ABSTRACT

Title of Thesis:	TEMPORAL VARIATIONS OF IEEE 802.11b SIGNAL STRENGTHS IN AN IN-BUILDING ENVIRONMENT
Degree candidate:	Roopa Mogili
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Thesis directed by:	Professor Ashok Agrawala Department of Electrical and Computer Engineering

Recent emergence and popularity of The IEEE 802.11b Wireless Local Area Networks (WLANs) in a host of current-day applications has instigated a suite of research challenges. The 802.11b WLANs are highly reliable and wide spread. The ease and low cost of deployment make this networking paradigm very convenient for a myriad of applications in markets such as retail, warehousing, academia, healthcare and manufacturing.

In this work, the emphasis is on the 802.11 received signal strength (RSSI). The RSSI plays a vital role in any communication system. In any communication, the signal is detected only if the RSSI is above a threshold but it can vary depending on the power of the sending signal, and the losses that occur during transmission. In this work, we study the temporal characteristics of RSSI in the real-working

environment by conducting a controlled set of experiments. Our results indicate that a significant variability in the RSSI can occur over time. Some of this variability in the RSSI may be due to systematic causes while the other component can be expressed as stochastic noise. We present an analysis of both these aspects of RSSI. We treat the moving average of the RSSI as the systematic causes and the noise as the stochastic causes. We give a reasonable estimate for the moving average to compute the noise accurately. We attribute the changes in the environment such as the movement of people and the noise associated with the Network Interface Card (NIC) circuitry and the network access point as causes for this variability. We find that the results of our analysis are of primary importance to active research areas such as location determination of users in a WLAN. The techinques used in some of the RF-based WLAN location determination systems, exploit the characteristics of the RSSI presented in this work to infer the location of a wireless client in a WLAN. Thus our results form the building blocks for other users of the exact characteristics of the RSSI.

TEMPORAL VARIATIONS OF IEEE 802.11b SIGNAL STRENGTHS IN AN IN-BUILDING ENVIRONMENT

by

Roopa Mogili

Thesis submitted to the Faculty of the Graduate School of the
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Advisory Committee:

Professor Ashok Agrawala, Chair
Professor Udaya Shankar
Professor Virgil Gligor

DEDICATION

To my parents and sisters.

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Sincere thanks to Moustafa Youssef for his help and efforts with setting up the environment for the experiments. I owe many thanks to my colleague Prabha Ramachandran and Arunesh Mishra for critiquing and helping me refine many of the ideas in this thesis.

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Chapter 1

Wireless Networking

1.1 Introduction to wireless networks

A Local Area Network (LAN) [1] is a group of computers and associated devices that share a common communication medium. This communication network serves users within a limited geographic area. The most common type of LAN is Ethernet.

A Wireless Local Area Network (WLAN) [2] is a flexible data communication system implemented either as an extension to, or as an alternative for, a wired LAN within a building or a campus. Using electromagnetic waves(radio or infrared), WLANs transmit and receive data over the air, minimizing the need for wired connections. Thus, WLANs combine data connectivity with user mobility and enable movable LANs through simplified configuration. Wireless LANs have gained wide popularity in a number of markets, including health care, retail, manufacturing, warehousing and academic arenas.

1.1.1 An application of a WLAN

WLANs increase the effeciency in managing the manufacturing processes and the inventory in businesses. Many businesses benefit from using WLANs to manage their manufacturing processes. This lowers operating costs. Because the connections between the manufacturing equipment and main control systems are wireless, the company can reconfigure the assembly process at any time from anywhere, saving time and money. A WLAN can also track and update inventory in real-time, increasing the efficiency and accuracy dramatically. In a retail environment, as soon as a clerk purchases or stocks a product, a wireless management solution can update the inventory. In the manufacturing environment, WLANs can keep the raw materials and finished product statistics up-to-date. Employees equipped with wireless-enabled bar code scanners can check or change product prices and/or check the number in stock. The improved accuracy provided by using a WLAN to manage inventory creates a chain reaction of benefits. Because the clerks enter the information directly into the main computer via handheld scanners, there is no paperwork to deal with. This significantly reduces human error when entering data, which leads to very accurate financial records. This is important to manufacturing companies because accurate financial records ensure correct taxes are paid and fines are kept to a minimum.

1.1.2 Working of a WLAN

A Basic Service Set (BSS) consists of two or more wireless nodes or stations (STAs) which have established communication, through the coordination of a special node called an access point (AP). The function of an AP is to form a bridge between wireless and wired LANs. APs are typically not mobile, and form part of the wired network infrastructure. The AP receives, buffers and transmits data between the WLAN and wired network infrastructure. A single AP can support a small group of users. The Extended Service Set (ESS) consists of a series of overlapping BSSs connected together by means of a distribution system. In a typical LAN this distribution system is the ethernet. Each ESS is uniquely named by a Service Set Identifier (SSID). Mobile nodes can roam between APs and hence a campus wide coverage is possible.
End users access the WLAN through wireless LAN adapters, which are implemented as PC cards in notebook computers, or ISA or PCI cards in desktop computers.

1.2 Introduction to IEEE 802.11

The IEEE 802.11 standard [3, 4] refers to a family of specifications developed by the IEEE for wireless LAN technology. This standard defines the Medium Access Control (MAC) and physical layer (PHY) for a LAN with wireless connectivity. It addresses local area networking where the connected devices communicate over the air with other devices that are within radio transmission range. There are several specifications in the 802.11 family:

- *802.11* - This standard for WLANs operates at a radio frequency of 2.4 gigahertz (GHz) with a data rate of 1 to 2 Megabits per second (Mbps). 802.11 uses either the Frequency Hopping Spread Spectrum (FHSS) or the Direct Sequence Spread Spectrum (DSSS) modulation technique.

- *802.11a* - A supplement to 802.11 standard for WLANs. It provides a maximum data rate of 54 Mbps in the 5GHz radio frequency band. 802.11a uses an Orthogonal Frequency Division Multiplexing (OFDM) encoding scheme rather than FHSS or DSSS.

- *802.11b* - Another supplement to the 802.11 standard for WLANs. The physical layer of the IEEE 802.11b operates at the radio frequency of 2.45 gigahertz GHz with a maximum bit rate of 11Mbps. It uses the Direct Seqence Spread Spectrum (DSSS) modulation technique. At the MAC sublayer of the data link layer, 802.11b uses the carrier sense multiple access with collision avoidance (CSMA/CA) as the MAC protocol.

- *802.11g* - One of the recent IEEE standards for WLANs which provides data rates higher than 20 Mbps in the 2.4 GHz radio frequency band.

Wireless LANs such as the 802.11b are very popular and wide-spread as they provide simple wireless connectivity and data delivery.

1.3 Received signal strength indicator (RSSI)

1.3.1 Probe requests and responses

In the 802.11b WLAN, the communication between the access point (AP) and a station is based on probe requests and responses[5]. The base station in the medium searches for access points (APs) in radio range using the 802.11 management frames known as probe request frames. The probe request frame is sent on every channel the station supports in an attempt to find all access points in range that match the SSID and the data rate. APs within range respond with a probe response frame. The station decides which AP is the best based on the signal strength of the incoming packet. The term used for measured signal strength is the received signal strength indicator (RSSI). The station connects to the access point which responds with the strongest RSSI. This RSSI depends on the power of the sending signal and the losses that occur during transmission.

1.3.2 Losses during transmission

The 802.11b wireless channels are shared by other users and may be afflicted by interference from microwave ovens, Bluetooth devices or other 802.11b devices. There could also be a propagation loss in the strength of the signal due to the presence of people, walls, metal objects, etc.

1.3.3 Temporal variability in the RSSI

The variability in the RSSI measured at a fixed location is called the temporal variability in the RSSI. The short-term temporal variability is the variation in the RSSI from one second to the next. These variations can be observed if the RSSI is measured on the same day and location at different times of the day for a certain duration of time. The long-term temporal variations of the RSSI is the variability in the RSSI over a period of time, from one day to the next. The long temporal variations of the RSSI can be observed if the RSSI is measured on different days at the same time and location for a certain duration of time.

1.4 Problem definition and contribution

In this thesis, we present the temporal variability of the IEEE 802.11b RSSI in the real working environment by conducting a controlled set of experiments. Signal strength measurements were made at different locations, on different days and during different times of the day. It is observed that the measured signal strength at a fixed position varies significantly over time. Therefore, the received signal strengths (RSSI) are treated as a non-stationary stochastic process. Different characteristics of the RSSI are presented. Causes for this variability in the RSSI are expressed as the temporal variability component and the stochastic white noise component. We present an analysis of both these aspects of variability in the RSSI.

The results from the analysis form the building blocks for other users of the exact characteristics of the RSSI. The results are also incorporated in WLAN location determination systems such as Horus and the Nuzzer Technology [6, 7, 8]

1.5 Organization

The rest of the thesis is organised as follows. In chapter 2, the location and method of data collection is discussed. Chapter 3 discusses the causes for the variability in the RSSI. An analysis on the variability in the RSSI measured at one particular location is presented. In Chapter 4, a similar analysis on the variability in the RSSI measured at different locations is presented. We give a brief overview of the conclusions drawn along with future work in chapter 5.

Chapter 2

Related Work

The emphasis of our work is on the IEEE 802.11b received signal strength. We concentrate on the temporal variability in the RSSI. In this chapter we give a brief overview of the existing research in which the characteristics of the RSSI are of major importance. Most of the active research based on the RSSI is in the field of WLAN location determination. There are both deterministic and probabilistic techniques [9, 10, 11, 12, 13] for locating the users in a WLAN. Both these techniques exploit the signal strength received from an accesss point to track/locate users. We discuss some of the work in which the RSSI is of importance.

2.1 Importance of RSSI in the RADAR technology

RADAR [14, 15] is a radio-frequency (RF) based system for locating and tracking users inside a building. The RADAR technology records and processes signal strength information at mutiple stations as a part of the technique to track users inside a building. A premise of the work is that signal strength information provides a means of infering user location. The signal strength information and the signal to noise ratio at a location is logged in the data collection phase. RADAR uses a moving average of the RSSI to track a mobile user in a WLAN. A sliding window of 10 samples is used to compute the mean signal strength on a continuous basis. Hence, the exact characteristics of the RSSI are used in this technology.

2.2 Small-scale and large-scale variations in the the RSSI

There is research in progress [9], on the variations in the RSSI. The variations in the RSSI can be classified as the temporal variations, the small-scale variations and the large-scale variations in the RSSI. The signal strength varies over a large distance due to the attenuation of the RF signal. These are the large-scale variations of the RSSI. The small-scale variations happen when the user moves a small distance (order of wavelength). This leads to a change in the average received signal strength. For the 802.11b wireless network operating in the 2.45 GHz range, the wavelength is 12.5 cm, the variation in the signal strength is upto 10dbm for a distance as small as 3cm. There are techniques developed to overcome/compensate for these variations in the RSSI. These characteristics are termed as the noisy characteristics of a wireless channel. Current research also uses the probability distribution [16] of the received signal strength to address the noisy wireless channels in their techniques to locate users in a WLAN. The RSSI plays a vital role in a number of techniques used for the location estimation of users in a WLAN. This is an active research area which is still being explored. The significance and use of the RSSI in some of location determination technologies are discussed in this chapter.

Chapter 3

Experimental Setup

In this chapter we give details of the location of the RSSI measurements and the method adopted to make these measurements. We present the characteristics of the RSSI measured at one particular location. The goal of our data collection is to observe the variability in the RSSI as discussed in Chapter 1. In order to capture the temporal variations of the signal strengths, the test sets were collected at different locations (co-ordinates) on different days, during different times of a day and from different accesspoints.

3.1 Location of the experiments

The experiments were conducted on:

- The third and the fourth floor of the Computer Science building at the University of Maryland, College Park.
- The MIND Lab - 8400 Baltimore Avenue, College Park.

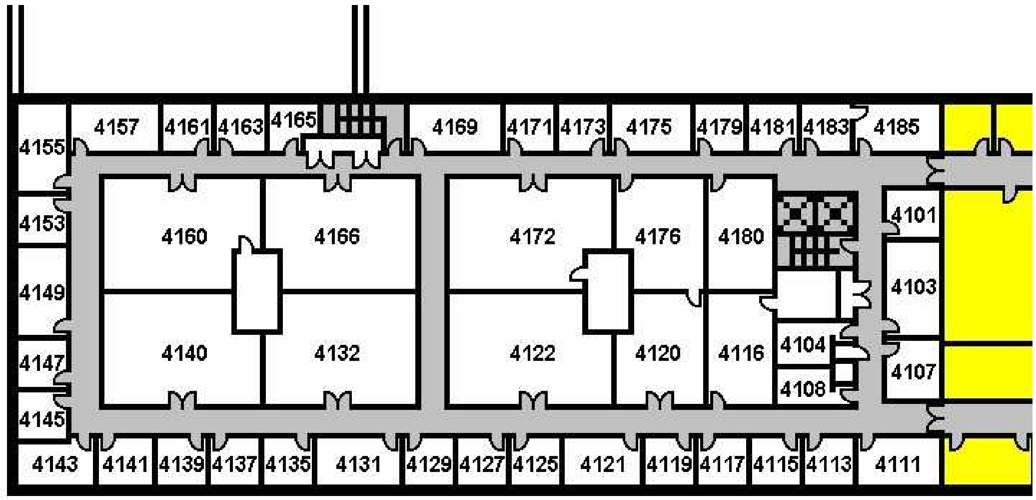


Figure 3.1: Plan of South Wing of the 4^{th} Floor of the Computer Science Building

On each floor, every wing is covered with 12 access points. Figure 3.1 shows the floorplan of a wing. The dimension of each wing is 224 feet by 85 feet. The data sets were collected at different locations on all the wings of the 3rd and the 4th floor using the UMD(CS) wireless network. We have a total of 11 data sets collected at different locations. The locations chosen to make signal strength measurements are as shown in Table 3.1.

Location	Date	Duration of Time
AVW 4127	February 14th, 2003	11:00 AM to 7:18 PM
MIND Lab	February 22nd, 2003	11:46 PM to 8:08 PM
AVW 4160	February 26th, 2003	4:03 PM to 12:15 AM
AVW 4141	February 27th, 2003	3:00 AM to 11:18 PM
AVW 4171	March 3rd, 2003	4:00 AM to 12:18 PM
AVW 4449	March 6th, 2003	7:02 PM to 3:16 PM
AVW 3450	March 9th, 2003	8:30AM to 11:16 PM
AVW 3264	March 10th, 2003	11:50 PM to 8:04 PM
AVW 4104	March 28th , 2003	12:45 PM to 9:03 PM
MIND Lab	April 7th, 2003	6:00 PM to 12:06 AM
AVW 4169	April 15th, 2003	8:00 AM to 4:18 PM

Table 3.1: Locations at which the RSSI measurements were made

3.2 Method of data collection

3.2.1 RSSI measurements

Using the device driver along with the API, developed by researchers at the University of Maryland, [17, 18], we measured the RSSI values at each location with varying sampling rates. The cards used to connect to the UMD (CS) network were Lucent Orinoco NICs supporting a data rate upto 11Mbps. The total number of sample signal strengths collected at different locations vary from 10000 to 30000 with varying sampling rates. We chose these ranges to ensure that the total duration of time for which the RSSI was measured from a fixed location, varied from 2.5 hours to 8.3 hours. We use these test sets to present the analysis of the variability in the RSSI over a period of time.

Instead of confining the sampling rate to 1 sample per second, the sampling rates were varied from 3 to 5 samples per second. These samples were collected 0.1 or 0.2 seconds apart. For a sampling rate of 4 samples per second taken 0.1 seconds apart, then the samples were collected at the intervals as shown in Figure 3.2. The 4 samples are collected in the first 0.3 seconds. A probe request was sent 4 times during each second at the intervals shown in Figure 3.2 to record the reported RSSI. The RSSI at each second was taken as the average of all the samples collected in that second. These technique to measure the RSSI was chosen to accomodate the loss of samples at any particular second. Say, one of the samples was lost in a second then the average of the remaining samples was

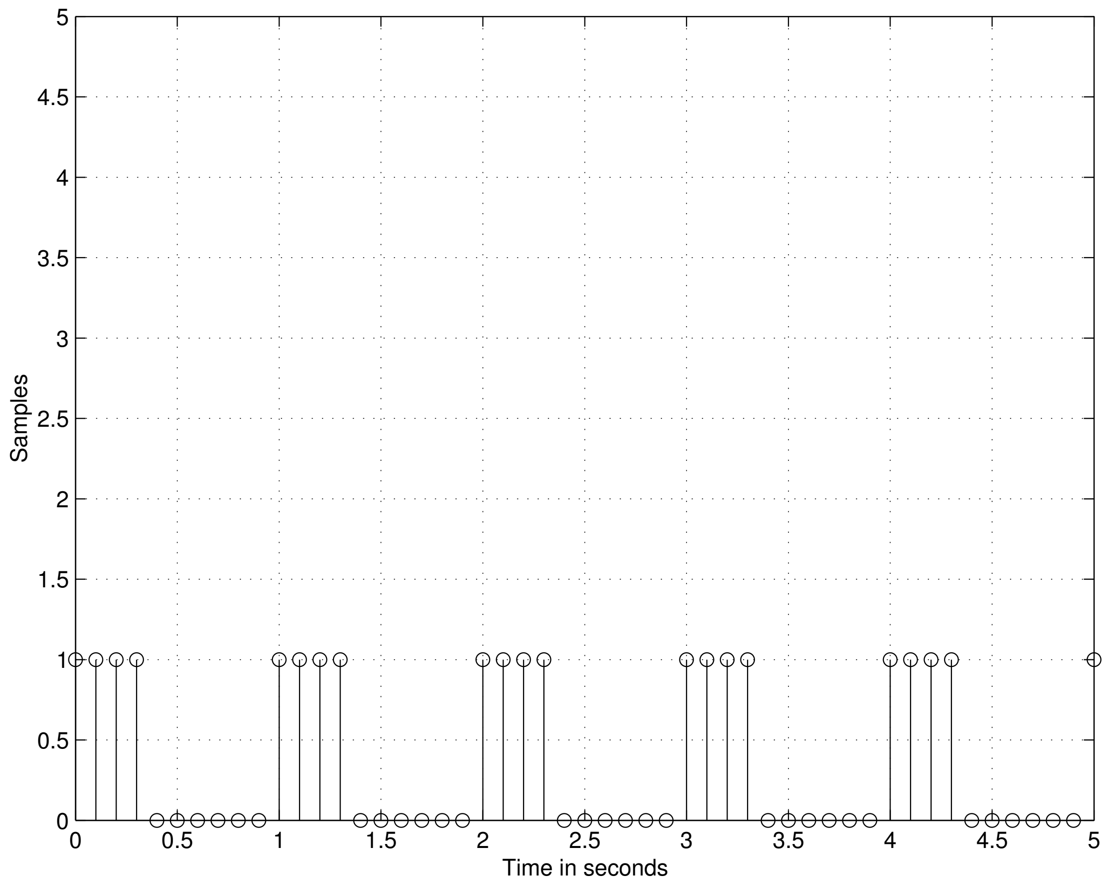


Figure 3.2: The intervals at which the samples are collected in the first 5 seconds of a test set. Sampling rate of 4 samples per second taken 0.1 seconds apart.

taken as the RSSI measured at that second. Therefore the average RSSI for each second is used in our analysis.

3.2.2 Data collected

The following data is logged along with the RSSI values measured:

1. The timestamp in milliseconds when the sample is collected in a particular second.
2. Magnitude of the received signal strength in dbm.
3. Magnitude of the noise associated with the access point in dbm.
4. The MAC address of the network access point from which the signal strength is received.
5. The SSID to which the MAC address belongs.

3.3 Characteristics of the RSSI

We discuss different characteristics of the RSSI, to present the behaviour of the RSSI over time:

1. Moving average(MA) of the RSSI
2. Standard deviation of the RSSI.
3. Autocorrelation between the RSSI values.

3.3.1 Moving Average

Moving average [19] is a derived sequence of the averages of successive subsequences of a given number of received signal strength samples in the test set to even out short-term fluctuations in the RSSI. In an 'n' sample Moving Average plot, each point on this graph represents the average of the respective sample and the n-1 number of preceding samples. Thus, computing the MA will smooth the pattern of means across samples. The number of samples (n) that are to be averaged for each point in the plot is specified.

3.3.2 Standard Deviation

Standard deviation gives a measure of the variation, or spread, of individual measurements. It is a statistic used to indicate how far away the measurements are from the mean values.

3.3.3 Autocorrelation

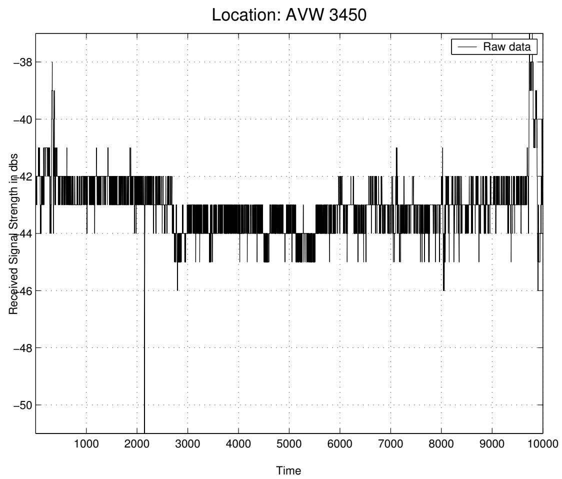
Autocorrelation [19] represents the common form of dependence across observations. Autocorrelation plots are a commonly-used tool for checking randomness in a data set. This randomness is ascertained by computing autocorrelations for data values at varying time lags. If random, such autocorrelations should be near zero for any and all time-lag separations. If non-random, then one or more of the autocorrelations will be significantly non-zero.

The characteristics defined above indicate the behaviour of the received signal strength measured over time. We use these characteristics to analyze the variability in the RSSI.

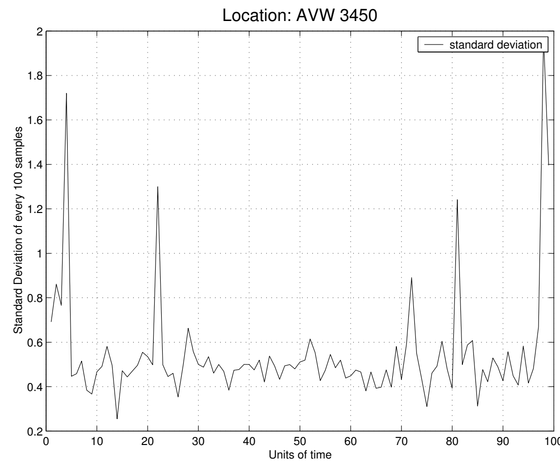
Let us consider one data set and its characteristics first. The parameters which vary in each data set are the location of the measurements, the total number of samples collected, the rate at which the samples were collected and the time of the day when the samples were colleted. The following details are with reference to one data set collected on the 3rd Floor of the Computer Science building.

- Location: AVW 3450
- Sampling rate : 1 sample per second
- Number of samples: 10000
- MAC address of the network access point: 00:40:96:46:19:4D
- RSSI measurements were made from 8:30 AM to 11:16 AM on March 6th, 2003.

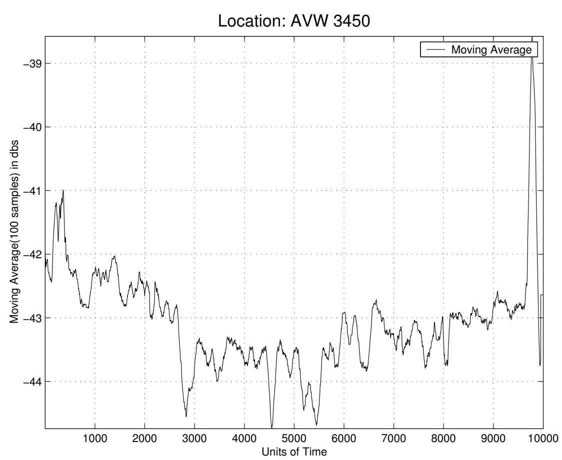
Figure 3.3 shows the characteristics discussed earlier in this section, plotted against time. It shows the general behaviour of the RSSI measured over time at AVW 3450. It can be inferred from Figure 3.3(a) that there is a variability in the received signal strength over time. The signal strength varies from -44 dbm to -38 dbm, with a data set mean to be -43.09 dbm. However, this is the raw data set



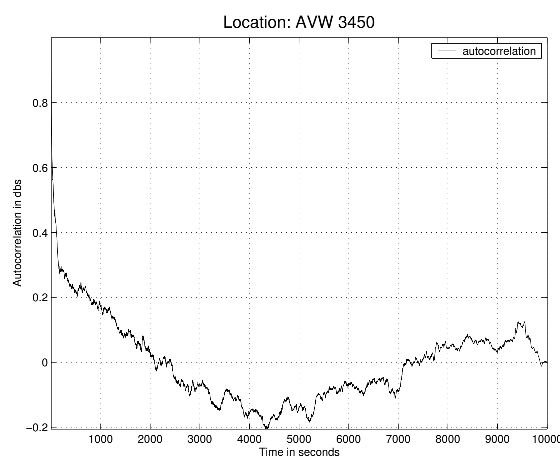
(a) Received signal strengths Vs Time



(b) Standard Deviation of every 100 sample signal strengths Vs Time



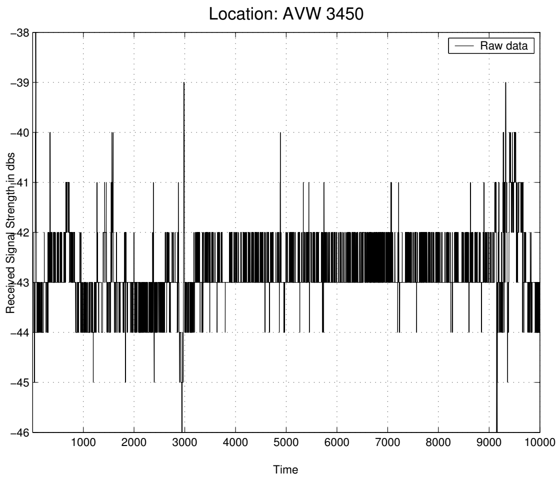
(c) Moving Average of the received signal strengths



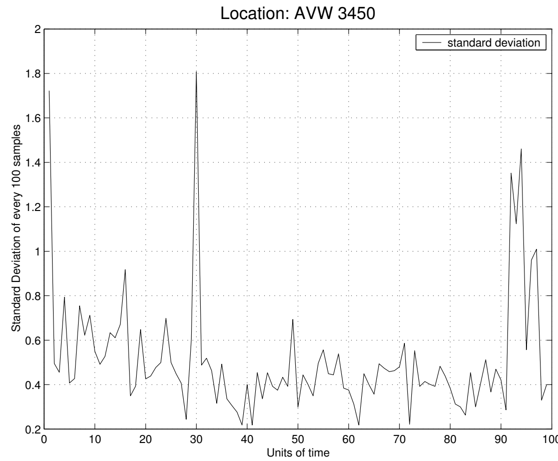
(d) Autocorrelation Vs Lag

Figure 3.3: Characteristics of the data set collected at 8:30 AM at AVW 3450 on March 6th, 2003

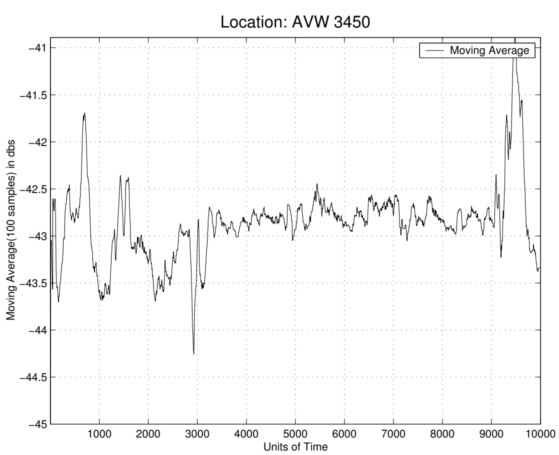
plotted against time. In order to smooth the data, and observe the slowly moving average of the received signal strength, the 100 sample moving average (time window of 100 samples) of the RSSI is plotted against time in Figure 3.3(c). In Figure 3.3(b) standard deviation of every 100 samples is plotted against time, to observe the deviation of the samples from the mean. The standard deviation for this data set is 0.99 dbm. Figure 3.3(d) shows that the autocorrelation between consecutive signal strength samples reduces to zero in about 2000 seconds. This correlation between the samples for a period of approximately 30 minutes makes very little sense and does not give much insight into the variability of the RSSI. In order to observe the short term temporal variations of the RSSI, we plot the characteristics of the RSSI measured at a fixed location during different times of the day. Figure 3.3 shows the characteristics of the RSSI measured from 8:30 AM to 11:16 AM. Figure 3.4 shows the characteristics of the RSSI measured from 4:30 PM to 6:45 PM and Figure 3.5 shows the characteristics of the RSSI measured from 9:45 PM to 12:02 AM. These figures show the variability in the RSSI over time (one day) measured at the same location. Figure 3.3(a), Figure 3.4(a) and Figure 3.5(a) show the variability in the RSSI during different times of the day. It is observed that although the mean of the RSSI remains almost the same throughout the day, there is significant variability at certian times of the day. Figure 3.3(a) shows a sudden variation in the RSSI at about 11:00 AM. A significant change in the RSSI values can also be observed in Figure 3.4(a) and Figure 3.5(a) at approximately 6:00 PM and 11:00 PM



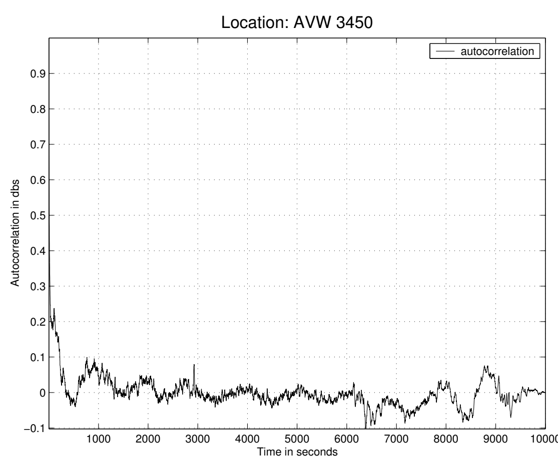
(a) Received signal strengths Vs Time



(b) Standard Deviation of every 100 sample signal strengths Vs Time

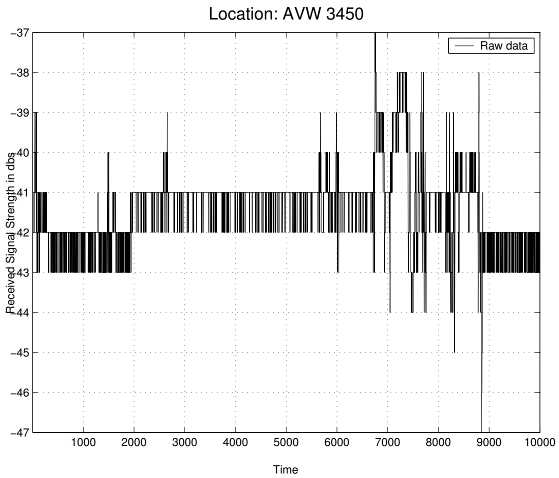


(c) Moving Average of the received signal strengths

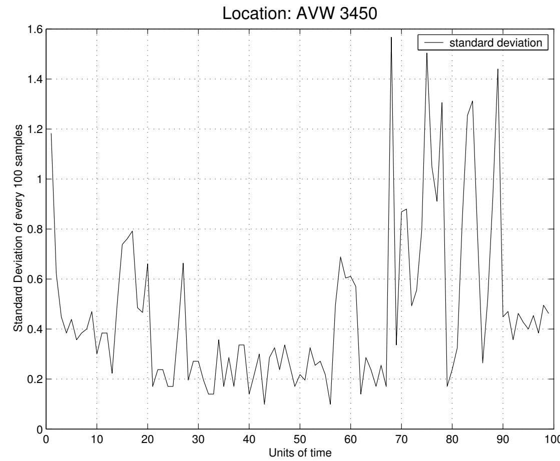


(d) Autocorrelation Vs Lag

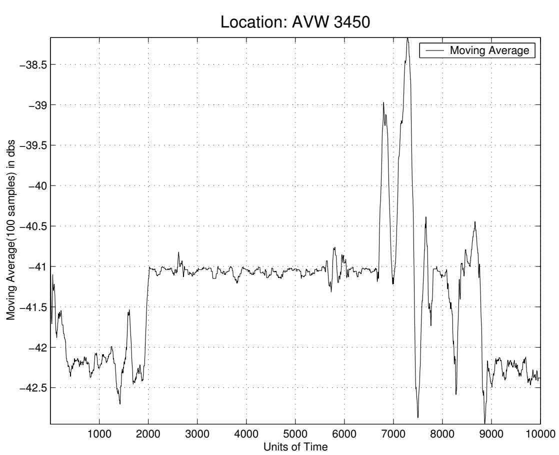
Figure 3.4: Characteristics of the data set collected at 4:30 PM at AVW 3450 on March 6th, 2003



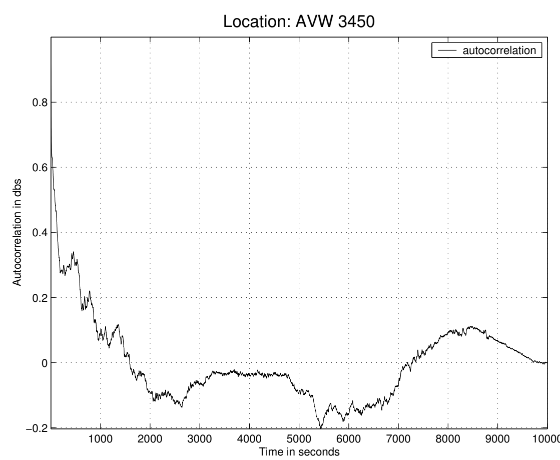
(a) Received signal strengths Vs Time



(b) Standard Deviation of every 100 sample signal strengths Vs Time



(c) Moving Average of the received signal strengths



(d) Autocorrelation Vs Lag

Figure 3.5: Characteristics of the data set collected at 9:45 PM at AVW 3450 on March 6th, 2003

Time of the day	Mean	Std deviation
8:30 AM	-43.09 dbm	0.99 dbm
4:30 AM	-42.86 dbm	0.70 dbm
9:45 PM	-41.35 dbm	0.96 dbm

Table 3.2: Mean and Standard deviation of the RSSI during different times of the day

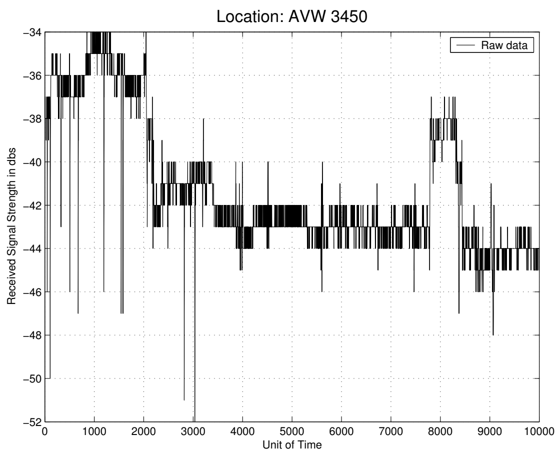
respectively. We attribute the changes in the environment such as movement of people to this sudden variability in the RSSI at certain times of the day.

Table 3.2 gives the mean and the standard deviation of the RSSI measured at a fixed location, during different times of the day on March 6th, 2003.

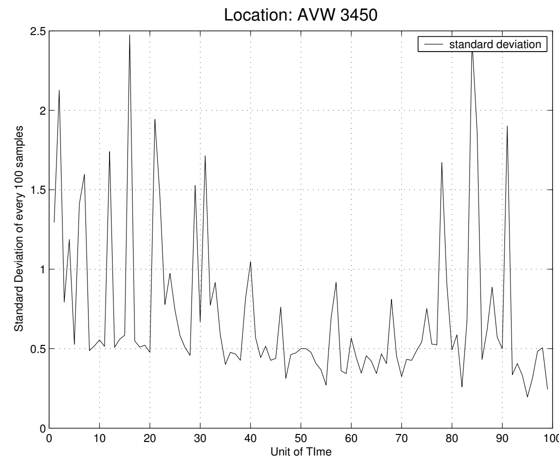
The long term temporal variations in the RSSI are observed from Figure 3.6 and Figure 3.3. These figures show the characteristics of the RSSI measured at the same location and during the same times of the day but on different days.

Figure 3.3 and Figure 3.6 show the variations in the RSSI from one day to the next, as they are collected from the same location (AVW 3450) on consecutive days. It is observed that the variability in the RSSI during 8:30 AM and 11:16 AM on the 7th of March is more than it was on the 6th of March. Table 3.3 shows the mean and standard deviation of the RSSI measured on consecutive days.

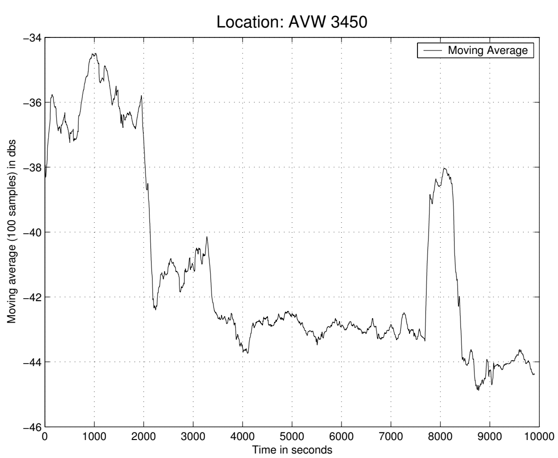
In this chapter we show the short term and the long term temporal variability in the received signal strength over time, with the help of data sets which were collected particularly for this purpose.



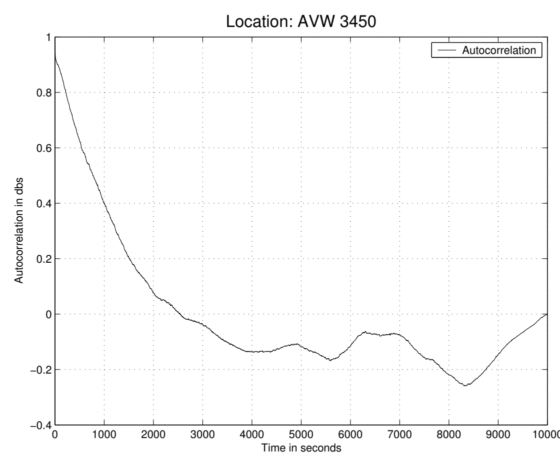
(a) Received signal strengths Vs Time



(b) Standard Deviation of every 100 sample signal strengths Vs Time



(c) Moving Average of the received signal strengths



(d) Autocorrelation Vs Lag

Figure 3.6: Characteristics of the data set collected at 8:30 AM at AVW 3450 on March 7th, 2003

Date	Mean	Std deviation
March 6th, 2003	-43.09 dbm	0.99 dbm
March 7th, 2003	-41.94 dbm	3.0493 dbm

Table 3.3: Mean and Standard deviation of the RSSI measured on consecutive days between 8:30 AM and 11:16 AM

Chapter 4

Analysis of the variability in the RSSI

The technique we use to analyze the variability in the RSSI over time, treats the sample signal strength received from an access point as a *time series*.

4.1 Introduction to stochastic processes

A time series [19] is a set of observations generated sequentially in time. It can also be treated as a *stochastic process*. A stochastic process [20] is a sequence of random variables $s(t)$ with t taking on integer values. For a stationary stochastic process, the statistical characterization of a process is independent of time at which the observation of the process was initiated. If such a process is divided into a number of time intervals, the various sections of the process exhibit essentially the same statistical properties.

4.2 Nonstationary stochastic model

In Chapter 3, we observed that the measured RSSI varies over time. This variability arises from some unknown phenomenon. Therefore, we may have to treat the successive RSSI values as a nonstationary stochastic process $s(t)$.
This variability in the RSSI can be due to two components.

- The non-stationary or temporal variability component
- The white noise component

We represent the non-stationary aspect of this variability as the moving average of the RSSI. The moving average as discussed in Chapter 3, eliminates the sudden fluctuations in the RSSI. Therefore, the moving average is a smoothing function and gives a good measure of this component.
The term noise [20] is used customarily to designate unwanted signals that tend to disturb the transmission of signals in a communication sdystem. In our analysis the white noise accounts for the noise associated with the wireless channel, accesspoint and the NIC circuitry.
We model $s(t)$, as the combination of these two components. Therefore,

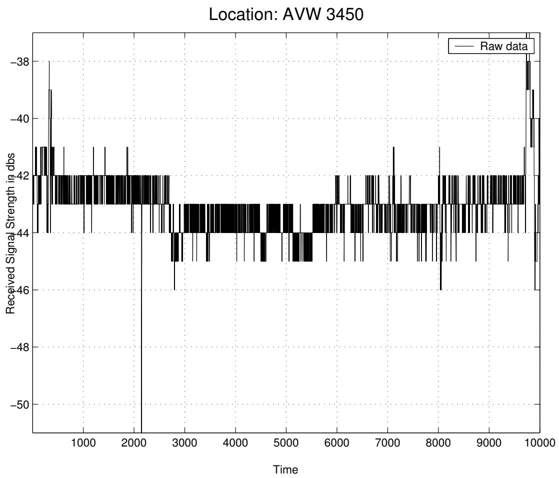
$$s(t) = x(t) + n(t) \tag{4.1}$$

where, $x(t)$ represents the temporal variability of the signal strengths and $n(t)$ is the white noise associated with the network access point. From equation 3.1, the noise is given by

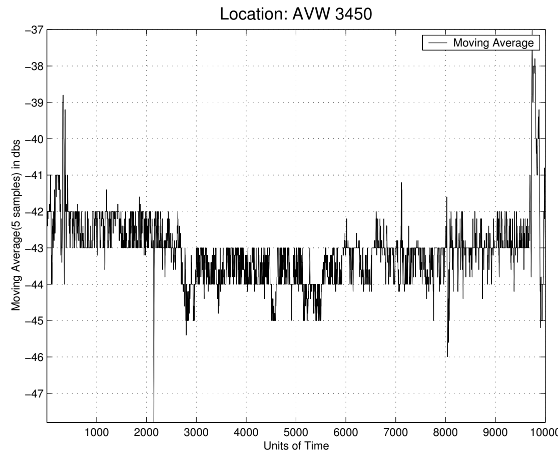
$$n(t) = s(t) - x(t) \tag{4.2}$$

From our experimental data, we have the values for the process $s(t)$. It is therefore essential to obtain a good estimate for the moving average of the RSSI, in order to compute the noise. Consider the data set from Chapter 3 collected from the 3rd floor of the Computer Science building. Figure 4.1(a) shows the measured RSSI values against time. These values as represented by $s(t)$ as discussed earlier. Figure 4.1(b) shows the 5 sample moving average of the RSSI represented by $x(t)$. Figure 4.1(c) shows the noise $n(t)$ plotted against time. $n(t)$ is obtained by subtracting out the 5 sample moving average from the original RSSI values from the raw data set. $n(t)$ and the autocorrelation function are represented by figures 3.1(b) and (c) respectively. As expected the noise autocorrelation drops to zero immediately, confirming that $n(t)$ represents random white noise.

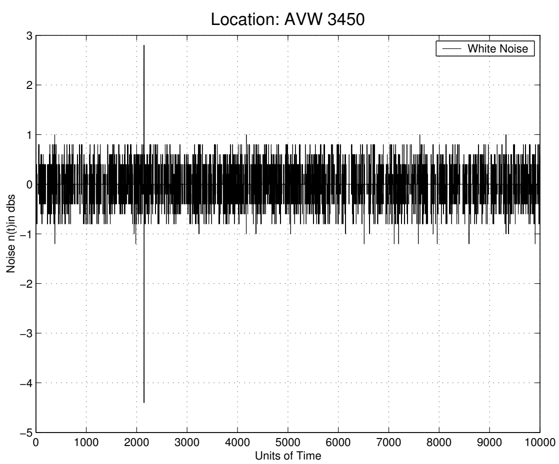
We note that the basic structure of the components remains almost the same atleast till the window size is 50. We compute the Mean Square Error (MSE) between the 50 samples moving average and the 5 samples moving average to verify this statement. The MSE gives the mean of the squares of the difference between the RSSI at each point in the 50 sample MA and the 5 sample MA plots. The components of the variability in the RSSI for the two plots are said to be closer if the MSE is lower. The MSE in the two MAs in consideration is 0.115



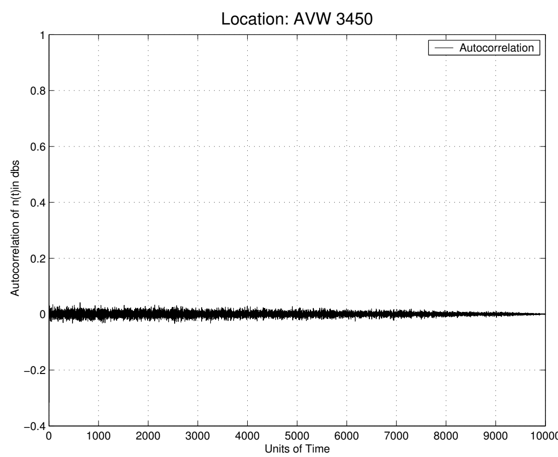
(a) Raw data set



(b) 5 samples moving average of RSSI



(c) The noise component n(t) of the variability in the RSSI



(d) Autocorrelation of n(t) Vs Time

Figure 4.1: Variability in the RSSI at AVW 3450

which is quite low. Figure 4.2 gives the difference between the two moving averages over time.

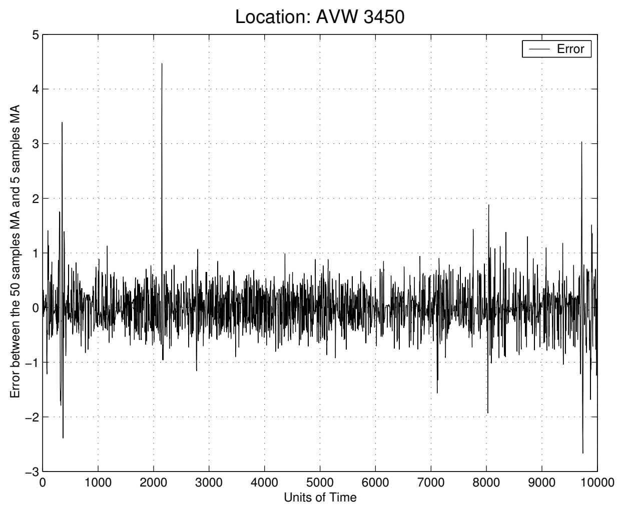


Figure 4.2: Difference between the 50 sample MA and the 5 sample MA

4.3 A reasonable estimate for the moving average (MA) value

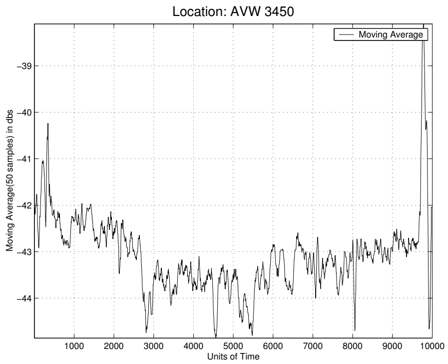
As mentioned earlier, it is essential to obtain a good esimate for the moving average. In order to obtain a good estimate for the moving average (MA) which represents the temporal variability in the RSSI, we computed the moving average with a series of varying window sizes. We arrive at a good estimate for the moving average by changing the size of the sliding window. It is seen that keeping the window size small (say 5 samples), gives a reasonable estimate for the moving average. Figure 4.3 validates this statement.

It is observed that as the window size increases(50, 500, 1000 samples) in Figure 4.3(a), Figure 4.3(c) and Figure 4.3(e), there is more structure to the corresponding noise autocorrelation function shown in Figure 4.3(b), Figure 4.3(d) and Figure 4.3(f). This is due to the temporal component of the variability. It can be seen that the correlation of the noise is distinctly different in the 50 samples moving average shown in Figure 4.3(a) and in the 1000 samples moving average shown in Figure 4.3(e). The 50 sample MA gives a better estimate for the MA than the 1000 sample MA. Table 4.1 gives the mean and the standard deviation of the noise component for different window sizes. The

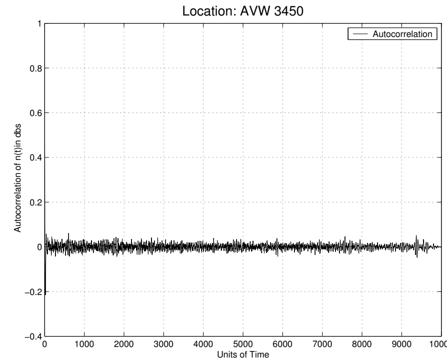
Window size	Mean	Std deviation
5 sample MA	7e-005 dbm	0.29 dbm
50 sample MA	-4.42e-004 dbm	0.52 dbm
500 sample MA	-0.003 dbm	0.75 dbm
1000 sample MA	-0.0142 dbm	0.78 dbm

Table 4.1: Mean and Standard deviation of noise component

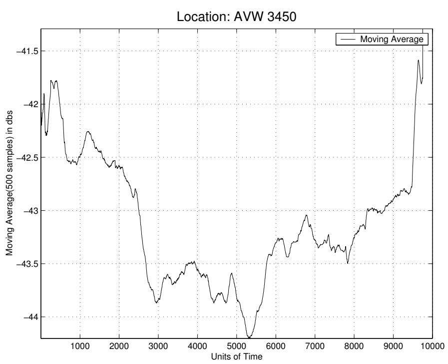
standard deviation of the noise increases with increasing window size for the moving average, which is not good for identifying the noise characteristics. For a good estimate of the moving average the deviation of the noise should be low. We can infer from Figure 4.3 and Table 4.1, that a smaller averaging window (about 5 samples) gives a better estimate for the moving average.



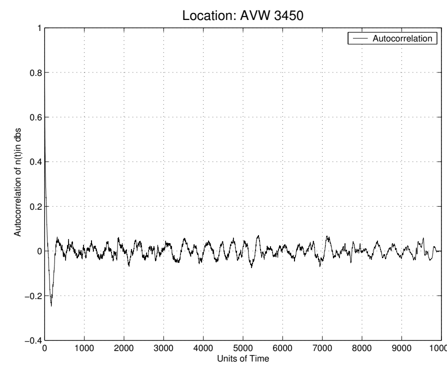
(a) 50 samples MA of the RSSI



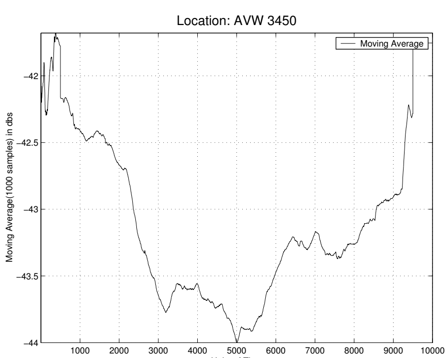
(b) Autocorrelation of n(t)



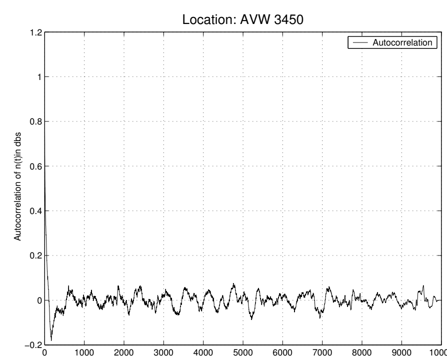
(c) 500 samples MA of the RSSI



(d) Autocorrelation of n(t)



(e) 1000 samples MA of the RSSI



(f) Autocorrelation of n(t)

Figure 4.3: MA with increasing window size and the corresponding noise correlation

4.4 Overview of the analysis

In this chapter, we chose the data from one location to study the analysis of the variability of the RSSI. We address the aspects of this variability, by using a stochastic model of the sample signal strengths measured. In the end, we arrive at a good estimate for the moving average of the RSSI, by comparing the variability components.

Chapter 5

Variability in the RSSI at different locations

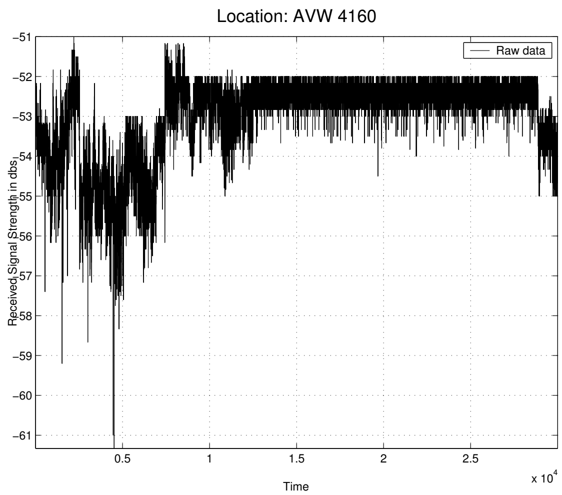
In Chapter 4, we presented the analysis of the variability in the RSSI at a single location. We repeated this analysis on test sets collected at different locations to validate our conclusions. In this chapter we present the same analysis on the RSSI measured at different locations. It is seen that the results from chapter 3 hold good for all the locations from which the RSSI measurements were made. The variability in the RSSI at two different locations measured at different times of the day are also presented in this chapter.

5.1 Location - AVW 4160

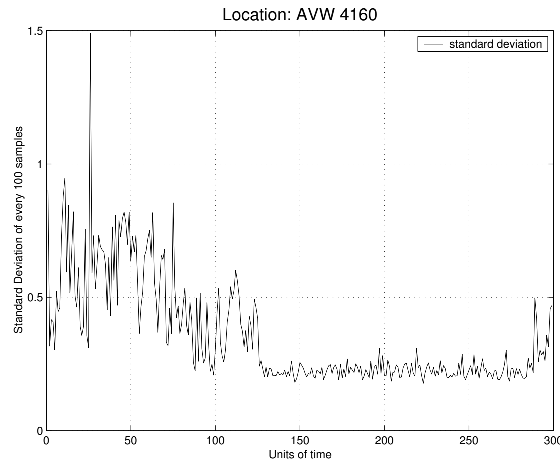
We consider a test set collected on the 4th floor of the Computer Science building at the University of Maryland, College Park. The following are the parameters which have changed from the test set referred to in Chapter 4. This test set was collected from a different access point, at a different time of the day and the measurements were made for about 8.3 hours.

- Number of samples: 30000
- Sampling rate: 5 samples taken 0.1 seconds apart every 1 second.
- MAC Address of the network access point : 00:40:96:46:01:6F
- RSSI measurements were taken between 4:03 PM and 12:15 AM on February 26th, 2003.

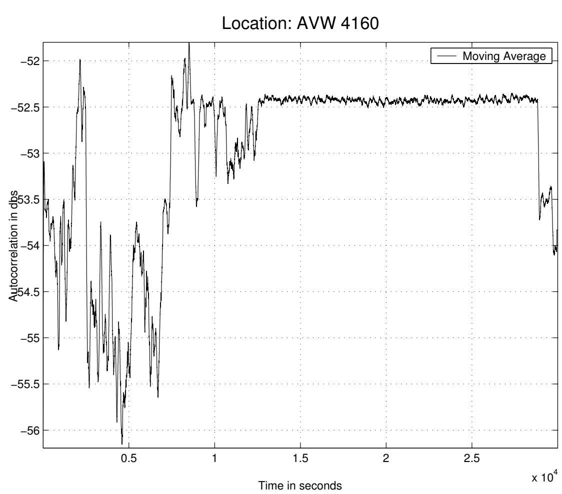
Figure 5.1 shows the characteristics of the RSSI at AVW 4160. From Figure 5.1(a), it is seen that the there is a significant variability in the RSSI especially in the first 3 hours of the measurements. As discussed in Chapter 4 the moving average represents the temporal variability component of the RSSI. The mean and the standard deviation of the RSSI measured are -52.98dbm and 1.011 dbm respectively. Figure 5.2 shows the plots of the two components which are attributed to the variability in the RSSI. Figure 5.2(a) shows the 5 sample MA of the RSSI measured from this location. The corresponding noise $n(t)$ shown in Figure 5.2(a) is obtained by subtracting the 5 sample MA in Figure 5.2(a) from the raw data set shown in Figure 5.1(a). As expected, it is observed from Figure 5.2(c) that the noise is uncorrelated and random. Figure 5.2(d) shows the error between the moving averages with window sizes of 50 and 5 samples is very low. The Mean Square Error between the two moving averages is 0.04 dbs which is negligible. Therefore we can still hold that the basic structure of the noise correlation remains the same atleast till the window size is 50 samples. Figure 5.3



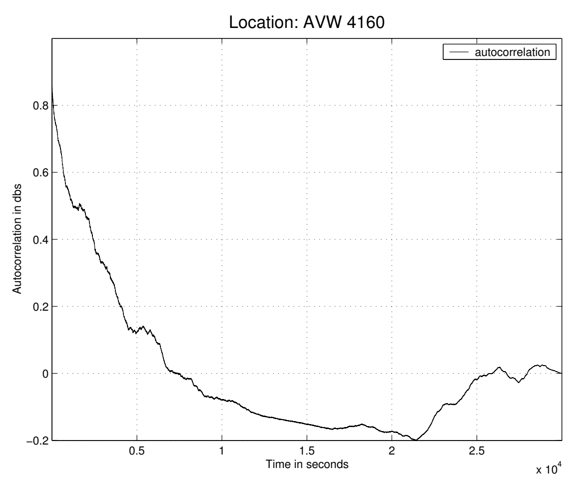
(a) Received Signal Strength Vs Time



(b) Standard deviation of every 100 samples Vs Time

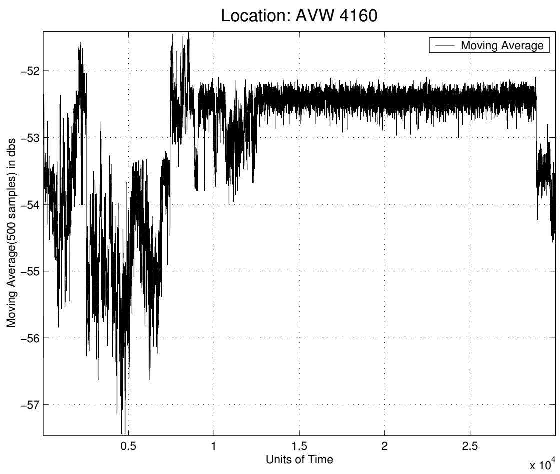


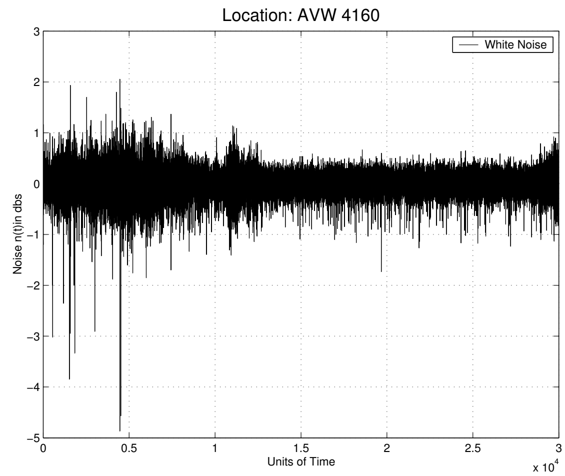
(c) Moving Average of the received signal strengths



(d) Autocorrelation Vs Lag

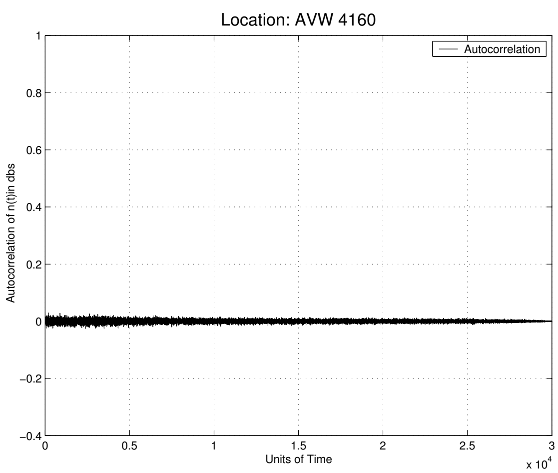
Figure 5.1: Characteristics of the data set collected at 4:03 PM at AVW 4160

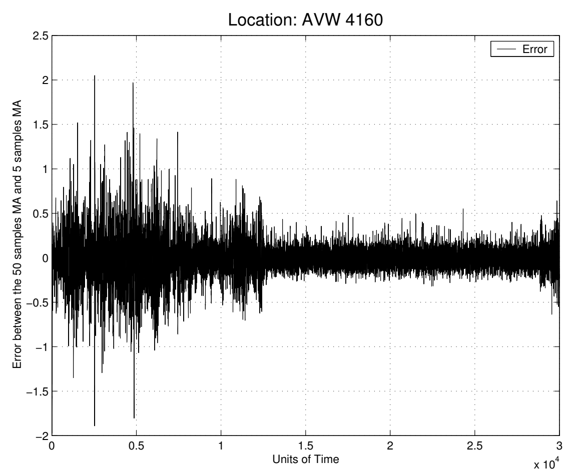




(a) 5 sample moving average of the RSSI

(b) The noise component n(t)

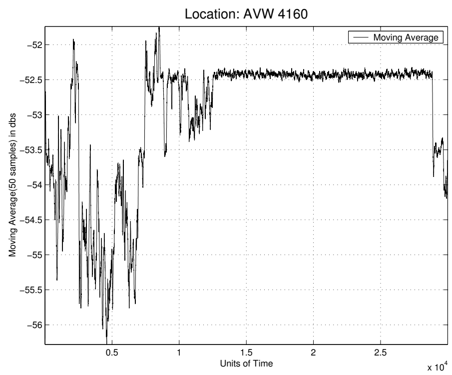




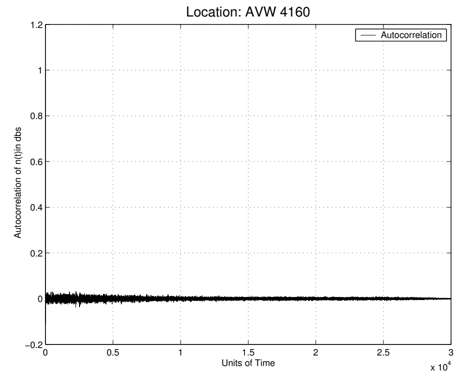
(c) Autocorrelation of n(t)

(d) Error Vs Time

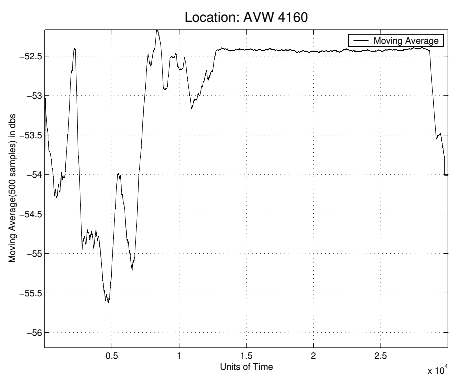
Figure 5.2: Variability in the RSSI at AVW 4160



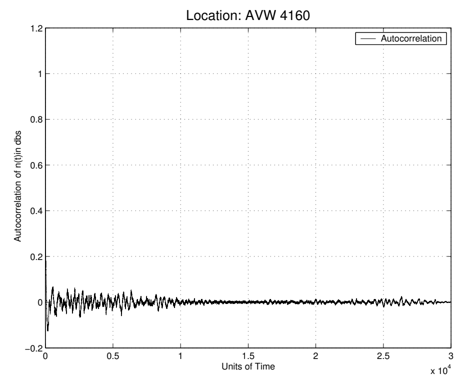
(a) 50 samples MA of the RSSI



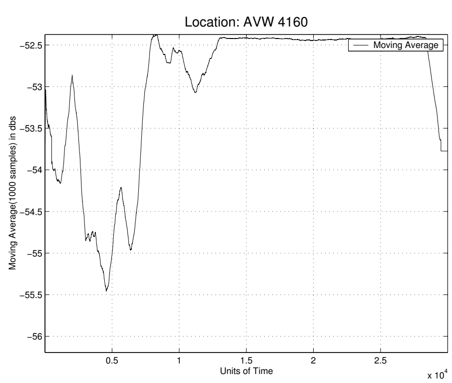
(b) Autocorrelation of n(t)



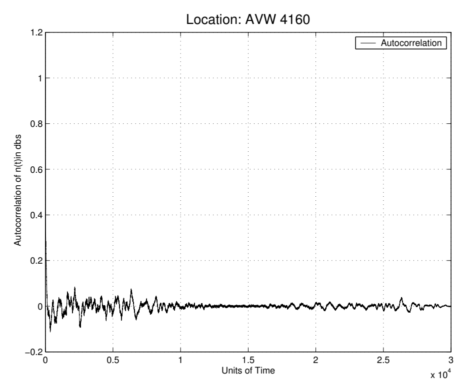
(c) 500 samples MA of the RSSI



(d) Autocorrelation of n(t)



(e) 1000 samples MA of the RSSI



(f) Autocorrelation of n(t)

Figure 5.3: MA with increasing window size and the corresponding noise correlation

shows the corresponding noise correlation when the window size is greater than 50 samples for the MA. It is observed in Figure 5.3 that the structure of the correlation in Figure 5.3(b), Figure 5.3(d), Figure 5.3(f) varies with increasing the window size for the moving average shown in Figure 5.3(a), Figure 5.3(c). Figure 5.3(e). Therefore the variability in the RSSI measured from this location behaves in the same way as it did for the location referred to in Chapter 4. As the window size increases the standard deviation of the noise increases as expected. This explains the structure of the noise correlation graph.

Window size	Mean	Std deviation
5 sample MA	-1.28e-005 dbm	0.28 dbm
50 sample MA	9.47e-004 dbm	0.36 dbm
500 sample MA	5.02e-004 dbm	0.45 dbm
1000 sample MA	-0.0027 dbm	0.48 dbm

Table 5.1: Mean and Standard deviation of noise component

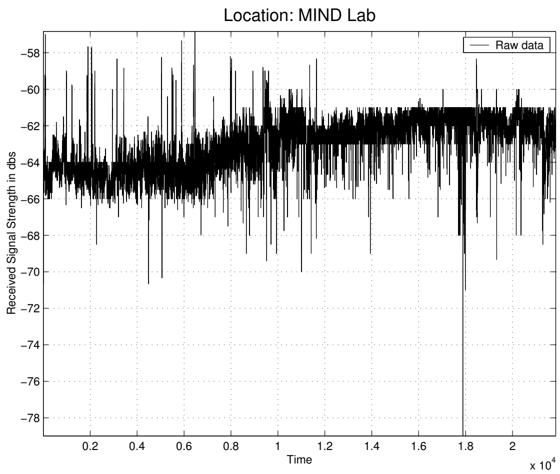
Once again, there is more structure to the correlation, as the window size increases due to the variability in the RSSI. Therefore, we infer that smaller the window size for the moving average, the better the estimate for the MA. In our analysis, the 5 sample MA gives a reasonable estimate.

5.2 Location - MIND LAB - 8400 Baltimore Avenue

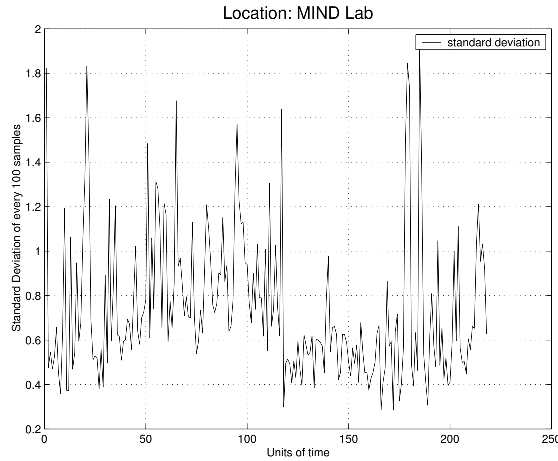
We chose another test set to verify that the results of the analysis match those from the previous test set. This data set was collected in the MIND Lab-8400 Baltimore Avenue, College Park. The RSSI measurements were made using the wireless network deployed in the building.

- Number of samples: 22000
- Sampling rate: 6 samples taken 0.1 seconds apart every 1 second.
- MAC address of the network access point: 00:60:1D:21:70:F0
- RSSI measurements were made between 6:00 PM and 12:06 AM on April 7th, 2003 at the MIND Lab.

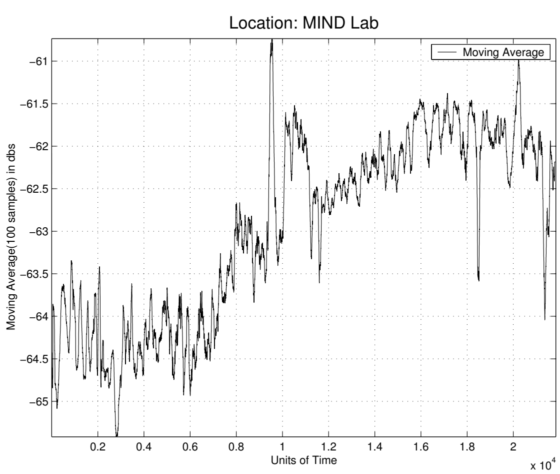
Figure 5.4 shows the general characteristics of the RSSI measured at the MIND Lab. Figure 5.4(a) shows the plot of the raw data set against time. Figure 5.4(c) shows the 100 sample moving average of the data set. The mean and the standard deviation of the measured RSSI are -62.96 dbm and 1.5 dbm respectively at this location. Figure 5.5(a) and Figure 5.5(c) shows the plots of the 5 sample MA and the corresponding noise. As expected, the noise correlation shown in Figure 5.5(b) falls to zero immediately. Figure 5.5(d) gives the difference between the 50 sample MA and the 5 sample MA. The Mean Square Error(MSE) between the 50 samples MA and the 5 samples MA is 0.08 dbm. In order to verify that smaller window sizes give better estimates of the moving



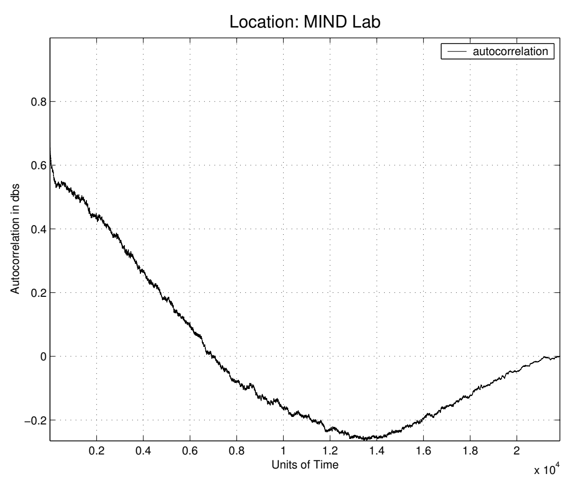
(a) Received signal strength Vs Time



(b) Standard deviation of every 100 samples Vs Time

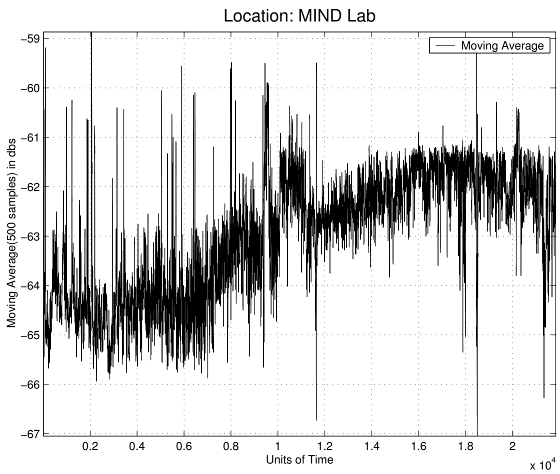


(c) Moving Average of the received signal strengths

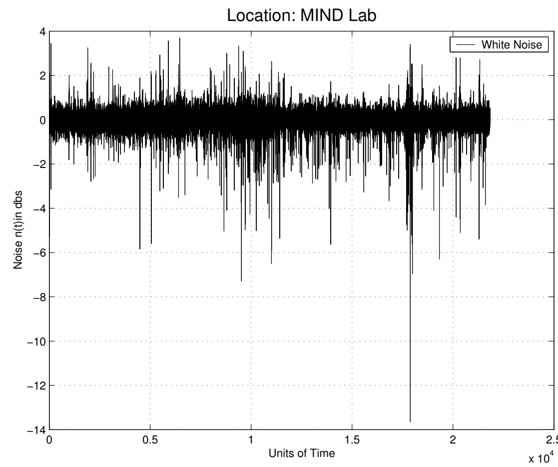


(d) Autocorrelation Vs Lag

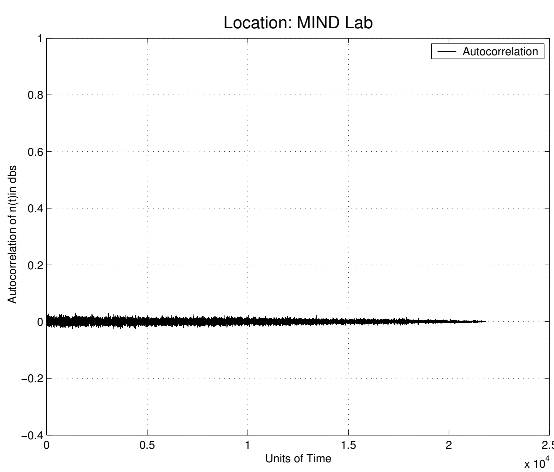
Figure 5.4: Characteristics of the data set collected at 6:00 PM at the MIND LAB



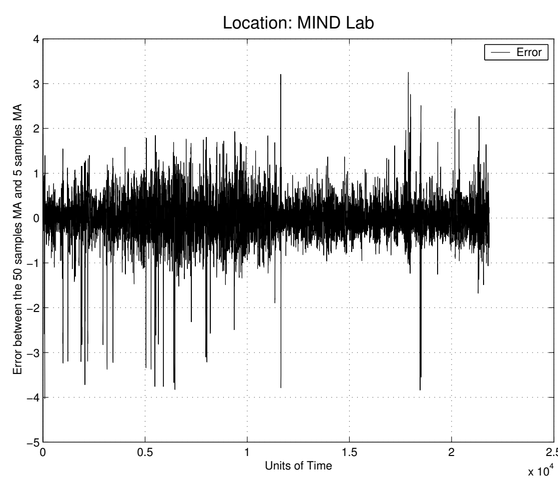
(a) 5 samples moving average of the RSSI



(b) The noise component n(t)

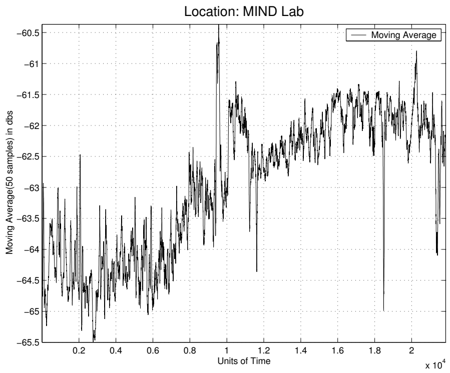


(c) Autocorrelation of n(t)

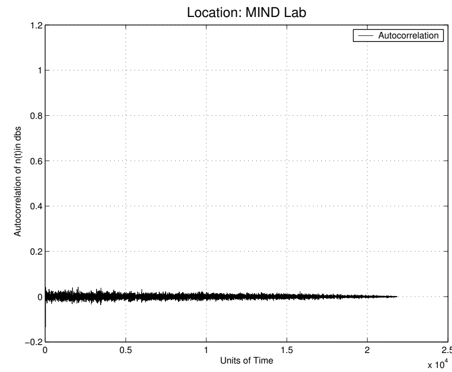


(d) Error Vs Time

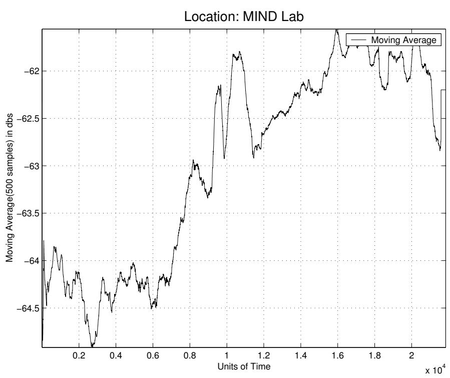
Figure 5.5: Variability in the RSSI at MIND Lab



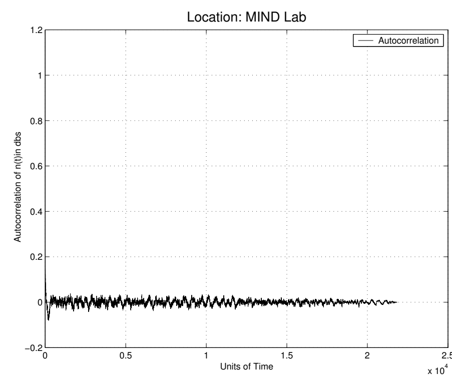
(a) 50 samples MA of the RSSI



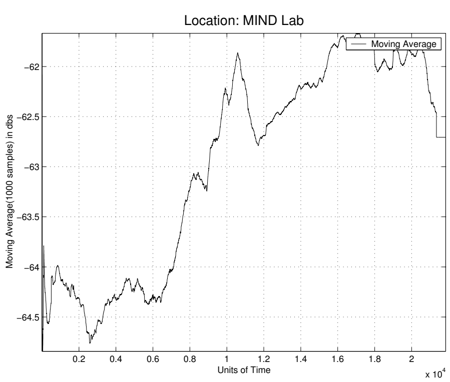
(b) Autocorrelation of n(t)



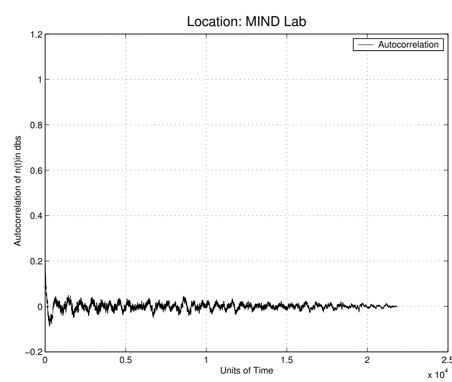
(c) 500 samples MA of the RSSI



(d) Autocorrelation of n(t)



(e) 1000 samples MA of the RSSI



(f) Autocorrelation of n(t)

Figure 5.6: MA with increasing window size and the correponding noise correlation

average, we plot the the moving averages for varying window sizes(50, 500 and 1000 samples) shown in Figure 5.6(a), Figure 5.6(c), Figure 5.6(e) along with the corresponding noise correlation in Figure 5.6(b), Figure 5.6(d) and Figure 5.6(f). The correlation graphs again show that there is more variability in the RSSI as the window size increases and the standard deviation of the noise increases with the window size for the moving average as shown in Table 5.2.

Window size	Mean	Std deviation
5 sample MA	-5.37e-005 dbm	0.54 dbm
50 sample MA	-4.37e-004 dbm	0.76 dbm
500 sample MA	-0.004 dbm	0.84 dbm
1000 sample MA	0.0069 dbm	0.88 dbm

Table 5.2: Mean and Standard deviation of noise component

We note that the results of the analysis are the same for all the data sets collected at different locations. The conclusions drawn in Chapter 4 are thus valid.

Chapter 6

Conclusions and Future Work

In this chapter, we first present the brief description of the analysis of the variability in the RSSI. This is followed by the conclusions drawn from these results of the analysis presented in the previous chapter. In the last section, we briefly outline the future work and the motivation for performing this analysis.

6.1 Results of the Analysis

The results from the data collected show that when the location at which the RSSI is measured is fixed, there is significant variability in the RSSI. This variability in the RSSI is due to

- The changes in the environment such as the movement of people.
- The noise associated with the network access point and the NIC circuitry.

It can be seen from the raw data graphs at different locations that there is more variability in the RSSI during the working hours (about 8:00 AM to 6:00 PM) of the day when there is maximum movement, than at other times of the day. This leads us to conclude that the variability in the RSSI is caused partly due to the presence of people in the vicinity.

We decompose this variability in the RSSI into two components, the non stationary component also called the temporal variability component and the noise component. The changes in the environment account for the temporal variability component. We model the RSSI values measured as a nonstationary stochastic model and use the characteristics of this model to represent these components of the variability. The moving average of the RSSI represents the temporal variability component.

6.2 Conclusions

In order to identify the noise characteristics in our system, it is essential to obtain a good estimate for the moving average of the RSSI. The results of our analysis show that a reasonable estimate for the MA is obtained when the sliding window for the average is small. From our analysis good statistics were obtained when the number of samples used for averaging was 5. We then repeated the analysis on data sets collected at different locations and found that the results were the same.

6.3 Future Work

Many RF-based WLAN location determination systems [9, 14, 15, 16], are based on the measurements of the RSSI to locate a wireless client in a WLAN. The stochastic variability of the RSSI makes it more difficult to get a good estimate of the location. The accuracy of such an estimate can be improved by taking into account the non stationary nature of the variability in the RSSI. One location estimation technology which makes use of the results presented here is Horus [6, 8]. Horus uses a similar moving average of the RSSI and takes into account the high correlation between these samples. Another technology called the Nuzzer technology [7], uses the variability in the RSSI to detect the presence of people.

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