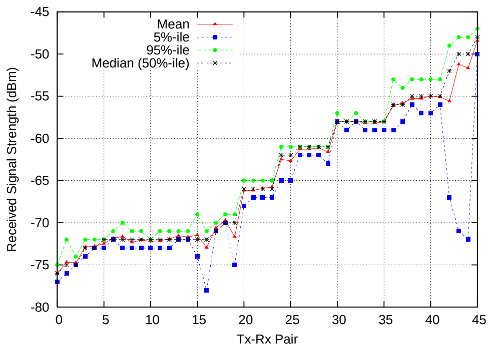


**Figure 5.12. Variation in RSSI**

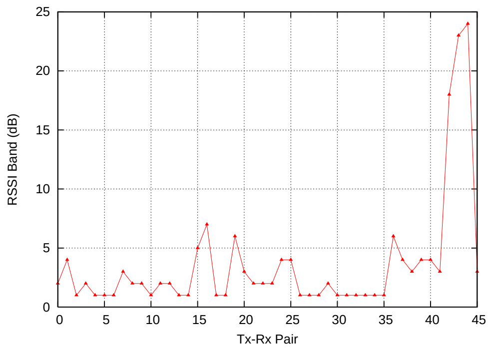


**Figure 5.13. RSSI Variation Band: $5^{th}$%-ile to $95^{th}$%-ile**

quirks were also observed while the cards were connected using a RF cable so that the wireless channel was effectively eliminated.

These experiments lead us to conclude in this case that the RSSI variation, though dependent on the environment is within about 3-4 *dB* in most cases. In all our experiments where we had a clear LoS between the transmitter and the receiver, this band was restricted to a maximum of 4 *dB*.

We ran a set of similar tests on the data available from the Roofnet study and found that even in their data, in most cases the RSSI band was not wider than 5 *dB*. Some links in Roofnet did show a larger band (6 to 11 *dB*).

### 5.5.2 Long Term RSSI Variability

We conducted two long duration experiments at the *Apt* and the *Apt2Dorm* locations to study the long term stability of RSSI. In each location we had one transmitter and three receivers placed at different positions (see Figure 3.4 for the experimental setup and 3.5(b) for the experimental location. In the *Apt* location we ran our experiment for 24 hours while in the *Apt2Dorm* location we ran the experiment for 48 hours. During the experiment the transmitter continuously sent 1400 byte packets with an inter-packet time of 20ms at a data rate of 11Mbps. The statistics for the data gathered from the experiments is placed in Table 5.2.

The table shows that even over long durations of time the RSSI band ($5^{th}$-percentile to $95^{th}$-percentile) is within 5 *dB* in cases where LoS is available. In fact it can be seen that in one non-LoS case as well the RSSI band was only 2 *dB*.

### 5.5.3 Operating Close to the ‘Steep Region’

Subsections 5.5.2 and 5.5.1 show, that in most cases, irrespective of LoS or non-LoS, the RSSI band rarely exceeds 4 *dB*. In a few non-LoS cases it tends to exceed 4 *dB*. We now examine the effect of operating close to the ‘steep region’.

| **Location** | **Rx Position** | **LoS ?** | **Duration (hrs)** | **RSSI 95%-ile (dBm)** | **RSSI 5%-ile (dBm)** | **RSSI band (dB)** |
|---|---|---|---|---|---|---|
| **Apt** | 1 | Yes | 48 | -66 | -69 | 3 |
| **Apt** | 2 | No, foliage | 48 | -69 | -77 | 8 |
| **Apt** | 3 | No, foliage | 48 | -76 | -82 | 6 |
| **Apt2Dorm** | 1 | Yes | 24 | -75 | -77 | 2 |
| **Apt2Dorm** | 2 | Yes | 24 | -70 | -71 | 1 |
| **Apt2Dorm** | 3 | No, foliage | 24 | -79 | -81 | 2 |

**Table 5.2. RSSI Variation: Long Term**

To illustrate the point we choose a receiver position in the *Vill* location. In this position, at a data rate of 11 Mbps, we observed an error rate close to 25%, which is '*intermediate*' (neither 0% nor 100%). The average RSSI of the received packets is -80.5 *dBm*. Figure 5.14 is a CDF-plot of the RSSI values received during the experiment run. In Figure 5.15 we plot the error-rate vis-à-vis the Bin Number (100 packet bins). Looking at both the graphs one can notice that the error-rate becomes unpredictable when one is opearting close to the steep region. We have observed similar variations in other locations

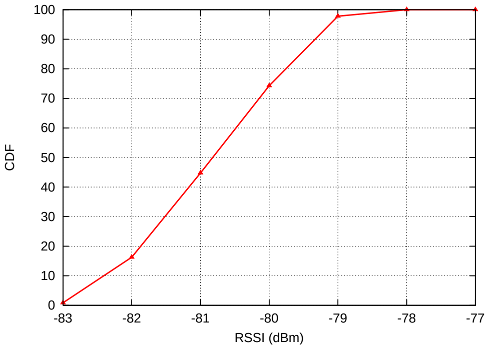


**Figure 5.14. Location Vill: CDF of RSSI**

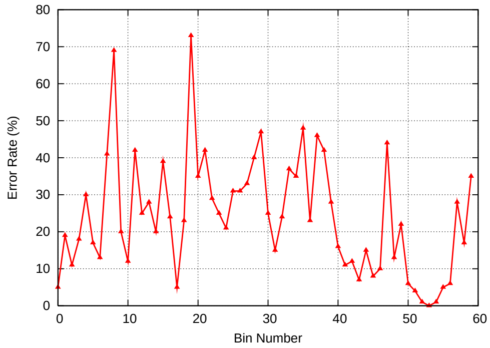


**Figure 5.15. Location Vill: Variation in Error Rate**

### 5.5.4 Sector Antenna

The above experiments were all also carried out with a sector antenna (90° beamwidth, gain – 17 *dBi*) and we found that the same conclusions can be drawn even in the case of a sector antenna.

## 5.6 Summary of Results

To summarise, we find:

- Interference, not multi-path, is the main cause of intermediate delivery probabilities.
- Using the available hardware, it is difficult to use the noise floor level reported by the card to guage the level of interference being experienced by a node or to predict the link-quality.
- In the absence of interference, there exists a 'threshold' value of RSSI for a given environment, above which the error rates are stable and low. In such a position, *link abstraction* holds.
- RSSI is stable over long and short time scales and the RSSI variation is within 3-4 *dB* in most cases. However, as one moves/operates a link closer to the '*steep region*', error rate varies thereby making it difficult to predict link behaviour.

## 5.7 Design Implications

Our results, articulated above, have a number of implications. We think that the above results present a fresh perspective on a number of issues. We now elaborate.

### 5.7.1 The Link Abstraction

The absence of a link abstraction implies that error rates on a link may vary anywhere between 0% to 100%. The Roofnet study [13] suggests that out of all the link in their network, links with such intermediate error rates are predominant. In light of this metrics like ETX [17] and WCETT [21] have been proposed to find the best links through such networks. However, our results indicate that it is feasible to achieve link abstraction.

In the absence of external interference, our data on long-term RSSI variation suggests how it is possible to achieve link abstraction. For example, if we wish to ensure that link abstraction holds for a link in the network, we need to ensure that the RSSI at the receiver is above the RSSI threshold that we see in our error rate vs RSSI plots. From Fig 5.3 we can see that it is close to -79 *dBm* for a 11Mbps link. Further we can observe a variation of 3-4 *dBm* in RSSI over a longer time scale. We need to account for this variation while designing the link. Hence if we assume a threshold level of about -75 *dBm*, then the link should exhibit stable, low error rates.

This approach is also valid when trying to determine the transmit power when two nodes want to communicate with each other in an existing network. If links are formed as above it would be possible to build links with stable, predictable behaviour.

### 5.7.2 Implications on Routing

**Routing Metrics:**
Much research has focussed on the design of routing metrics that will distinguish between links that have error rates between 0% and 100% ([19], [20], [17], [21]).

De Couto et al. in [19] report that there exist many cases in a WMN where choice of a hop count as a metric results in poor throughput. the reason they point out, is that most routes in such cases have an error rate that is low enough that the routing metric chooses to use the root, but high enough such that it affects the total throughput of the link. They thus advocate that proper attention must be paid to the quality of the link when choosing a route. They also mention the problems of using various parameters as routing metrics. Some are listed below:

- **Delivery Rate** – requires many packet transmissions to measure
- **Signal-to-Noise Ratio (SNR)** – may be useful as a link metric that is able to predict the delivery rate of a link quite fast.
- **Combination of route metrics** – Combining route metrics is not straight forward.
- **Expected total number of transmissions** – proposed metric to account for self interference.

In [17], De Couto et al. then propose the use of Expected Transmission Count (ETX) metric. The ETX metric tries to minimise the expected number of transmissions (including retransmissions) that may be required to deliver a packet to its final destination. The ETX metric incorporates the effect of losses and interference along the successive links in a path. The authors compare the performance of this metric on a wireless test bed and find that ETX performs better than a minimum hop-count metric. However, ETX prefers to transmit over shorter link to minimize global resource usage and also does not prefer diverse channel paths.

In [20], Draves et al. compare different metrics like minimum hop count, minimum per-hop RTT, per-hop packet pair and ETX against each other. They test each metric on a 23-node wireless test bed located indoors in a typical office space. Their nodes are primarily laptops. They observe that the ETX metric has the best performance when all the nodes are stationary, while the per-hop RTT and the minimum per hop packet pair metrics perform poorly as links tend to interfere with one another. In a mobile scenario, however, the minimum hop count metric performs the best.

In [21], the authors try to account for interference and try and take advantage of channel diversity in a multi-radio, multi-hop kind of setting. Their metric - WCETT tries to use a weighted average of the amount of time required to transmit a packet to the destination and the transmission time required to transmit a packet over hops on the same channel. Thus WCETT prefers paths that use diverse channels over paths that use the same channel

The variability in RSSI means that if one operates close to the the *RSSI threshold*, the RSSI values overlap the *steep region*. In such a scenario the link experiences with *intermediate* error rates. Figure 5.15 indicates the instability and variation in error rate that is seen when operating close to the RSSI *threshold/steep region.* If we observe Figure 5.15, the variability in error rate is very evident. Now consider a link that uses the ETX metric to estimate the link quality. In the experiment for which the figure is drawn, packets were being sent at an interval of 20ms. Each plotted point on the graph represents 100 transmitted packets (bin) or a time period of 2 seconds. If we consider the first bin we see the error rate is 20%. This changes to 11% over 2 seconds and then to 30% in the next two seconds. In case of such variability being observed on a majority of links in the network (as observed by the Roofnet study), a routing metric will continuously change paths in the routing table trying to select the best link. However, by the time it selects a link, the error rate on that link has changed drastically. Such rapid changes in the observed error rate would thus make metrics like ETX [17] and WCETT [21] unstable.

**Opportunistic Routing:**
In [15], the authors propose an integrated routing and MAC protocol. EXOR aims to improve the throughput of large unicast transfers. Instead of committing to a route and then forwarding a packet, the source broadcasts the packet and then depending on who all received the packet, chooses a receiver to forward the packet over the next hop. The goal is to choose the node closest to the destination to forward the packet. EXOR works under the assumption that loss rates will increase as the number of hops in the path increases. EXOR also tries to make use of anomalies while transmitting i.e. a transmission being received by a node further away toward the destination that does not receive packets from the source directly in the normal course.

EXOR chooses to work around interference and this may be the best option if the external interference cannot be controlled. It may however be difficult to achieve performance guarantees in such a situation. We feel thus that it may be better to control external interference, if possible, than to wait for an opportune moments to get packets across. It may be possible to control interference by a number of methods:

- **By planning the channel allocation** – this may be possible in settings where there is control over how nodes are set up e.g.: rural network, planned urban deployment by a municipality or a university/campus network.
- **Topology planning** – planning the topology of the network in a way such that interference is minimised. Topology planning will essentially involve deciding things like how and where to place the antennas, what antennas to use, what transmit powers to use at each node, whether to have more than one radio at a node or not and so on..
- **TDMA MAC** – Another method to reduce the interference can be to use a mechanism at the MAC layer. CSMA/CA MACs are susceptible to cases of ‘hidden node’ that cannot be fully solved in spite of the RTS/CTS mechanism. In such cases, a TDMA-based MAC can prevent interference by ensuring that transmissions are slotted serially and no two nodes transmit

at the same time, thus inadvertently causing interference.

**Interference Aware Routing:**
There have been efforts in literature that have focussed on trying to route packets based on the amount of interference ([34], [22]). These efforts try to reduce *self-interference*, i.e., interference created by a link on other links of the same wireless network. The work in [29] tries to determine the amount interference present and then tries to predict link performance.

However, our observations indicate that there is a inherent 3-4 *dBm* variation in RSSI. In addition, we have not observed any significant additional variation in RSSI due to external interference. Further our earlier observations about interference in Section 5.4 indicate that given our present hardware, trying to determine the amount of interference from the noise floor level reported by the card or based on the average noise level (as suggested in [34]), may not be accurate. Whether such interference estimation is possible using appropriately designed hardware is an open issue.

### 5.7.3 Implications on MAC

CSMA/CA based MACs try to avoid interference/collisions by using a distributed model, wherein each node senses the common medium and defers accessing it if it is occupied. The use of a mechanism like RTS/CTS to tide over the *hidden node* problem, is not foolproof. This is due to the fact that the *interference range* of a transmitter is much larger than its *signal range* (the range at which its transmissions can be received correctly).

Another solution to this problem, especially applicable in the case of network like FRACTEL, which may have a single gateway, and most nodes communicating with the gateway, with little communication amongst themselves, it would be possible to implement a TDMA based MAC where a central entity controls the access to the medium and thereby prevents interference amongst links in the network.

# Chapter 6

# Conclusion and Future Work

Based on our experiments and our analysis of results, we conclude that

- There exists a threshold value of RSSI, such that operating a link at an RSSI above that will ensure that the link experiences stable, low error rates. In such a scenario, the link abstraction holds for a link.
- There exists a *steep region* close to the receive sensitivity of the receiver where the error rate becomes unpredictable. The width of the *steep region* varies depending on the environment in which the link is operating.
- We find that *interference* destroys the correlation between error rate and SNR/RSSI, thereby invalidating the concept of link abstraction. Instead of trying to work around *interference*, it would be a good idea to try and control *interference* so that links with predictable quality can be built.
- The feasibility of the link abstraction has important implications for routing, and network design both in WSNs and in WLANs. The *link abstraction* makes it possible to design very simple routing algorithms that do not have to continually track the state of a metric and thereby the quality of the link. In WSNs, where the longevity of the network is a primary requirement, the use of simple routing protocols also helps to reduce the traffic overhead thus eventually helping to to increase the overall network lifetime.
- By using external antennas it is possible to substantially extend the communication range of a WSN device especially in Line-of-Sight environments. This simplifies network design by bringing a larger number of nodes closer to the gateway. The antenna gain also helps to improve the link quality such that link abstraction now holds for a larger number of links. Simplified routing can thus be used to eventually increase the lifetime of the network.

# Future Work

The following can be pursued to further the work completed as part of this thesis:

- Even though our work highlights *external interference* as a definite source of links with intermediate losses, we feel it would be important to design and perform experiments both controlled and in real environments that can specifically assess the effect of multipath in the setting envisaged by FRACTEL
- With the 5 GHz band being de-licensed in India with effect from $19^{th}$ Jan 2007 [25], it would be instructive to perform a similar channel characterization for that band. It would be interesting to to see if a combination of 802.11b links (for the long distance segment) and 802.11a links (for the shorter segments) can be used.
- The ability to run a TDMA MAC over COTS wireless equipment has already been tested ([24], [28]). The ability to achieve a finer time synchronisation and the ability to synchronise over over multiple hops will aid the study of the effectiveness of a TDMA MAC to reduce interference without affecting network throughput/capacity.
- We have not yet carried out experiments to determine the effect of interference as on links in WSNs we have done in the case of WMNs. It would thus be instructive to study the effect of interference on links in a wireless sensor network.

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