Wireless Communications in Substations

Power Systems Engineering Research Center

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Wireless Communications in Substations

Final Project Report

Power System Monitoring Using Wireless Substation and System-Wide Communications

Part I

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Power Systems Engineering Research Center

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Preface

The Power Systems Engineering Research Center sponsored the research project titled "Power System Monitoring Using Wireless and System-Wide Communications." This project consisted of two parts:

- Part I: Wireless Communications in Substations
- Part II: Mobile Agent Software Applications

This report is Part I. Part II is in a separate report.

Executive Summary

This report concerns wireless communications for substation monitoring. Software, firmware, hardware and the transmission media have significant bearing on the performance of wireless communication in a substation environment. In this report, we focus mainly on physical-layer characteristics since this layer is the principle distinction between substation applications and other well-studied applications.

For this project, we first characterized the particular transmission media for a substation environment. This characterization was based on previously published measurements as well as on assumptions and analyses found in the standards and technical literature. Then, we investigated the corresponding probable impacts of the substation environment on the effectiveness of spread-spectrum modulation techniques. Based on this work, we concluded that realistic assessment of the effectiveness would be best found through field testing.

Several scenarios were considered for substation data measurement and communications. The desired performance statistics were identified for each test and the required measurement devices, configurations and operation modes were carefully selected, programmed and modified to meet testing objectives. The actual field tests were subsequently conducted in several substation yards and the recorded data were acquired for post-processing. Statistical analysis of the collected data suggests that classical distributional analysis that is widely used is not appropriate unless incorporated with time-series analysis.

We investigated the potential impacts on wireless communications quality of the slow-varying and fast-varying electrical and environmental processes in substations. Based on the results, we developed general recommendations for candidate wireless systems. For example, we noticed that signal level variations have a stronger dependency on substation location (e.g. in rural or industrial regions) rather than on variations in substation power delivery. Furthermore, this report implicitly presents a methodology for wireless site surveys that can be adopted for related power system applications.

We studied the noise sources and their statistical behaviors in a substation environment. Given these noise profiles, the presumed conditions under which regular wireless systems are designed may not hold true anymore. To investigate this, we considered the worst-case (i.e., worst noise) analysis for these two core modulation formats: Direct Sequence Spread Spectrum (DSSS) and Frequency Hopping Spread Spectrum (FHSS). According to this worst-case analysis, given the same noise power, the performance of the DSSS indicates approximately 5 dB superior to that of FHSS. However, assessment of the likelihood of the occurrence of these worst-case situations in a substation requires field measurements of the noise profile. The result of the measurement not only affects decisions on selecting one of these modulation schemes, but also reveals the capacity bounds for the wireless network.

Table of Contents

Table of Contents (continued)

Table of Figures

1. Introduction

1.1 Background

Today's available processing power and well-developed signal processing algorithms promise a new paradigm for more reliable communications serving power generation, management and transmission.

The following list indicates some basic advantages of using a wireless system over a cabled system in substation applications:

- Cheaper than (often-expensive) cabling version
- More relaxed constraint on isolation level and clearances
- Portability/mobility
- Reduced susceptibility to unstable grounds
- Convenience and ease of installation
- Easier implementation of higher Insulation Protection (IP) of instruments
- Extend range and flexibility of data acquisition and I/O (configurations and locations).

Substation switching operation, corona effect, and gap discharge breakdown are among the major causes of high frequency electromagnetic interferences which directly impact wireless communication quality. Furthermore, the radio wave propagation influences wireless communication in substations in several ways. Antenna gain, size, and electrical isolation and grounding are among the major concerns in this project. The impacts of external environmental conditions (such as a wide fluctuation of temperature, high humidity, excessive vibration, and significant pollution) are also of interest.

A robust, easy-to-implement, cost-effective, and feasible wireless technology as the physical layer of the substation communication is the focus of this project. The above requirement entails a set of initial criteria used in our research.

The existence of high power fields and transients in these environments should be carefully studied as it may impact the wireless link. A number of investigators have already contributed to understanding the detrimental effects of switching transient fields on the VHF, UHF and other radio band channels ([1], [2] and [3]). This project tries to offer the most appropriate wireless strategy for the substation environment. Equipment layout, metallic bodies of obstacles, multi-path propagation, antenna displacement, robustness and security are among the major issues which call for a separate analysis for this special application with respect to other widely considered wireless system applications. To our knowledge, no specific experiment has yet been done on the detrimental effects of impulse power station noises on the Industrial, Scientific and Medical (ISM) frequency band wireless channels that are dedicated by the FCC for such purposes.

To perform an accurate comparative analysis among different wireless implementations requires measurement and inspection of a wide spectrum of modulation, coding and implementation techniques. The existence of several protocols at different network layers makes it almost infeasible to compare systems in a sensible manner at the protocol level.

A better alternative is to trace the behavior of existing implementations and apply the lessons learned to evaluate new designs. This is the approach adopted in this project. We first improved our understanding of the noise profile in the substation environment as well as the wireless channel behavior. Then, we tried to develop realistic models, and validate them. We tried to offer a methodology for the design of a wireless system based on a set of measurements, observations and theoretical analysis. This approach will also provide us a way to implement realistic network and mobile configurations for comparing existing protocols and algorithms that are used in the off-the-shelf devices. We contacted several vendors that supply the wireless devices and traced other similar studies to build an appropriate, experienced-based knowledge for the project.

1.2 Overview of the Problem

Vast commercial application of wireless communications has required comprehensive theoretical and practical studies in this area. Except for limited applications like satellite communication, the channels are identified to be interference-limited due to the multiplicity of wireless devices in the corresponding spectrum.

The magnitude and the effect of ambient noise, juxtaposed to interferences, differ from one place and time to another. Several measurements have been comprehensively conducted over the last 35 years [3]. On-going technological changes, channel utilizations, atmospheric impacts, and other parameters necessitate a frequent, updated measurement, and comprehensive analysis campaign. This analysis might suggest considerable changes to the man-made noise model that is presently used in radio link design. Proximity, power settings, number of the wireless devices in the network, and even the choice of modulation and coding format closely depend on the magnitude of noise and interference impacts. For instance, if the channel is identified as an interference-limited channel, increasing the power setting will not improve the link quality, while power setting is a crucial factor in noise-limited channels [4]. For instance, if we doubled the transmission power level from all wireless devices, they would cause twice as high an interference level, leaving us with the same Signal-to-Interference ratio, and thus the same bit-error probability.)

1.3 Report Organization

The first part of this report investigates the raison d'etre of this project. We will justify the necessity of considering a particular strategy for analysis of a wireless link for substation applications. In this part, we shall introduce some basic knowledge about the so-called man-made noise and its probable detrimental effects on the link quality. Some already-developed noise models are also presented in this part. Identifying the measurement objectives, the measurement plan will be explained in the third part of the report. In this section, first few key parameters that we shall use in our analysis are introduced, then the available methods of measuring these parameters are proposed and the appropriateness of deploying these methods are investigated. In the fourth part of the report, the empirical results are presented and analyzed. Based on the post-processing in this subsection, a generalized methodology for a wireless survey in the substation environment is proposed. The post-processing of the recorded data suggests a few fundamental recommendation practices which should be considered by wireless design engineers for these particular environments. The resulting specifications also help system engineers and field technicians to efficiently evaluate or configure the settings of the off-the-shelf radios, or to consider practical preferences among the available radios, ensuring more reliability for monitoring applications.

2. Theoretical Analysis and Technical Observations

2.1 Introduction

In this part of the project, we have investigated the impact of the transient noise on the Direct Sequence Spread Spectrum (**DSSS**), and Frequency Hopping Spread Spectrum (**FHSS**). These two spread spectrum techniques are the core modulation schemes for Industrial, Scientific and Medical (**ISM**) frequency band communication. We have first identified the noise sources and their statistical behavior in a substation environment. Given these noise profiles, the initial conditions under which regular wireless systems are designed, may not hold true anymore. This further serves as the justification for selecting the type and method of measurement that is discussed in the next section. The measurement helps us understand the detrimental impact of the noise on selected modulation schemes.

2.2 FCC Regulations Regarding ISM Frequency Band Usage

The Federal Communication Commission (FCC) has allocated three frequency bands in Part 15 of the FCC Regulations to operate on a secondary basis [5]. The primary users are government systems, and industrial, scientific, and medical (ISM) users. While the FCC favorably treats spectrum usage, it sets certain technical restrictions on transmitter power and modulation. Part 15 mandates that unlicensed equipment must not cause harmful interference to the primary users while allowing spread spectrum devices to operate at up to one watt (i.e., 30 dBm) of transmit power with an Effective Isotropic Radiated Power (EIRP) not to exceed 36 dBm (i.e., 4 Watts). These devices must be able to accept any harmful interference (<1 W) to their own operation. Given these strict regulations, Part 15 is a welcoming ticket for spread spectrum users since a spread spectrum device with an output power of just 0.1 Watt (at 900 MHz) can have an outdoor coverage transmit range of up to one-half mile. Non-spread spectrum devices in this frequency range are limited to approximately 0.07 watts of output that can operate approximately up to 300 ft outdoor range.

2.3 Investigation of the EMI impact on Wireless Channel

One particularly detrimental characteristic of the channel of interest is the presence of ambient electromagnetic interference (EMI) produced by power lines and power switching devices. The electromagnetic fields radiated by these interfering sources may occur as spurious signals and, hence, are a source of noise [6].

Such noise is often impulsive in nature, and is thus distinguished from the thermal Gaussian noise produced in the receiver itself. A pulse that is **K** dB (**K** is defined according to the received signal-to-noise ratio) greater than the RMS steady noise is usually considered to be impulse noise. Pulses below this level are merely peaks of the steady noise. Impulse noise transients are counted when they exceed a specified threshold.

The followings are some facts about the impulse noise.

- Impulse noise is measured in counts per unit of time. A count is an excursion of the noise waveform above a specified threshold level. At the end of the counting period, the counter will display the number of times that noise impulses exceeded the threshold.
- Impulse noise is loosely defined as the threshold at which the count is an average of one per minute. (Actual specifications are more complex and specify 5 or 15-minute intervals.)
- Impulsive noise is often more important to determining system degradation than Gaussian noise, especially at VHF frequencies and higher.
- Impulse noise is also sometimes measured using a holding tone. The holding tone is useful when the equipment sequentially measures impulsive noise, hits and jitter.

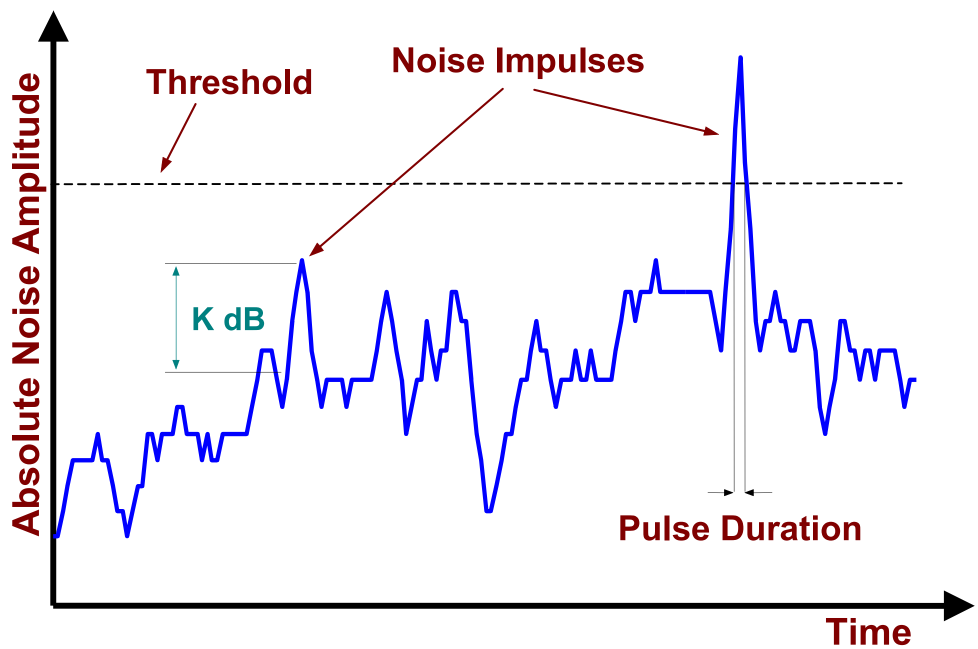

Figure 1 A simple base-band model of impulsive noise

2.4 Noise Sources in Substations

We refer to the term noise as an undesired disturbance within the frequency band of transmission. In radio transmission we are especially concerned about the electromagnetic noises which are time-varying in nature. These noises can impact our transmission in two ways. They can propagate to our devices through electrical connection via power supplies. Caution should be used to either isolate the wireless circuit by using battery-powered devices or to use high-frequency-stabilized power supplies to mitigate this effect. The other way of noise contamination is through radio wave radiation for which the impact is stronger.

There are two main types of radiated radio noise sources in substations: [7]

a) Gap breakdown

b) Line conductor corona.

Gap discharge radio-noise is produced by a rapid flow of electric current in the air gap between two points of unequal potential occurring on electric-power equipment. The current-surge accompanying avalanche ion production is of very brief duration, consisting of one or several impulses persisting for a few nanoseconds. These noises are strongly impulsive in nature. The statistics of this phenomenon is directly related to the electrical incidents, tripping or switching. In power-line applications, random noise (often considered Gaussian) is a component of the total noise caused by the discharge [8].

Corona discharge is also a threshold transition process that requires that a minimum potential gradient in the vicinity of a charged object be exceeded before the effect is manifested. The charge object need not be an electrical conductor.

Either source may be comparable or exceed the noise levels of other man-made noise sources. A strong impulsive noise produces a uniform disturbance over our useful frequency spectrum. A noise source might create impulsive noise in one system and a random noise in a different system. The radio noise produced by these phenomena exhibit RF components of substantial magnitude in the UHF-TV band (470-806 MHz) [3].

2.5 Review of the Noise Impact on Spread Spectrum Schemes

2.5.1 DSSS

The transient noise caused by the switching activities in a substation, can be modeled as a sharp pulse. For simplicity, we normalized the transmission time slots to one. We assume that the pulse width is greater than $\boldsymbol{T_b}$. This is a valid assumption for data communication in ISM frequency bands.

The bit error probability is [4]:

$$P_b = \rho \,.\, Q(\sqrt{\frac{2E_b}{N_j}\ \rho})$$

where $\boldsymbol{P_b}$ is the Bit Error Probability (BER), $\boldsymbol{E_b}$ is bit energy, ρ is the fraction of the time that the transient pulse is considerably high, and $\boldsymbol{N_j}$ is the single-sided noise power spectral density, calculated from:

$\boldsymbol{N_j = J/W}$

in which $\boldsymbol{J}$ is the total time-average power of the transient noise in the bandwidth frequency of our spread spectrum transmission $\boldsymbol{W}$. The detailed calculation can be found in [4]. Figure 2 shows the Variation of BER with respect to ρ in DSSS.

For data devices, BER should be typically less than 10^{-5}. Proper source coding usually decreases this amount. According to the above equation, the following will achieve a low BER:

1- Increasing $\boldsymbol{E_b}$: FCC set certain limitations on increasing the signal power.

2- Decreasing N_j: This means decreasing the noise or other interferences that account for noise. Hence, this term is related to other devices which share the same frequency as well as the substation noise.

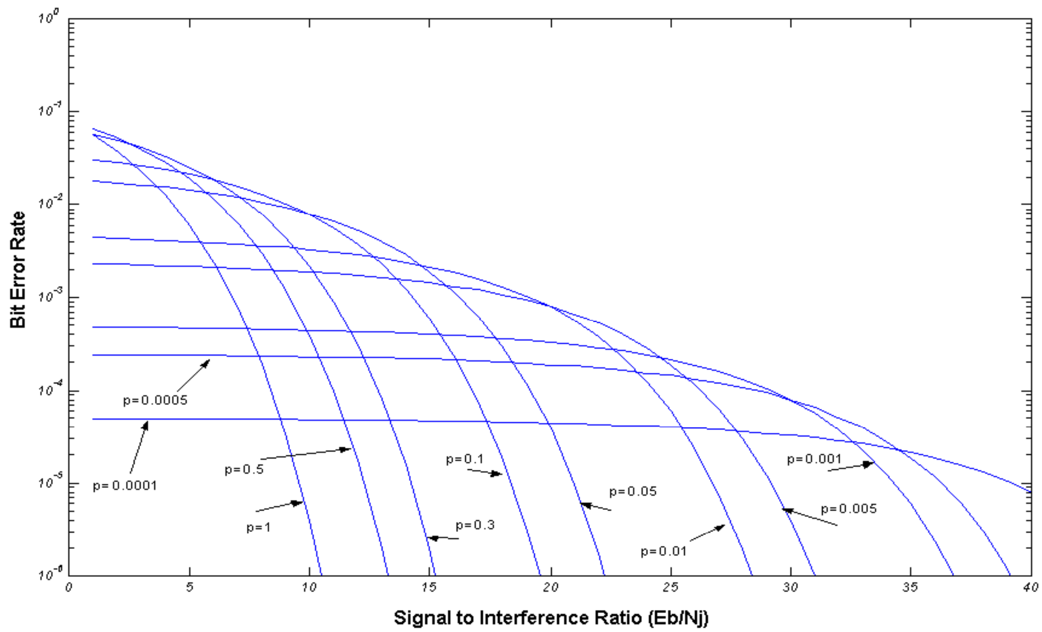

Figure 2 Variation of BER with respect to ρ in DSSS

Differentiating the above equation with respect to ρ, the value of ρ that maximizes the bit error probability is calculated as follows:

$$P_b^{\,*} = \begin{cases} \dfrac{0.083}{\dfrac{E_b}{N_j}} & , \dfrac{E_b}{N_j} > 0.709 \\ Q\left(\sqrt{\dfrac{2E_b}{N_j}}\right) & , \dfrac{E_b}{N_j} \leq 0.709 \end{cases}$$

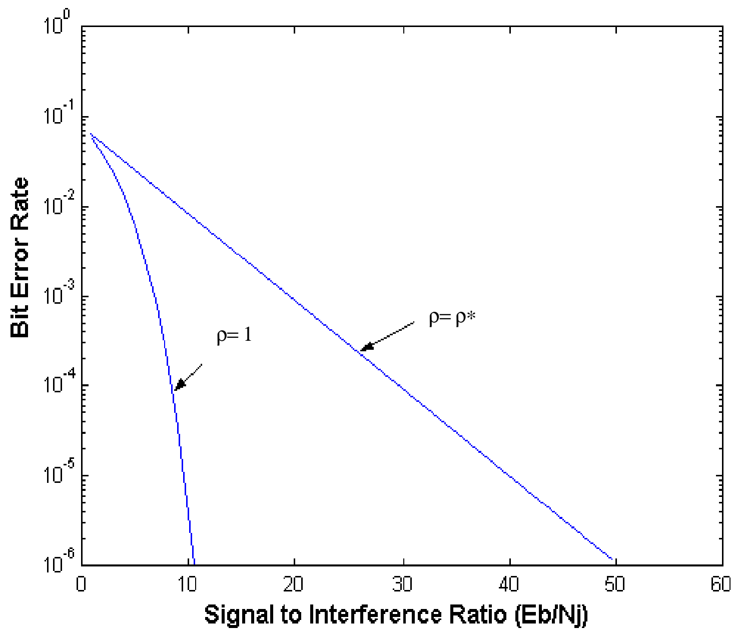

Figure 3 Comparison between a constant power noise ρ = 1 and worst-case high power transient noise ρ = ρ*

Figure 3 shows the distinct difference between a constant power noise ρ = 1 (which is often the case for calculating the performance of the DSSS) and our worst-case high power transient noise ρ = ρ*.

The 40 dB difference in the signal-to-noise ratios (SNRs) between these two cases shows that high power transients can do much more harm to the DSSS system than the (usually considered) constant power noise. Analyzing the figure shows that there is a point at which the DSSS radio performance fails drastically with a decrease in the signal-to-noise ratio (which is very likely during power line switching activities).

2.5.2 FHSS

As for DSSS, FHSS performance can be drastically degraded for a fraction of the transmitted bits, resulting in a high average error probability. In FHSS, and in the presence of multi-tone or partial-band noise, the signal corrupts one (or a few) of the frequency hops. The only difference in our methodologies for analysis for DSSS and FHSS emerges from the fact that the worst-case noise for the FHSS is partial band noise rather than impulsive noise for the DSSS.

The bit error probability calculation for FHSS is given as:

$$P_b = \frac{\rho}{2}\exp\left(-\frac{E_b}{2N_j}\rho\right)$$

Figure 4 shows the impact of the partial-band noise on bit error rates versus different signal to interference ratios.

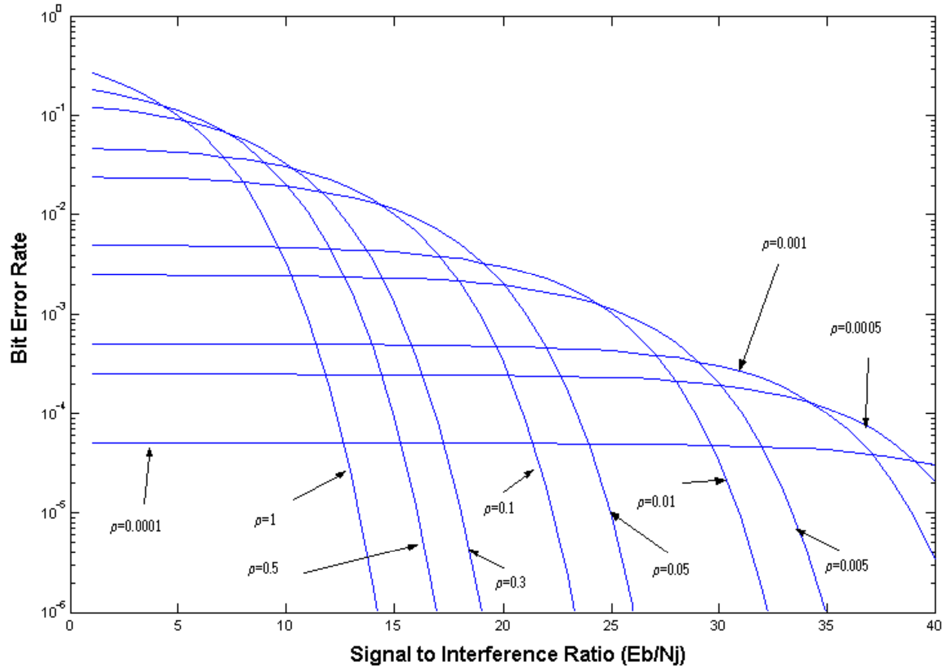

Figure 4 Variation of BER with respect to ρ in FHSS

Similar to DSSS analysis, the worst-case calculation amounts:

$$P_b^* = \begin{cases} \dfrac{e^{-1}}{\frac{E_b}{N_j}} & , \dfrac{E_b}{N_j} > 2 \\ \dfrac{1}{2}\exp\left(-\dfrac{E_b}{2N_j}\rho\right) & , \dfrac{E_b}{N_j} \leq 2 \end{cases}$$

Plotting this value indicates a 40 dB difference between the broadband noise and the worst-case partial-band noise for the same power (Figure 5).

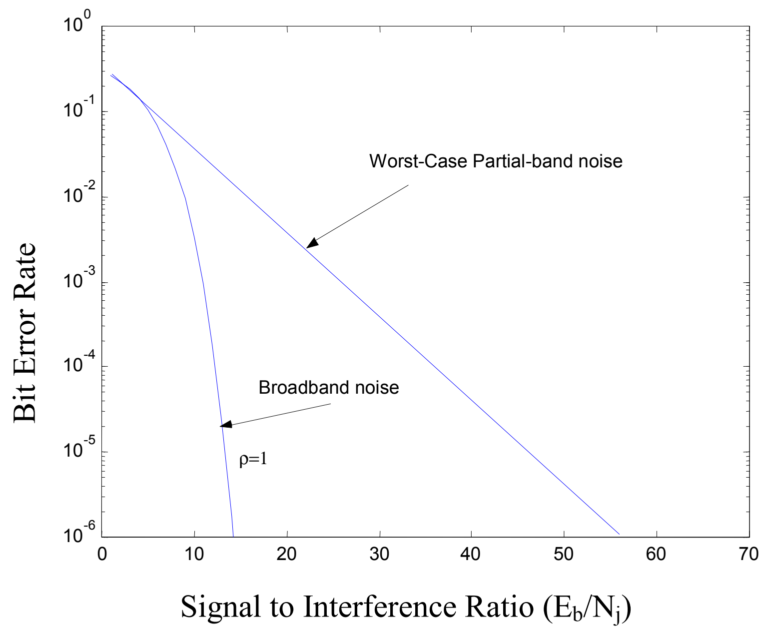

Figure 5 Comparison between the broadband noise (ρ = 1) and the worst-case partial-band noise (ρ = ρ*)

2.5.3 Crude Comparison of DSSS and FHSS

A true efficiency tradeoff between FHSS and DSSS has not been done under any comprehensive assumptions. FHSS, loosely speaking, averages the interference and it is more appealing when continuous spreading bandwidth is not available. FHSS uses a form of nonlinear modulation from the implementation perspective and consumes less power, while DSSS is a linear process and requires more power.

To juxtapose the performance of these schemes, we considered the worst-case (i.e., worst noise) analysis for the two core modulation formats: FHSS and DSSS (Figure 6).

The partial band noise impact on the uncoded FHSS system is analogous to the impulsive noise effect on the uncoded DSSS mentioned earlier. In both analyses, there is a considerable degradation by concentrating more of the noise power on the fraction of the transmitted uncoded symbol. There is a notable difference in the definition of the fraction □ in DSSS analysis and in FHSS analysis. For the uncoded FHSS system, impulsive noise transients and partial-band noise have the same detrimental effect on performance. The combination of these two types of noises, given constant noise power, would give the same result as the partial-band noise alone.

The text above provided the comparison of uncoded spread spectrum techniques. In practice, forward error correction codes enhance the performance of both modulation schemes.

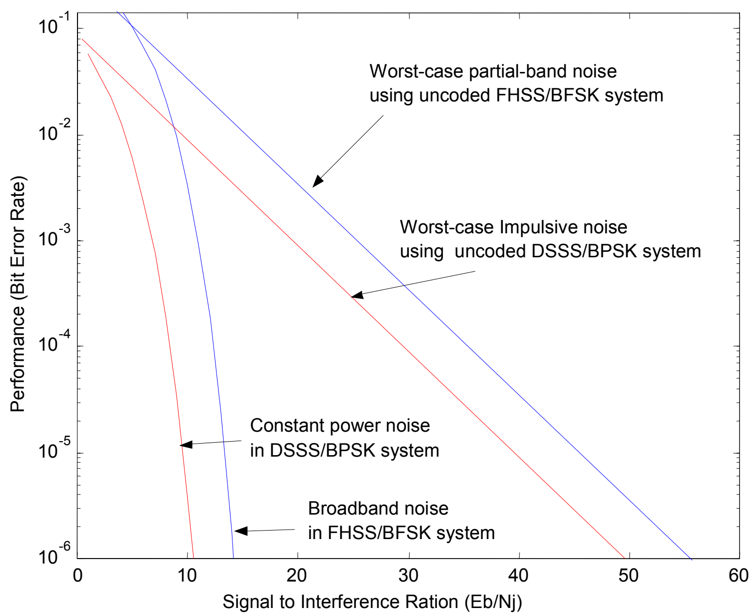

Figure 6 Worst-case performance comparison of FHSS and DSSS

2.6 Scenarios in which Spreading the Spectrum is Inefficient

In section 5.6 of this report, it is noted that tetherless batteries combat high power traveling waves in AC power supply of the radios. In these cases when the power is limited, it is more efficient to use Time Division Multiple Access (TDMA) or Frequency Division Multiple Access (FDMA) since these techniques do not contribute to the noise by having the devices jam one another [9]. For substation applications, at this moment, it might seem that this case is out of the question due to almost ample access to the regulated power supply. As an afterthought, when the number of wireless devices in the network increases, the system designer may find the overall power consumption of the wireless network not negligible anymore. Furthermore, the lower the amount of power that is injected to the wireless channel, the more the capacity is available for the wireless network. Fortunately, today most spread spectrum devices are equipped with power control schemes which not only reduce the power consumption of the radio but also avoid excessive interference pollution of the bandwidth spectrum.

2.7 Conclusion

The worst-case noise for the FHSS is partial band noise while that of DSSS is the impulsive noise. According, to this worst-case analysis, given the same noise power, the performance of DSSS is approximately 5 dB superior to that of FHSS. However, assessing the likelihood of the occurrence of these worst-case situations in a substation requires field measurements of the noise profile. Field measurements provide useful information for selecting a modulation scheme and reveal the capacity bounds of the wireless network.

3. Field Measurement

3.1 Introduction

This section provides the background for identifying important qualifying parameters of radio transmission, understanding and quantifying probable errors, and codifying the effects of these errors on a specific reported value. In this project, we focus our survey on substation noise impacts in the 900 MHz Industry, Scientific, and Medical (ISM) band, and the 2.4 GHz frequency band.

Measurement setups have been formed to enable long-period test runs in different substation yards to inspect the long-time impact of substation noise on the wireless channels [10]. The variations of the noise profile in the substation have been closely observed and discussed in this survey.

3.2 The Principal Parameters

Telecommunications engineers are generally concerned with link budget and time dispersion. The link budget is identified by the amount of received power that may be expected at a particular distance or location from a transmitter. It determines fundamental quantities such as transmitter power requirements, coverage areas, and battery life. Time dispersion arises from multi-path propagation whereby replicas of the transmitted signal reach the receiver with different propagation delays due to the propagation mechanisms described above. The time-dispersive nature of the channel determines the maximum data rate that may be transmitted without requiring equalization. The mean excess delay (τ) is the first central moment of the power delay profile and indicates the average excess delay offered by the channel. The RMS measure of the spread of power about the value of τ, $\sigma(\tau)$, is the most commonly used parameter to describe multipath channels.

In this survey, we mainly focus on the variations of the levels rather than the absolute magnitudes of the measured parameter, unless otherwise explicitly expressed. In most wireless design quality analysis, the magnitude of the Signal to Noise ratio (S/N) and Signal to Interference ratio (S/I) are of more importance than the absolute values of signal, interference and noise levels individually.

We define “signal” as the wanted message, or the object of the particular reception that is conveyed over the wireless link. Furthermore, the term “noise” addresses electromagnetic disturbances and unwanted signals which do not carry relevant information (i.e., interferences) or cannot be interpreted as a useful portion of the message by our receiver device under the test (i.e., multipath components). A good receiver (e.g., RAKE receivers), however, can convert the latter part into useful signal. The average noise level indicates the level of background noise and interference at the measurement site.

Given the stationariness of the devices during our measurement run and the dominance of substation noises, we ignore the (slow/fast) fading components in this application. Furthermore, in power-line applications, the random noise is considered to be a component of the total noised caused by a discharge [8]. We expect to observe three types of noises in substation applications: background noise, incidental impulsive noise and unwanted signals.

We define the background noise as the total sources of disturbances in the link and the measurement system independent of the presence of the signal. The Trichel streamers and glow corona also contribute to this background noise. The incidental impulsive noise is due to the gap breakdown discharge phenomena (often caused by circuit breaker tripping) that have been discussed in the noise source section of this report. The ideal method of tracking these phenomena is to apply fast response measuring devices (i.e., peak detectors) for long runs and recoding the receptions during tripping as well as investigating the seasonal effects and climate impacts.

Most wireless devices interpret the signal levels using RSSI values, which are defined by the firmware of the device. Clear-cut conversion formulas for these devices are barely available since the RSSI values are subject to time invariant non-linearity. The vendors usually provide the RSSI to dBm conversion table instead. New devices have the ability to report the signal levels in dBm format. RSSI is defined by the firmware design and each manufacturer calculates the RSSI differently for their devices. In this project, we convert the values to dBm values and then to voltage levels because our analyses are based on these quality parameters. Measuring the average packet rate also reveals the percentage of data packets that are received on the first try at each radio site.

The survey duration should be long enough to include any seasonal trend. Examples of the sources of these trends are weather cycles, seasonal interferences from other devices using the same frequency bands, and diurnal variation of electrical power consumption (which may lead to noise variations). In order to study these cyclic patterns, corresponding data of the candidate-influencing factors should be prepared and an analysis should be deployed to measure the correlation of noise variations to these sources.

3.3 The Accuracy of the Measurement

Measurement quality is quantified in terms of bias, short-term variability or instrument precision, day-to-day or long-term variability, and uncertainty. The continuation of quality communication is guaranteed by a statistical control program that controls both the short-term variability or instrument precision, and long-term variability, which controls bias and day-to-day variability of the process. The purpose of this characterization of quality is to develop an understanding of the sources of error in the measurement process and how they affect specific measurement results.

Assembling the components of the above-mentioned setup for the purpose of measurement is hard for any one-shot measurement. Even movement of the connecting wires would cause the setup to deviate from the correct calibration. There are few compact measurement devices for this purpose on the market that are designed for a drive-in type measurement.

3.4 Testing Practices

We conducted four separate sets of measurement experiments in 34.5 KV, 138 KV and 345 KV yards of three different substations. The experiment setups were designed based on the technicalities involved in the recording process, multiplicity of measuring parameters, availability of testing devices, and the specialty of the environment under the test.

We managed to record empirical data from two of these experiments. The other two resulted in our further hands-on knowledge about the most appropriate and yet available measurement procedure and setup in this particular environment. In this report, we consider it fruitful to elaborate on all of our measurement setups. The experiments, the reasoning behind selecting the specific setup, and the resulting outcomes are discussed in the following section.

3.4.1 Propagation Profile Measurement

In most analog networks, measuring the transmission parameters is straightforward. Power levels are checked by a simple setup that can reveal coverage and network holes. Since in most of these analog transmission networks, single frequencies are used for transmission, checking each single frequency almost suffices to judge transmission quality of that channel. Although the spectrum analysis and the single frequency measurement in digital wireless protocols (e.g., spread spectrum technology) can reveal transmission impairments, these methods are unable to detect digital modulation impairments. For example, with spread spectrum technology, information is spread over a wide range of frequencies leading to greater security and less interferences. Measuring raw power does not always reveal problems with such systems. Special tools are required to measure quality parameters such as signal to interference ratio, bit or packet error rates, and pilot pollution.

We expect to have more accurate physical details using a channel sounder than parametric statistical models. A collection of power delay profiles gathered by this device helps us quantify time dispersion (e.g., maximum/mean excess delays, and RMS delay spread). Measuring the impulsive band-gap noises and their impacts on the digital wireless link is of our next concern. For this purpose, a set of high voltage switching manipulations is required.

The following describes the SIGTEK ST-515 channel sounder (which was available to us) regarding the abilities of these devices in propagation measurements.

> "The ST-515 Propagation Measurement System is designed to characterize a wide range of signal environments. Its multipath resolution and sensitivity handles wide coverage environments (Figure 7). The ST-515 uses a Direct Sequence Spread Spectrum based propagation measurement approach. It can characterize delay spread with a resolution below 30 ns. In addition, the same hardware allows measurement of both wide and narrow bandwidth interference. The ST-515 consists of three elements: a portable test transmitter, a measurement receiver and a standard PC (Figure 8). The standard test transmitter generates a probe signal. The measurement receiver tunes and filters the test signal. The ST-515 Propagation Measurement System can be used by wireless network planners to characterize communications environments." [1]

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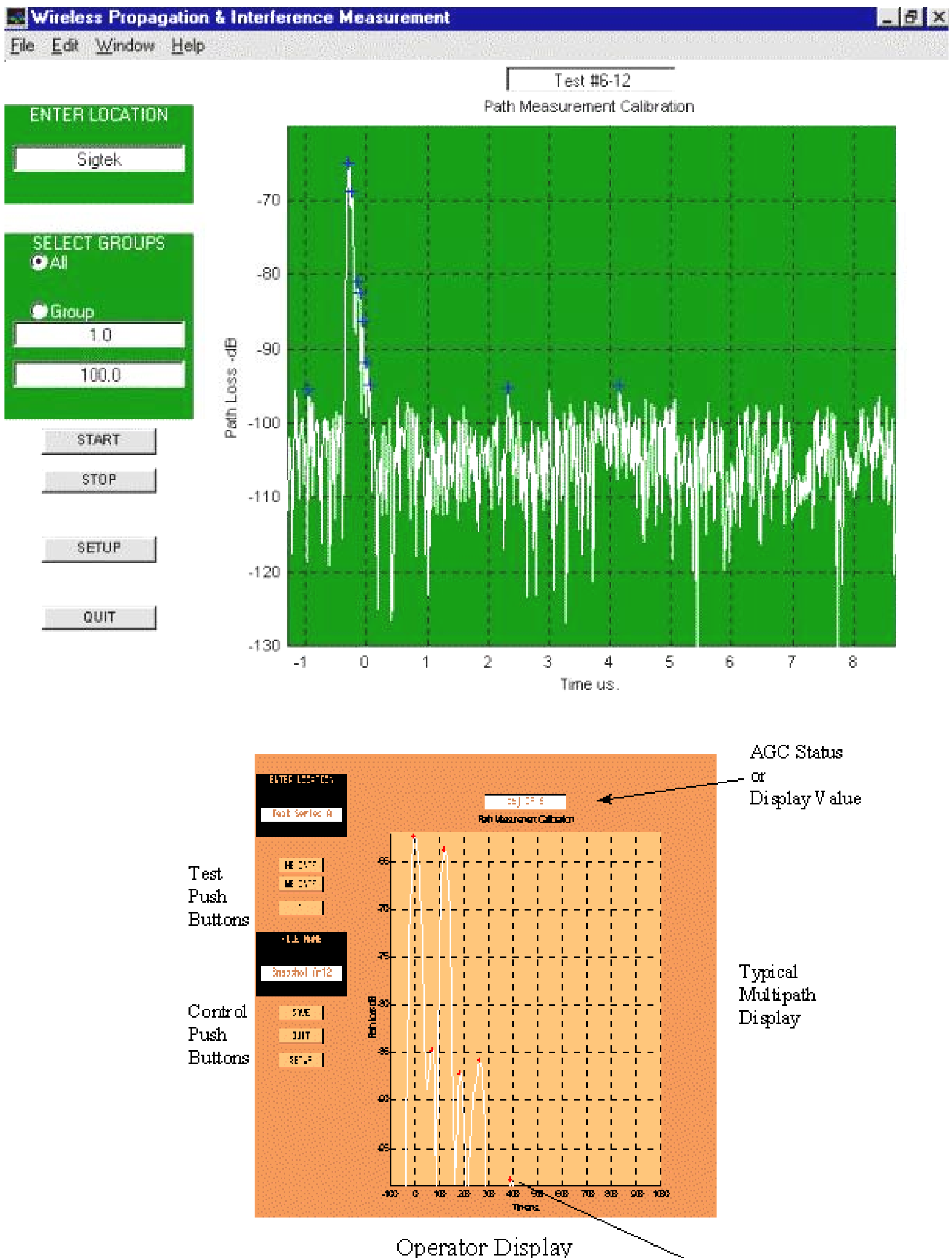
[1] The technical description and corresponding figures of ST-515 set are excerpted from SIGTEK Inc. with slight modifications. (http://www.sigtek.com).



Test Name:	Test Set #10012								
Current Row:	8								
Time	**Location**	**Test**	**Sub-test**	**Carrier**	**Data**				
4/22/97 15:34:39.39	Test Series A	MP Delay	1	-4 ns	116 ns	68 ns	260 ns	180 ns	388 ns
4/22/97 15:34:39.39	Test Series A	MP Level	1	-62 dB	-64 dB	-85 dB	-86 dB	-87 dB	-98 dB

Figure 7 SIGTEK ST-515 typical bulk processing display

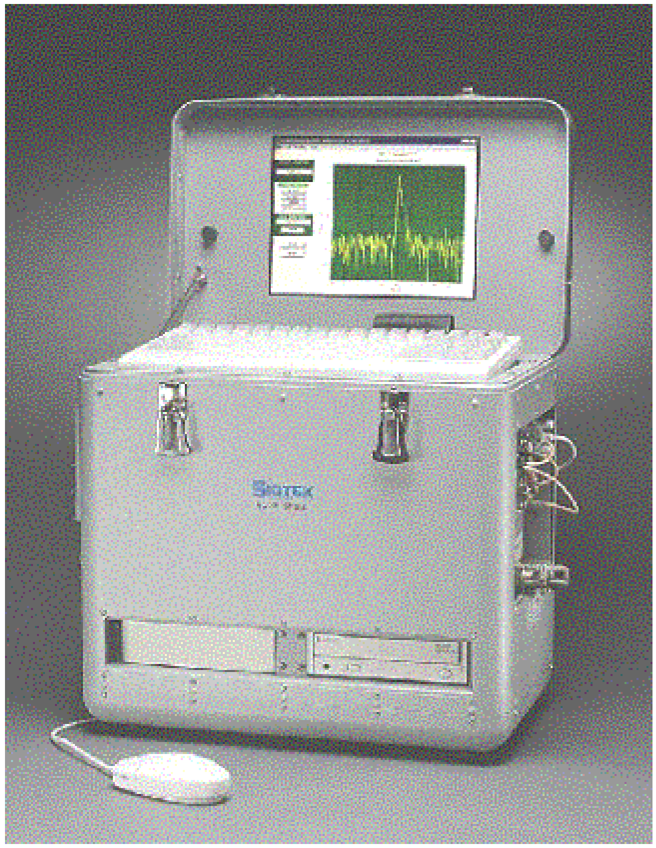


Figure 8 SIGTEK ST-515 (www.sigtek.com)

As can be seen, the characteristics of the device offer strong capabilities. In our first try, we set up the channel sounder, and installed the transmitter and the antenna part near the control room. We put the receiver on a wheel-cart to facilitate repositioning of the device for each measurement run. As a general rule of thumb, the testers should (1) avoid long cable runs for receiver power supply or use the battery operated portable power supplies (i.e., UPS), (2) deploy poly-phase surge arrestors for antenna protection, and (3) ground the chassis and the body of all metallic parts to ground level. Figure 9 and Figure 10 show our measurement setup. We started with the 345 KV yard. After conducting a few measurement runs, as we departed from the control room to the yard, we experienced loss of connectivity, which finally even prevented us to communicate with the A/D board of the receiver (probably due to some saturation phenomenon in the board). An excessive noise level is assumed to be the major cause of this problem. The error was cleared; nonetheless, we concluded that such oversensitive devices are not appropriate for this environment unless special grounding and protection provisions are considered from the manufacturer.

Figure 9 SIGTEK receiver located on a cart

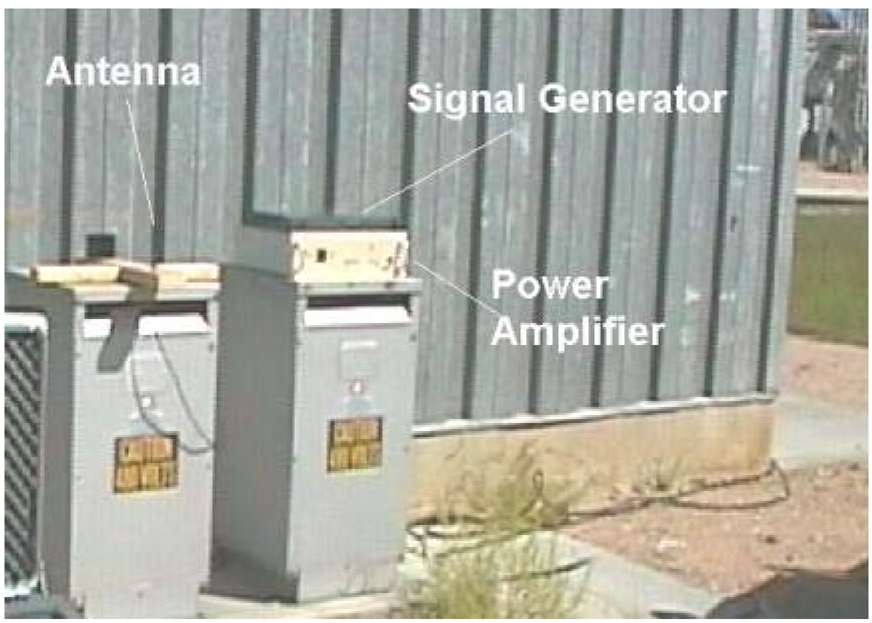


Figure 10 SIGTEK transmitter positioned by the control room

3.4.2 IEEE802.11 Based Site-Specific Measurement

The power devices, often having huge metallic cubicles, and the safety standard for the clearance from the overhead power-lines, sometimes make line-of-sight links impractical. As a result, there is a need to conduct an environment-specific analysis for substations. The second part of this section elaborates on our observations in an actual substation using off-the-shelf IEEE802.11-based wireless devices.

In this experiment, the transmitter was placed in a stationary position near the control room, where the base unit is more likely to be located, while the receiver is moved to different locations in the substation near the circuit breakers to gather several data samples. We used an Access Point (AP) as the transmitter and the handheld Grasshopper™ [2] (Figure 11) as the receiver. Access Points (AP's) usually utilize a network with the wired Local Area Network (LAN). In the project, nevertheless, we programmed and installed an AP by the control room (Figure 12) and used it for transmitting pilot signals, which can be measured by the handheld receiver. Channel 6 was chosen since it is almost located in the middle of the ISM band. Channels 1, 6, and 11 are used since these channels produce the least interference on each other.

The Grasshopper™ handheld receiver is designed specifically for sweeping and optimizing Local Area Networks.

Figure 11 Grasshopper receiver (2.4 GHz WLAN Sweeper)

The instrument measures coverage of direct sequence CDMA networks which operate on the IEEE802.11b standard allowing the user to measure PER (Packet Error Rate) and RSSI signal levels. The main application of this setup is to aid in finding the proper disposition of the hub and access points throughout the network. The device is capable of

[2] Berkley Varitronics Systems, Grasshopper manual version 1.9.

sifting the transmitter signal from the narrow-band multipath interferences (e.g., impulsive noises in the substation) and other frequency hopping systems sharing the same frequency bands.

Figure 12 IEEE802.11b Access Point (AP)

The grasshopper device was then positioned in several locations throughout the substation behind the circuit breakers and other metallic cubicles (Figure 13) and the corresponding received field strength were recorded.

Figure 13 Grasshopper device measurements are taken behind the metallic cubicles at different locations inside the substation

The gathered data is then incorporated into the model (discussed in the following paragraphs) to solve for the unknown parameters.

In this analysis, we utilize a general path loss (P_L) model. It uses a parameter, n, to denote the power law relationship between distance and received power as a function of distance, d. Then, the path loss P_L (in decibels) is expressed as:

$$P_L(d) = P_L(d_0) + 10n \log\left(\frac{d}{d_0}\right) + X(\sigma)$$

Where n = 2 for free space and is generally higher for wireless channels.

The term $P_L(d_0)$ simply gives P_L at a known reference distance d_0 which is in the far field of the transmitting antenna (typically 1km for large urban mobile systems, 100m for micro-cell systems, and 1m for indoor systems) and X(σ) denotes a zero mean Gaussian random variable (with units of dB) that reflects the variation in average received power that naturally occurs when a P_L model of this type is used. Since the P_L model only accounts for the distance that separates the transmitter and receiver and not any of the physical features of the propagation environment, it is natural for several measurements to have the same T-R separation, but to have widely-varying P_L values. This is due to shadowing that may occur at some locations and not others.

Introducing a new random variable for describing the physical features of the propagation environment improved our model. We call it X_e. The path loss model becomes:

$$P_L(d) = P_L(d_0) + 10n \log\left(\frac{d}{d_0}\right) + X(\sigma) + X_e$$

where X_e is the site-specific random variable, which depends on the location of the transmitter and the receiver. The acquired data from the Grasshopper, along with distance measurements, are used to estimate the above-mentioned unknown parameter.

This model incorporates the physical layout characteristics of a substation rather than electrical impacts of high voltage switching interferences on wireless links. On the other hand, we cannot guarantee that the achieved model for a typical substation works for another substation, even if they are similar in layout. Having said that, we attempted to work out the problem using the linear regression method. This resulted in too many outliers to maintain the model conformity. As to the above setbacks, we skip discussing the results in this part.

Aside from attempting to reach a model for our environment, we can also define a coverage map for the access points and discover the regions for which the received signal strength is below a predefined threshold value (e.g., –75 dBm by manufacturer recommendation of the testing instrument).

3.4.3 900 MHz Long-Term Site Survey

Although the spread spectrum modems are not the best fit for our application, we use as much available hardware and software features as possible to better understand the wireless channel.

Fortunately the diagnostic kit of FreeWave® modem devices has become available to us, which allowed long-term field surveys at our test sites. Thanks to the active cooperation and technical feedback from the vendor, we managed to program and configure a setup to meet our measurement demands. Using the diagnostic feature, three modem devices have been configured to log data transmission statistics and daily/weekly noise variation in one-minute time intervals. The main goal of the experiment is the long-term observation of “signal-to-noise” variations.

The setup consists of wireless modems, data devices and a processing unit. The modems operate at 900 MHz. The processing unit fetches the wireless quality parameters from the modems. We programmed the setup to acquire the accumulated wireless statistics from the radio at intervals of one minute. The data are then automatically recorded on a laptop machine for post-processing.

3.4.3.1 Proposed Setup

The core of the measurement is the diagnostic computer that receives the network information via RS232 port. The diagnostic software then handles the data decoding and logging. The measurement is supposed to be continuously performed for a few days.

The master radio is connected to a data communication device that we call the host computer. The task of the host computer in this measurement is to transmit randomly generated data to the master radio. This source data is simultaneously saved on the local processing unit. The master radio transmits this data to the repeater. The slave radio is programmed to receive the data echoed by the repeater radio.

The slave radio is connected to a data device that records the received data. This data is juxtaposed with the originally transmitted data to enable BER calculation of the network.

Figure 14 shows the measurement setup schematic. The diagnostic computer and the host computer are located in the control house. The master radio is mounted outside the control house facing toward the substation. The repeater radio is placed at the farthest circuit breakers away from the slave and from the master radio (i.e., next to the control room). We used a repeater radio to gather as much measurement data as we could for our statistical analyses. The slave radio alone cannot communicate with the master radio, and the stream of data should pass the longest (worst) path from the master to the repeater and then to the slave radio by this layout.

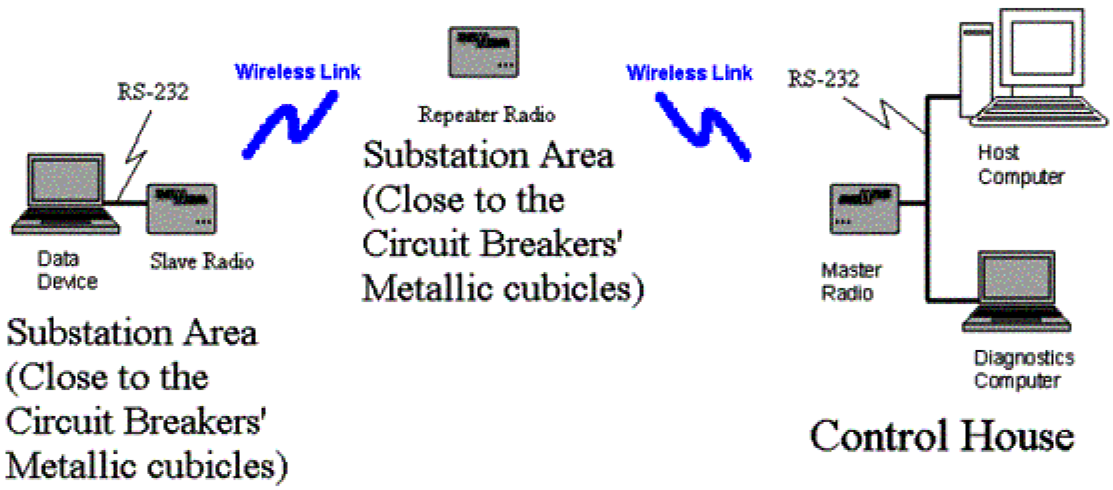


Figure 14 Measurement Setup Disposition Schematic

The problem with the above setup is the requirement for proper ventilation and air conditioning of the slave data device. Figure 15 shows the revised setup plan that relaxes the requirement for having a data device (which was a notebook or laptop computer in our case) by looping the data back to the master radio. A looping circuitry bounces the data coming to the slave radio back to the master radio. The diagnostic system keeps track of the radio statistics of the master, repeater and slave radios.

These measurements need to be performed for different voltage-level substations and the test needs to be run continuously for several days. The average signal and noise levels for modem devices can help us understand the power requirements, error probability and noise profile in substation environment. The observation of the probable variation of noise level during the day in a typical substation is among other benefits of these test runs. On the other hand, the reliability of the type of modulation used in the modems is investigated. Unfortunately, delay-spread cannot be measured by this setup and needs other measurement instruments.

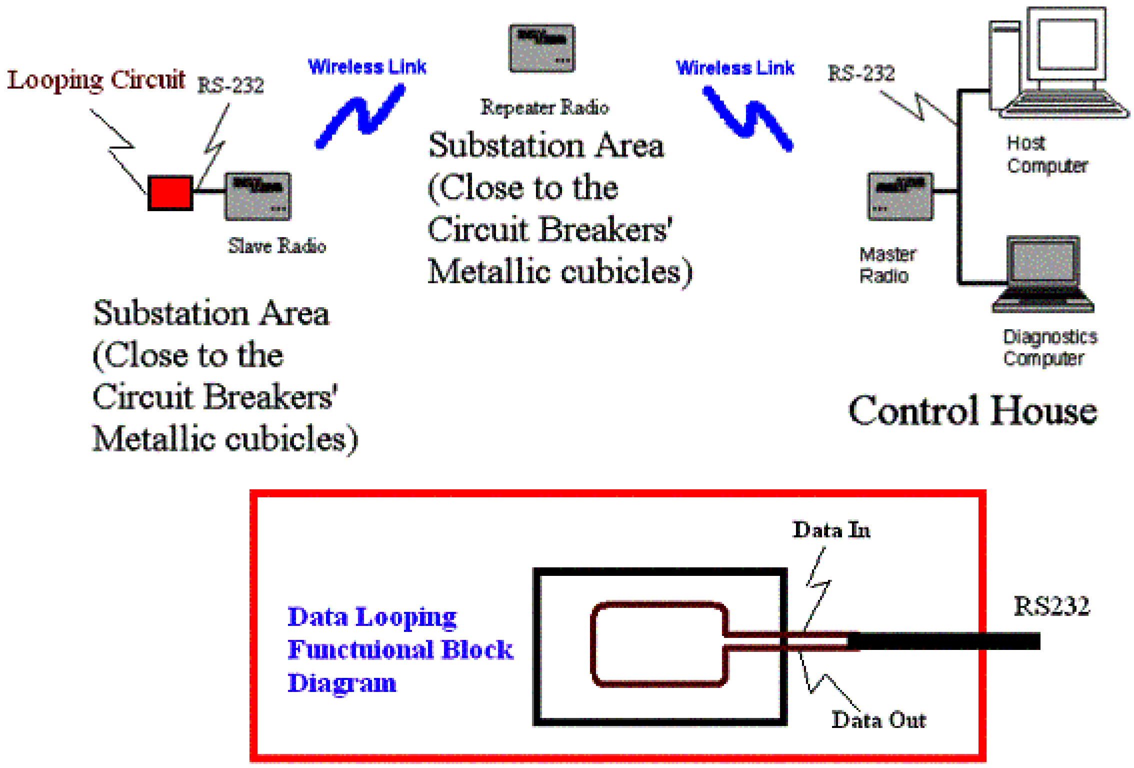


Figure 15 Revised Measurement Setup Dispositions

3.4.3.2 Actual Measurement Setup

Two laptops were deployed and programmed to emulate the continuous data communication to the virtual circuit breaker receiver and to handle the logging and background processing (Figure 16). Figure 17 shows typical dispositions of the radio transceivers.

The in-yard radio was installed 1.2m above the ground level and electrically attached/grounded to the metallic structures of the circuit breaker. Since the wireless communication analysis is aimed at monitoring operation of circuit breakers, we considered free-body metering to be inappropriate in this case [10]. Our measurement setup was subject to calibration error. We ignored this offset error as the general methodology adopted is invariant to this offset error and the background noise may induce offset in different locations.

The survey duration of our measurement run was about 14 days in each yard (i.e., the 34.5 KV, 138 KV and 345 KV yards) to include weather cycle extremes, and probable diurnal and weekly patterns. The noise calculations were done as a moving average of 256 readings during each frequency hop spread over the 902 to 928 MHz frequency spectrum. Each reading was about a 20 ms and the sample interval was approximately 5 seconds [11]. If multiple samples are taken at the same frequency in the time period, the most recent sample is deemed to be the most important and is assigned a weight of 256. On the other hand, a value that had been sampled 255 samples back is deemed to be least important and is assigned a weight of one. The average noise was calculated and recorded each one-minute interval using the above procedure. Hence, there are more than 20,000 observations per our data set. The processing unit also handled the data logging. Sensors recorded the body-temperatures of the instruments. This enabled us to check any probable correlation of the ambient temperature with our readings. The instruments have negligible or no correlation to the temperature deviation within the nominal range [12].

The resulting data of this setup were used for the 900 MHz analysis in the project.

Figure 16 Master radio data device and the diagnostic computer

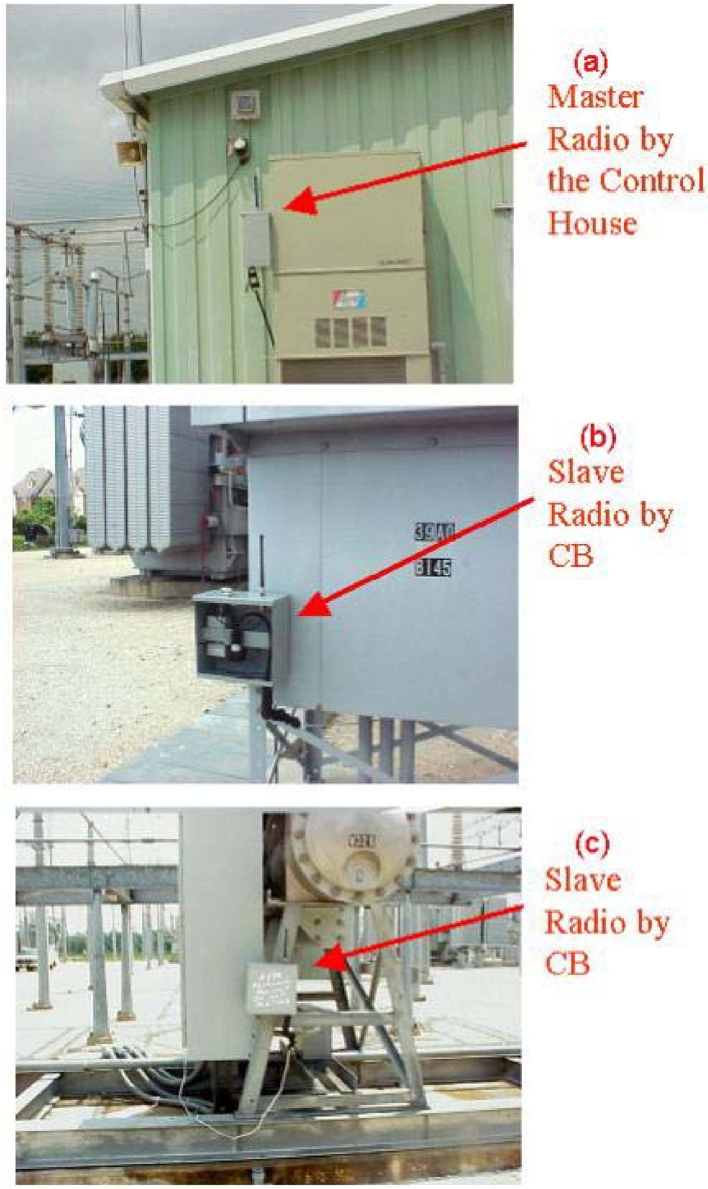


Figure 17 Equipment disposition

(a) Master transceiver, which is attached to the control room, is connected to the logging device (b). (c) Slave radios were connected to the metallic body of the circuit breaker.

3.4.4 2.4 GHz Long-Term Site Survey

We conducted a similar setup plan for the 2.4 GHz frequency band using IEEE802.11 compatible radios. The access unit was placed next to the control room with an omni directional antenna attached to it. The subscriber unit was placed at the far end of the substation, attached to the circuit breaker metallic structure. The radios use 79 channels in the 2400 to 2483.5 MHz frequency range using 9 hopping sequences per each hopping set. A program has been designed to continuously peak the link quality data from the radios, seeing that this feature was not a built-in function in the device. Then, these data were transferred, gathered and recorded each second. Specific provisions were made to avoid data congestion while polling the data from the radios.

The bandwidth occupancy of the 2.4 GHz frequency band is lower than that of 900 MHz band; hence, we expected to experience less interference from other radios in this spectrum. We skip explaining the installation details, as the setup was quite similar to the previous setup plan. The measurement runs were implemented in two 14-days periods, one in the 138 KV yard and the other in the 345 KV yard of the substation. These testing periods were chosen to be long to include atmospheric cycle extremes, and probable diurnal and weekly patterns.

The polled signal levels from the radios are in RSSI format. RSSI stands for Receiver Signal Strength Indicator and is used in the control loop of the firmware of the radio. Since RSSI is a relative index, the device works regardless of RSSI calibration to dBm values; hence, most vendors are reluctant to add a separate process to calibrate the RSSI of their radios. In addition, RSSI is not necessarily a linear index and the companies provide a conversion table for the mapping between these values.

We did the level calculations by utilizing the conversion table provided by the vendor. The recorded data from this experiment have been utilized for the 2.4 GHz analysis in the project.

4. Data Analysis and Post-Processing

4.1 Introduction

In this part, we analyze the data that we collected from our measurement setups described in the previous section. Wireless channels are, in general, difficult to analyze because the dynamism of the propagated signals is constantly changing in time and position. The communications media for one yard as compared to another yard of even the same substation are not the same. Surfaces of the metallic and non-metallic structures in the substation contribute to the level of received signal, noise and delay spread. For the above reasons, we do not focus specifically on the absolute values of our measurement results, but rather on the profile and the time-wise variations of the levels.

1- Our analysis procedures in the upcoming section are not sensitive to the magnitude of the signal levels but to their statistical behaviors or their distributions.

2- We report results from analysis of just one data set from our measurements, unless we specifically point out the non-conformity of other data sets for this analysis. This is done to maintain the flow of our reasoning.

4.2 Methodology

We considered three popular data analysis approaches: Classical, Bayesian and Exploratory Data Analysis. The difference among these approaches, which all yield engineering conclusions, is the sequence and focus of the intermediate steps. For the Classical approach, a model is first defined and the analysis is based on this model. For Bayesian analysis, data-independent distribution is imposed on the parameters of the selected model according to the engineering knowledge of the analyst. Then, the observed data and the a-priori knowledge about the distribution of the parameters are incorporated to construct interval estimates of the model parameters or even to validate the collected data. Finally, in the exploratory data analysis approach, the analyst focuses on finding the best-fit model to the collected data by discovering the behavioral patterns of the gathered data. Many of the radio engineers adopted the Bayesian approach, as there already exists some underlying assumptions about the radio propagation and noise profiles in the literature. The validity of the scientific conclusions becomes intrinsically linked to the validity of these underlying assumptions. In practice, since some of the assumptions are unknown or untested for specific applications, the validity of the scientific conclusions becomes suspect.

In the next part, we probe our measurement results. We will see that there is no appropriate distributional modeling to this problem. Hence, we base our analysis in the rest of the survey on the Exploratory approach. This method also requires fewer encumbering assumptions.

4.3 Noise Analysis

In wireless system designs, the probability that the noise exceeds a threshold level is crucial. In general, a model, defined by experience and theoretical conjecture of noise and its distribution, identifies the above-mentioned probability. Then, the maximum difference between the empirical and the hypothetical cumulative distributions are measured by some test statistics. This test is called “test of goodness of fit”.

In the Classical and Bayesian methodologies, an a-priori (distributional) model is defined before the analysis. In our case, nonetheless, it is difficult to identify a hypothetical distribution in the first place that copes with the empirical data. A suggested noise distribution of a typical substation is discussed in [2]. The suggested statistics depend upon the value of certain parameters in the noise distribution. The multiplicity of the parameters involved in this model, and the complexity of extracting them using long test runs while maintaining small time resolution, make it challenging to define an robust and appropriate hypothetical noise distribution for a substation.

From the measurement point of view, hypothesis testing is readily performed if the observations are normally distributed. (Based on the central limit theorem, the observations are therefore assumed as normally distributed.)

Usually the assumption of a normal distribution of the residuals for the parameter estimation is checked by these hypothesis tests. Such an approach is problematic if the estimates of the parameters are used to compute the theoretical normal distribution. If the estimates are falsified by the model deviations, then this already can be a reason for deviation from the normal a distribution.

There are other tests that get along without the assumption of a special distribution with which the test of a general linear hypothesis is not possible. In these tests, the sampling distribution depends neither on the explicit form of nor on the value of certain parameters in the distribution model. These test are called non-parametric or distribution free tests in the sense that the critical values do not depend on the specific distribution being tested. By means of goodness-of-fit tests, such as chi-squared test and Kolmogorov-Smirnov test, empirical or assumed univariate distributions can be compared with theoretical or hypothetical univariate distributions, for instance the univariate normal distribution. Kolmogorov-Smirnov (K-S) test has been considered to be the most appropriate test for our scenario among other non-parametric tests [13]. This is the method which has been suggested by IEEE [10]. Statisticians, however, prefer to use the modified K-S test: the Anderson-Darling (A-D) test [14]. A-D improves the K-S test by granting more weight to the tail of the distribution in the fitted model than to its mid-range, which allows a more sensitive test especially to fat tail distributions. The A-D test has the disadvantage that the critical values should be calculated for each distribution; however, this drawback is less intense since the tables of critical values are readily available and are usually applied with statistical software programs. Tables of critical values are already available [14] and are usually applied with a statistical software program.

4.4 Statistical Confidence of the Results

IEEE recommendations for site surveying methods suggest using the Kolmogorov-Smirnov method to calculate the statistical confidence of the measurement [10]. This approach works only when the Cumulative Distribution Function (CDF) is reasonably continuous.

In practical measurement, we do not always have the luxury of having both a high-resolution measuring device and a large dynamic range required for impulsive noise measurement. If we decrease the dynamic range to have a better resolution, then we miss the impulses that may occur. This trade-off is the source of our discontinuities in the Cumulative Distribution Function. The other way to work around the problem is to use the Moving Average technique to make a practically continuous cumulative distribution. Fortunately, our measurement setup allows a long duration survey resulting in a very large data set (more than 14,000 data samples per each data set). With such data redundancy, we might expect to achieve observation values in the vicinity of the average values of the actual data.

Figure 18 shows the Cumulative Distribution Function of 345 KV substation yard.

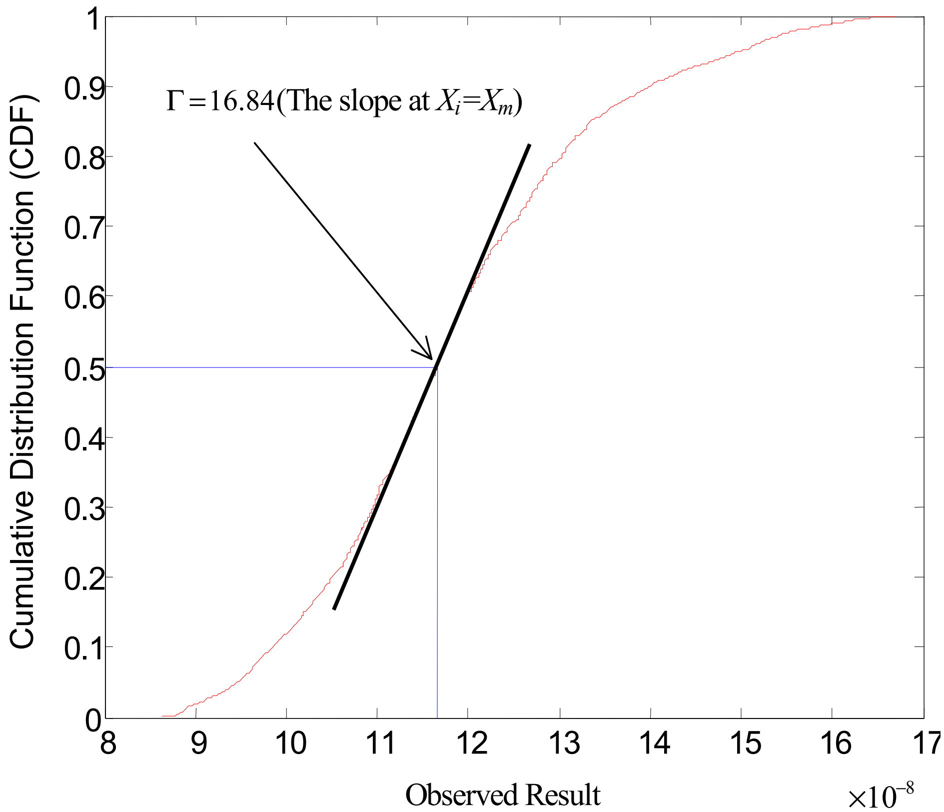


Figure 18 Cumulative Distribution Function (CDF) of the measured data

For large samples (more than 35 observations), of size N, the critical value of the distribution is defined as $d_\alpha(N)/\sqrt{N}$ in which $d_\alpha(N)$ is the maximum absolute difference between the sample and population cumulative distribution. For instance, if a 90% confidence is desired (i.e., the significance level (α) of 0.10) the maximum absolute deviation between the sample cumulative distribution and the population cumulative distribution will be at least $d_\alpha(N)/\sqrt{N}$. In other words, we can say that, for instance, the calculated median X_m is expected to lie within $\pm d_\alpha(N)/(\Gamma\sqrt{N})$ of the true population median with 90% confidence. We can any take other values of X_i and make the same calculation for that point.

This is a measure of the confidence in our data sampling and the results are independent of the form of the distribution function which characterizes the observe data [10]. Table 1 gives the calculated confidence percentages of our survey according to this method. The small value of the deviation from the actual median is due to the large sample size in our case (more than 14,000 samples); hence, according to this analysis, we can be almost sure about the confidence of our results.

Table 1 Expected Deviation with Respect to Confidence Levels for 900 MHz Measurement

Confidence Level	80%	90%	99%
Expected Deviation from the median	5.37×10^{-4}	6.12×10^{-4}	8.18×10^{-4}

The only drawback of this method is the difficulties in the calculation of the slope of the Cumulative Distribution Function at the data point of interest. This is usually implemented graphically rather than analytically.

In the next section, we will show that there are some fundamental problems that make this analysis questionable. We still keep this section in the report to follow IEEE recommendations on site surveying.

We analyzed the data to see if the results suggest that the use of distributional measures discussed above. One of the basic assumptions in determining whether a process is stochastic or deterministic is randomness. If the process is stochastic, each data value may be viewed as a sample mean of a probability distribution of the underlying population at each point in time. If the assumptions of randomness, fixed distribution, and constant scale and location are satisfied, then we can model a univariate process as:

$$\omega_i = \chi_0 + \varepsilon_i,$$

where ω_i is the observed variable, χ_0 is the underlying data-generating process or the source data, and ε_i is an error term.

If the randomness assumption of a process is violated, then we typically use a different model, such as a time series model. Then, we can identify the stochastic and deterministic components in the process.

Figure 19 shows the run sequence plot. It indicates that the data do not have any significant shifts in location or scale over time (hence they appear stationary). Autocorrelation plots [15] are commonly used as a measure to indicate randomness in a data set. (Note: the formula, which is used in [15], is in an autocovariance sense.) This randomness is examined by evaluating autocorrelations for observed values at different time lags.

The sample autocorrelation (autocovariance) plot (which is given in Figure 20 for 900 MHz and Figure 21 for 2.4 GHz measurement setups respectively) shows that the time series is not random, but rather has a high degree of autocorrelation between adjacent and near-adjacent observations.

Since the randomness assumption is thus seriously violated, the distribution approach is ignored because determining the distribution of data is only meaningful when the data are random. The plot exhibits an alternating sequence of positive and negative values that are mildly decaying to zero.

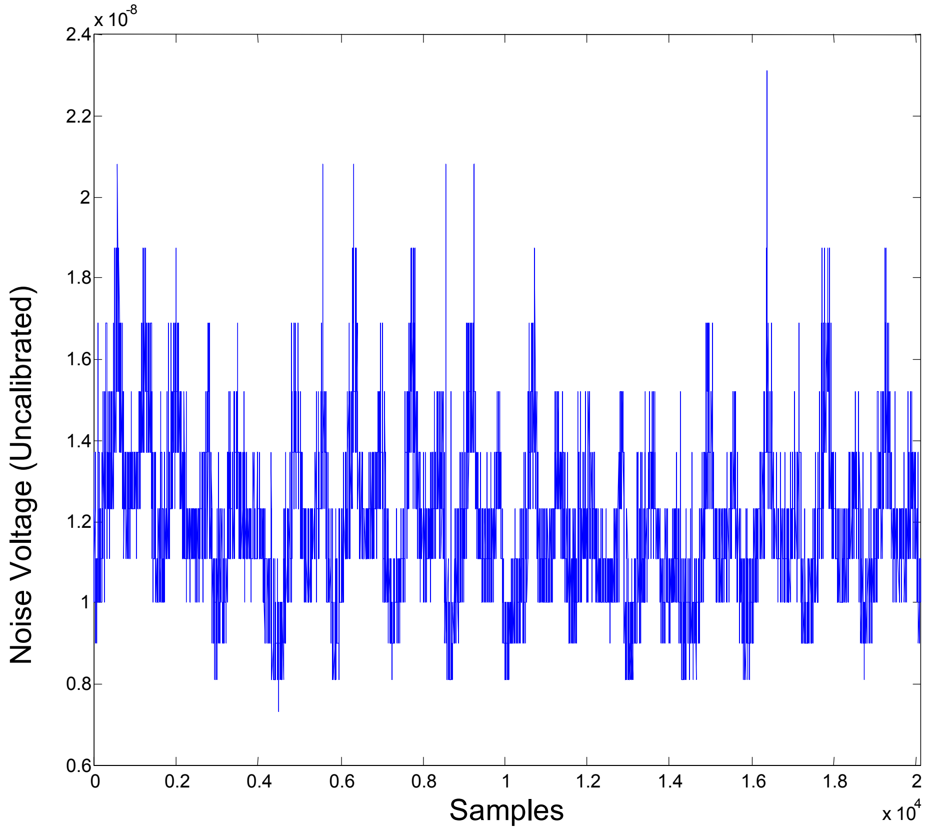


Figure 19 Run Sequence Plot of Noise Voltage

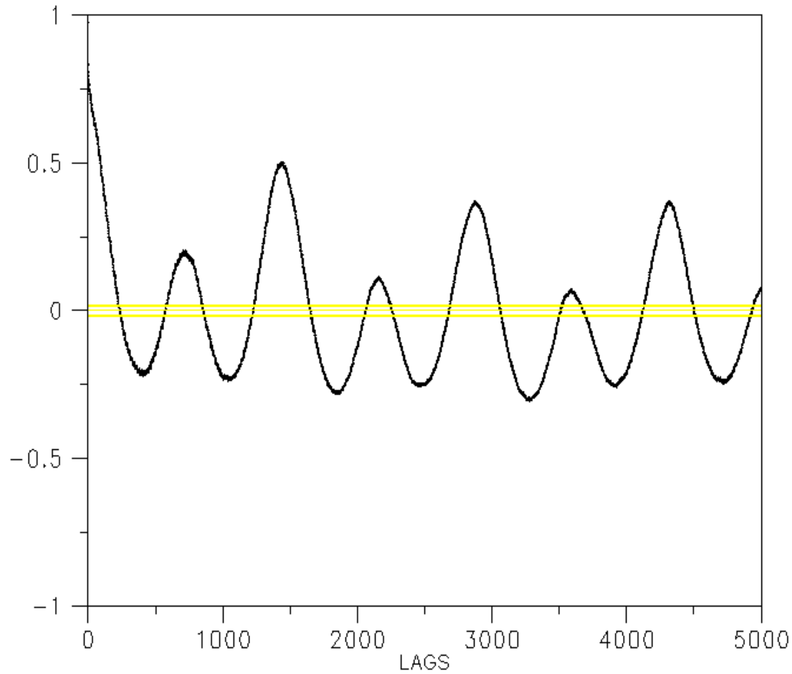


Figure 20 Sample Autocorrelation Plot (900 MHz measurement setup)

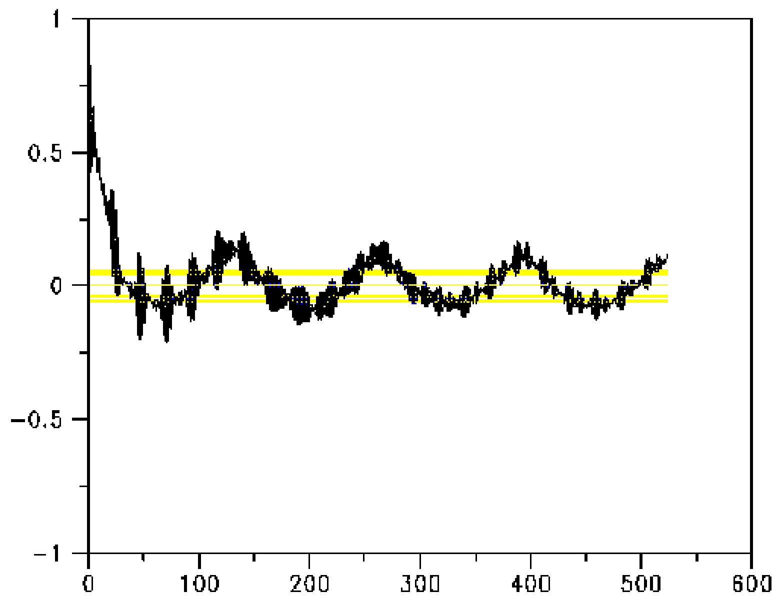


Figure 21 Sample Autocorrelation Plot (2.4 GHz measurement setup)

Figure 22 gives the lag plot of the data that further shows the presence of a few outliers in our data set. The above plots reject an appropriate distribution model for our data set.

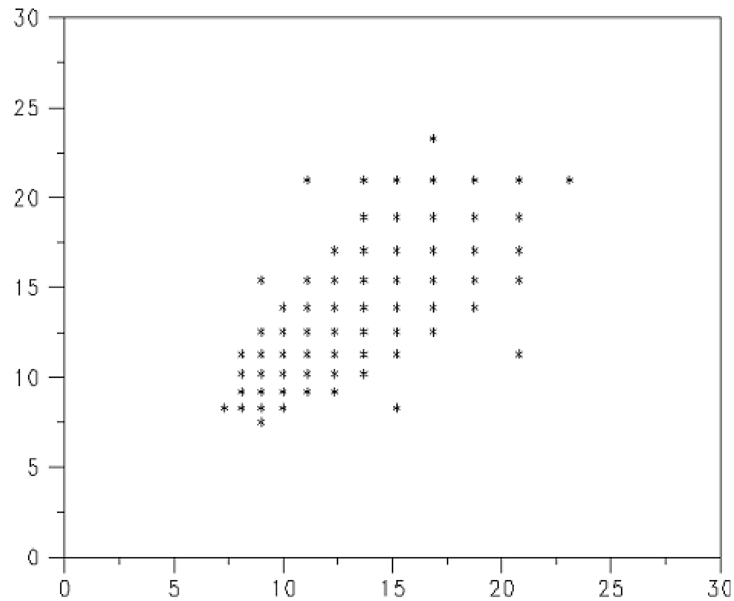


Figure 22 Lag Plot

4.5 Graph Interpretations

As seen from the run sequence plot, the data points taken over time seem to have an internal structure. Figure 23 shows recorded noise values for typical days of these two weeks. The data have an underlying pattern, along with some high frequency noise. At the same time, there does not seem to be any obvious seasonal pattern in the data. Although there is some high frequency component, there does not appear to be data points that are so extreme that we need to delete them from the analysis. These types of non-random data can be modeled using a time series methodology. We first have to obtain an understanding of the underlying forces and structure of the data set, and then fit a model and proceed to forecasting and/or monitoring. We observe that the data set is an almost trend-free set. In the next sections, we will attempt to fit an appropriate model based on the data structure.

4.5.1 Ambient Temperature Independency

To better investigate the probable relationship between the parameters, scatter plot analysis has been used. Scatter plot is a useful diagnostic tool for determining association. Figure 24 shows the scatter plot of the measured noise level versus the ambient temperature for one of our recorded data sets.

It appears that the noise and the temperature are (negatively) correlated and, furthermore, that the variation in the noise level does not depend on the temperature. Statisticians refer to this as homoscedasticity of the data.[3] This homoscedastic behavior is an underlying assumption for regression and suggests that the regular regression estimates may result to

[3] Homoscedasticity means that the variance around the computed regression line is finite and is the same for all values of the predictor variable.

the optimal fit for our hypothetical model that relates the noise and the temperature. However, further investigation shows that, regardless of the implemented regression method –(e.g., linear, nonlinear or weighted least square regression), this model cannot be properly validated once it is calculated. Furthermore, the model does not fit the other data sets that we have recorded, resulting in model inconformity among the data sets. In this report, we do not discuss the complexities involved in regression modeling using these two (or even incorporating other) variables, which finally led us to an inconsistent resulting model. Instead, we probe the fundamental assumption that there exists a cause and effect relationship between noise and the ambient temperature.

As an auxiliary tool, we employed a conditional plot (also known as a coplot). A conditional plot is a plot of two variables (i.e., temperature and noise here) conditioned on the value of a third variable. We select time as our conditioning variable. Figure 25 shows examples of the conditional plot in different instances chosen from one of our data sets. The survey duration of this data set was 14 days; hence, we have 14 data points in each graph that correspond to the measured parameters at the indicated time of day. The values have been chosen one hour apart for manipulation simplicity. Other snapshots result in similar graphs. As can be seen from the graphs (in particular Figure 25(g), (h) and (i)), the lack of predictability in determining the noise level from any given value of temperature for a given time, and the amorphous, non-structured appearance of the conditional plot, leads to the conclusion that there is no relationship (or correlation) between the temperature and the noise signal level at these (few of many) typical instances. These are not simply some outliers among our data set, since very similar patterns appeared in our data set in a cyclic manner.

There are several instances in which noise and temperature appear to be associated, as in Figure 25(a), (c) and (e); however, the presence of these associations does not necessarily prove a cause and effect mechanism let alone their homoscedasity. [4] We believe that the variation in bandwidth occupancy during the day is the probable cause of this spurious correlation between temperature and noise. The noise measurement was within 902-928 MHz frequency range. FCC allows land mobile, amateur radio, personal communication units and cordless telephones to work in this frequency band. The inadequacy of data at this stage cannot prove the magnitude of the impact that these devices have on our wireless link. However, this is the strongest hypothesis that we have. In particular, as can be observed from Figure 23 (a) and (c), the noise floor generally rises during the weekends, while the noise pattern maintains almost similar structure during the weekdays as in Figure 23 (b).

[4] For instance, the number of people watching the television and the ambient temperature may seem to be (negatively) correlated, since most of the people watch television during the night which is cooler (colder), but in fact there is no causality between these two.

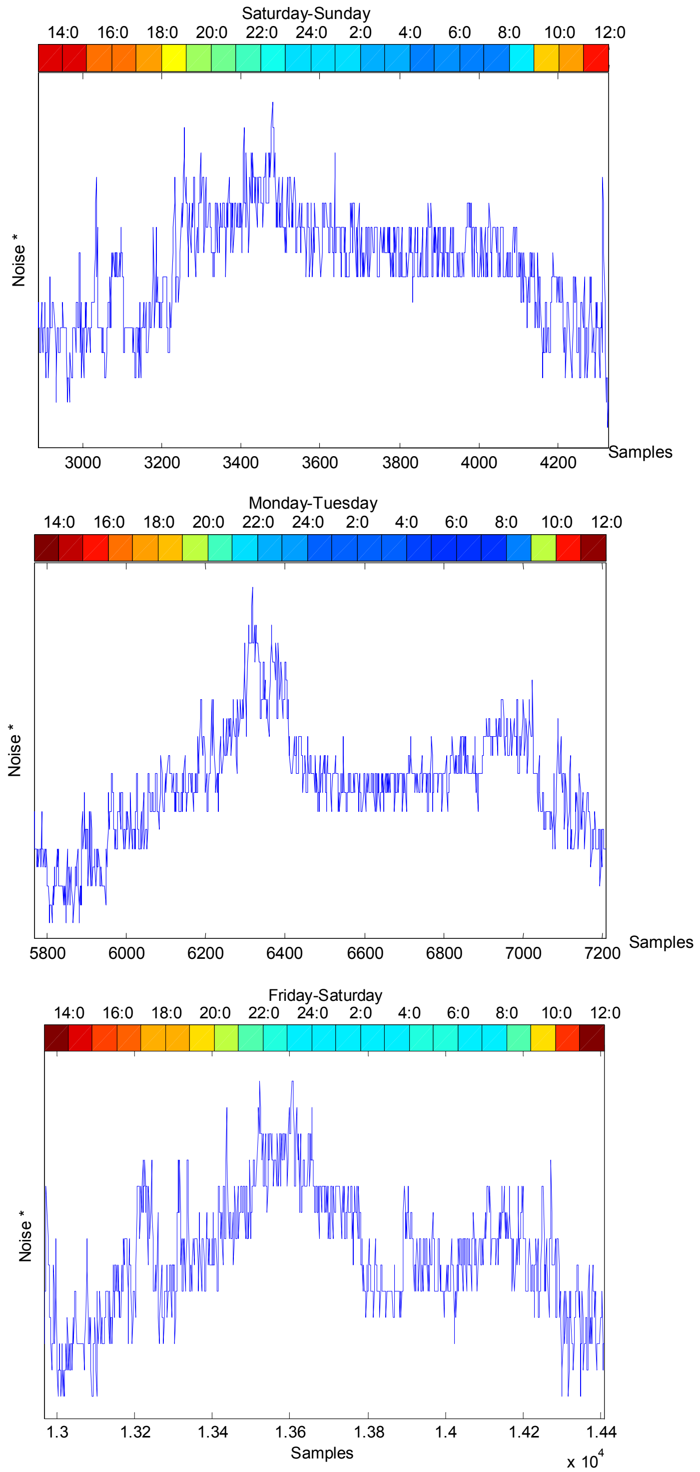


Figure 23 Recorded noise values and the intensity temperature bar for typical days of these two weeks

* The absolute value of the noise voltage is not of concern in this analysis so the units have been taken off of this axis.

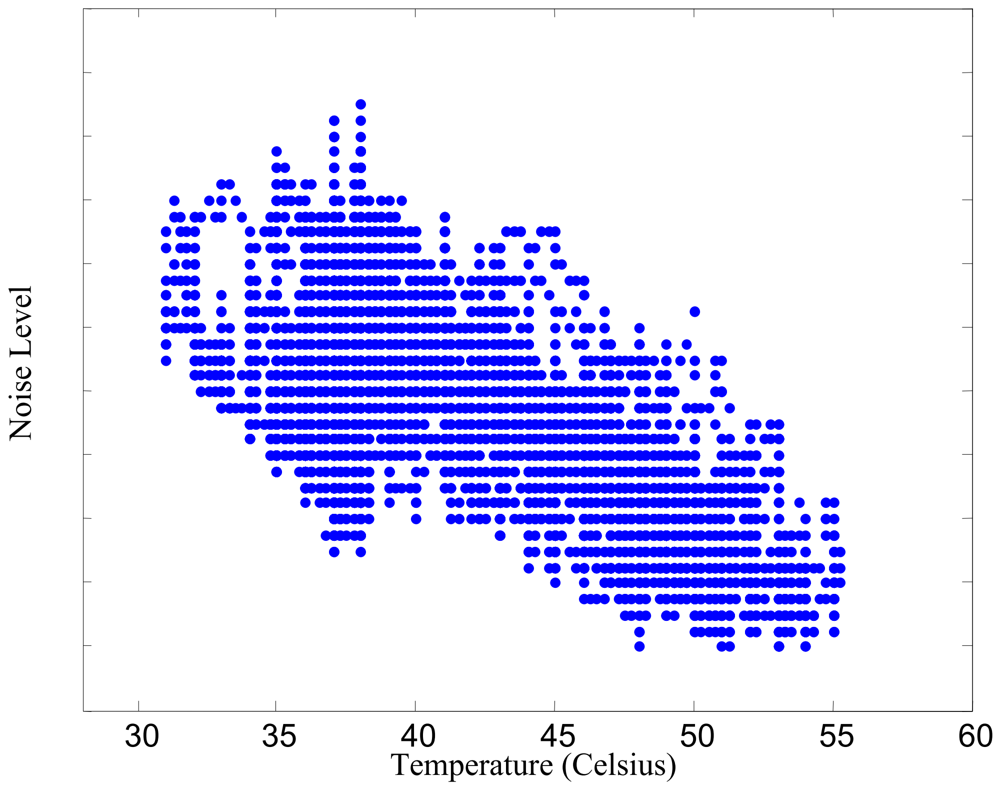


Figure 24 Scatter plot of the noise level versus the ambient temperature

* The absolute value of the noise voltage is not of concern in this analysis so the units have been taken off of this axis.

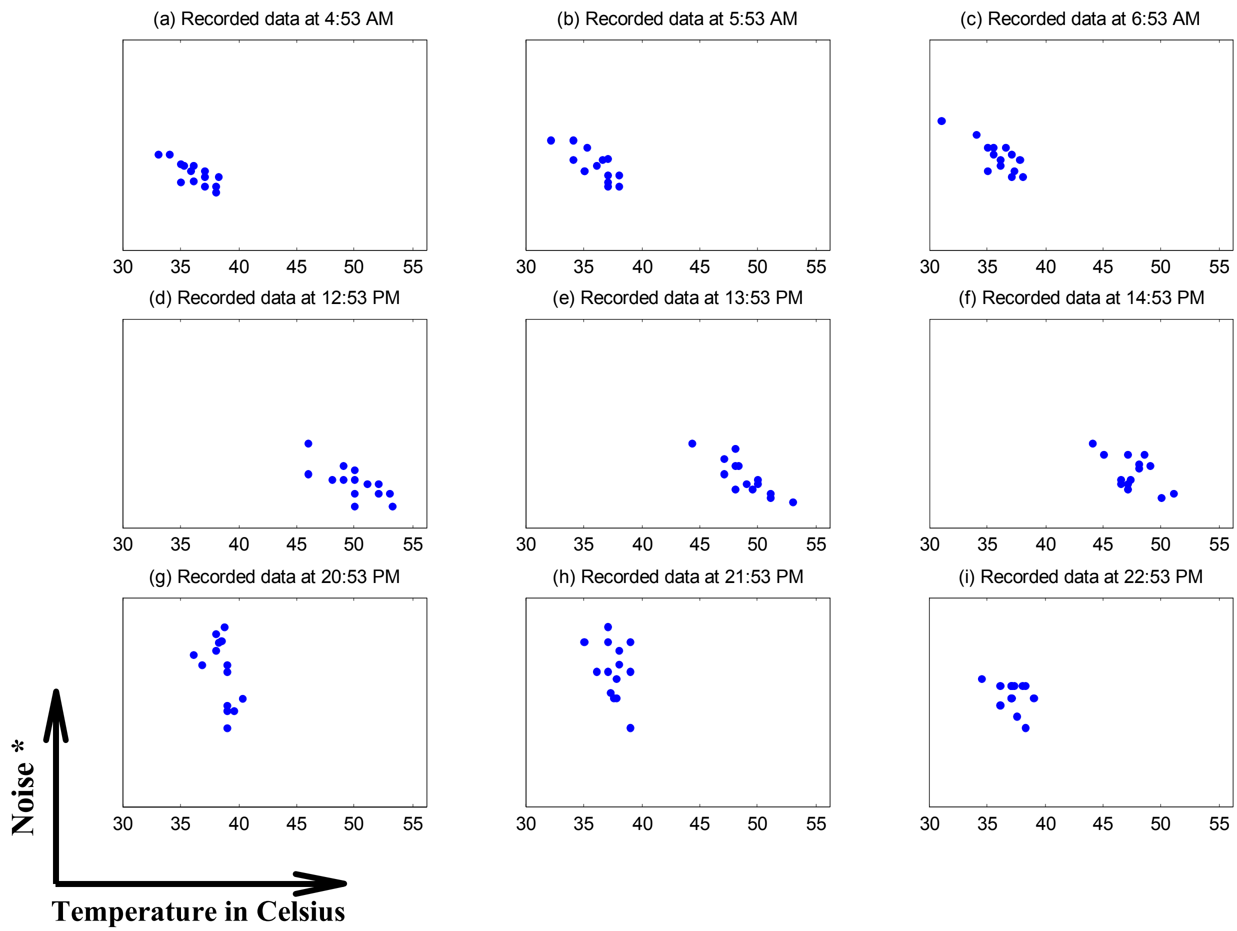


Figure 25 Conditional Plot

* The absolute value of the noise voltage is not of concern in this analysis so the units have been taken off this axis.

4.5.2 Substation Load Pattern Impact on the Wireless Channel

The association of the wireless quality with the load pattern in substations can be studied by deploying several sensors and simultaneous measurement of electrical and wireless parameters. High power signals in substation environment may generate detrimental high frequency components on our wireless channel.

Radiation loss incorporates the transformer losses. These radiations, however, are ultimately considered as the whole system thermal dissipation in power system analysis, but in here, to sharpen our analysis, we also recorded the power transmission parameters and the power factor of the transforms in the yard to observe their probable effect on our link.

Figure 26 shows the variation of the load pattern in substation during a typical day. The load pattern follows a time-series process. As a result, we juxtapose the time series run sequence of the load pattern with the run sequence of our radio quality. Figure 27 shows the scatter plot of these two parameters.

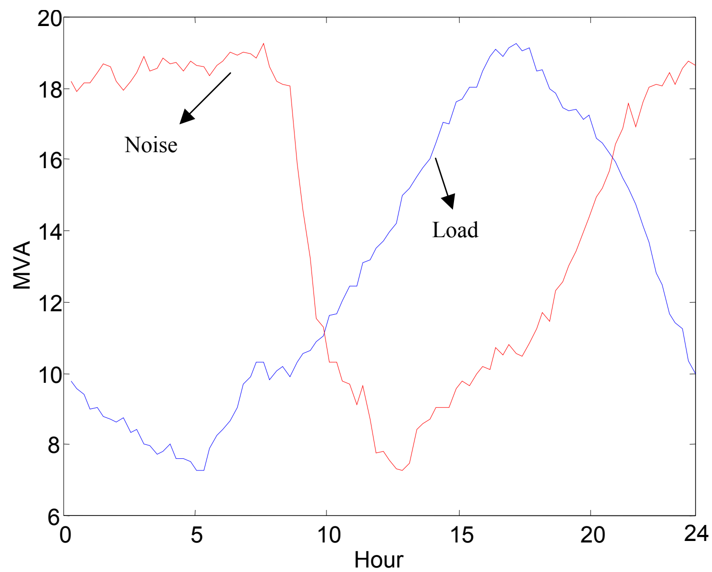


Figure 26 Transformer loading versus the noise level in the 2.4 GHz Frequency Band

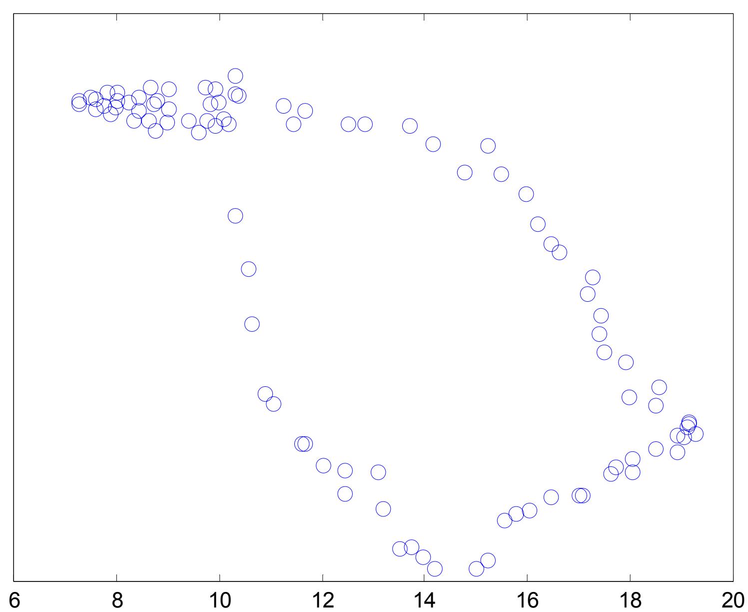


Figure 27 Scatter Plot of 138 KV transformer loading versus the noise level in the 2.4 GHz Frequency Band

* The variation of the noise level is in conformity with other data sets. Noise voltage level, however, is not of concern in this analysis so the units have been taken off of this axis.

Figure 26 and Figure 27 show that although there is a negative correlation between the transformer loading in the early morning, this correlation disappears during the day.

Hence, in sum, the transformer loading does not show any relationship with the noise level. Figure 28 and Figure 29 verifies the same conclusion for 900 MHz frequency band.

For both 900 MHz and 2.4 GHz frequency bands, we analyzed the instantaneous ingoing/outgoing voltage values, power factors, ambient temperatures as well as transformer temperatures. We found no obvious correlation in any of these variables with the variation of the average noise level in the long-term survey. Correlations with the average noise level (as opposed to real-time noise level) was the focus of our analyses.

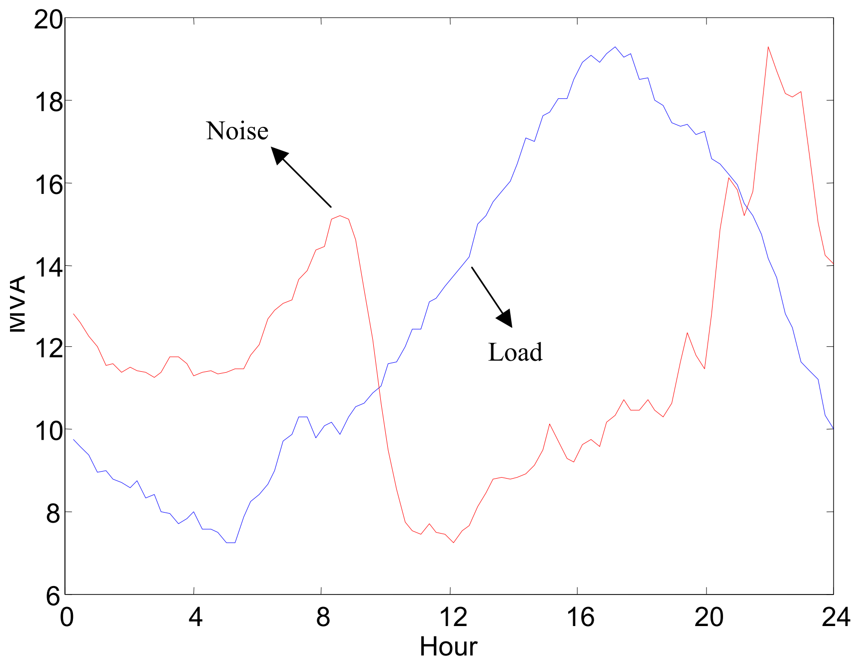


Figure 28 Transformer loading versus the noise level in 900 MHz Frequency Band

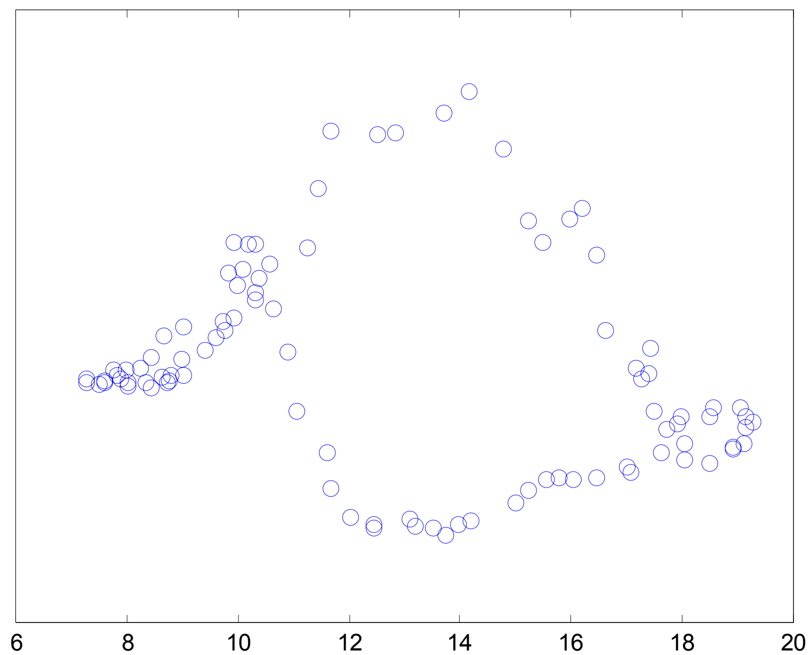


Figure 29 Scatter Plot of 138 KV transformer loading versus the noise level at 900 MHz Frequency Band

* The variation of the noise level is in conformity with other data sets. Noise voltage level, however, is not of concern in this analysis so the units have been taken off of this axis.

4.6 Univariate Time Series

Time series may be stationary or non-stationary. Many statistical analysis techniques are based on the assumption that the data are stationary. However, we can often transform the non-stationary time series into a stationary series either by taking the natural log, differencing or by taking residuals from a regression and then stabilizing the variance across time. Although seasonality also violates stationarity, we can usually apply a seasonal adjustment and render it amenable to time series analysis.

In our case, run sequence shows almost constant location and scale; there does not seem to be a significant trend. Sharp peaks also indicate that the ARMA model is more successful than the window estimation (e.g., Parzen window) [16]; hence, we adopted the ARMA modeling approach. Based on Wold's decomposition theorem, any stationary process can be approximated by an ARMA model (although this model might not be found easily). Once we fit the model, we inspect the residuals to ensure that they have a Gaussian distribution and thereby justifying our goodness of fit.

Box and Jenkins [15] popularized an approach and developed a systematic methodology for identifying and estimating ARMA models. We deployed Box-Jenkins systematic approach to model our data set. The next step was to determine the order of the autoregressive and moving average terms in the Box-Jenkins model. After fitting the model, we validated the time series model using residual analysis.

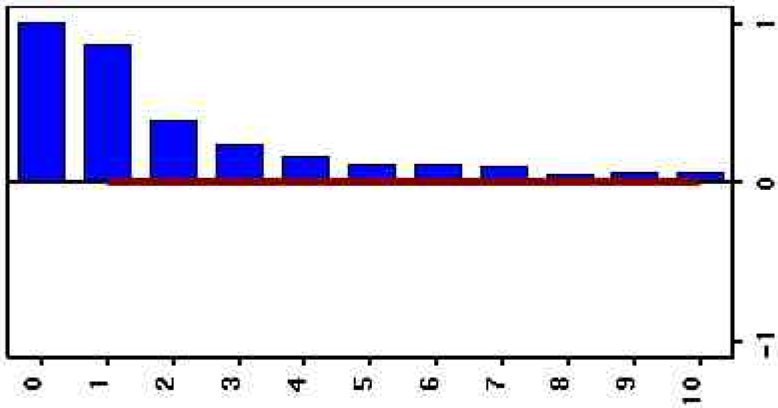


Figure 30 Partial Autocorrelation Plot

4.6.1 Model Identification

The autocorrelation plots (Figure 20 and Figure 21) show a mixture of exponentially decaying and damped sinusoidal components. This indicates that an autoregressive model, with order greater than one, may be appropriate for these data. The partial autocorrelation plot (Figure 30) should be examined to determine the order.

The partial autocorrelation plot suggests that an AR(8) model might be appropriate (since the amplitude becomes negligible at 8th lag). Hence, our initial attempt was to fit an AR(8) model. Model validation rejected this model since the resulting residuals failed to have a random Gaussian distribution. On the other hand, the presence of peaks and troughes in the run sequence plot suggested ARMA models as another potential fit. We adopted this more generalized model.

First, we used Akaike's Information Criterion to find a full AR model [16]. We used readymade statistical software for this purpose. An AR (27) model was found to provide the best fit of our data.

Second, we used stepwise ARMA method to look for the subset AR and obtain the alpha coefficient. The results suggested an AR(21) model with AIC=-4744.27 to be a better fit than the full AR model.

Third, we used the stepwise ARMA method to look for a subset ARMA model. We achieved p=36 q=24 (i.e., the orders of our ARMA model) having an AIC=-4812.06, which is less than full AR model. Next we needed to estimate our model's parameters and find the residuals. We used the Marquardt algorithm to calculate the MLE for the parameters of our model [16]. We found -1.0174, 0.6803, -0.3740, 0.0726, -0.0306, -0.0377, -0.3446, -0.9222, and 0.3474 for our alpha1 alpha2, alpha3, alpha17, alpha29, alpha36, beta3, beta21 and beta24.

4.6.2 Model Verifications

Next we checked the residuals of our model. If these residuals were white noise, then the chosen model would be judged to provide a proper fit. Using a Q-test we found a p-value of 0.07361. Hence, we did not find significant evidence to reject the hypothesis that the residuals were white noise. Hence, ARMA (36,24) was determined to be our final model. If we had failed to find residuals with Gaussian noise, we would have had to redo the procedure to find a better ARMA model.

4.7 Conclusion

The characteristics of the data set that we gathered from the substation site survey indicates that the classical distributional analysis is not an appropriate approach for prediction. The measured data has a strong non-random component with long-time memory and a stationary internal structure that calls for time series analysis. This structured can be modeled with an ARMA model according to Wold's decomposition theorem [17]. Although the order of the ARMA model might become ultimately high, prediction can be easily calculated by off-the-shelf statistic software. The observation and analysis of the measured data suggest that a (time sensitive) site-specific wireless design is appropriate for this application.

5. Identifying Reliable System Characteristics

5.1 Introduction

In this project, we explored identification of needed specifications for a wireless system. For this purpose we have to set general bounds on some system parameters. For instance, when using proper modulation, increasing the power results in a decreasing error rate; however, the output power of the devices must meet FCC requirements so the power has to be limited. On the other hand, we need to introduce minimum requirements for our communication network to insure that the wireless system is capable of carrying out its functions. For example, the baud rate of the devices should be high enough for timely data communications.

5.2 Achievable Baud Rate for a Wireless Channel

Structures that have fewer metal and hard partitions typically have small rms delay spreads on the order of 30 to 60 ns. Such structures can support data rates in excess of several Mb/s without the need for equalization. However, larger buildings with a great deal of metal and open aisles can have rms delay spreads as large as 300 ns. Such buildings are limited to data rates of a few hundred kilobits per second without equalization. This is what we also expected in our substation applications.

5.3 Maximum BER for Data Devices

The probability of a bit error, which is also known as Bit Error Rate (BER), determines the quality of the transmission system. Generally, speech transmission requires a BER of order 10^{-6} or less, and video transmission requires BER of less than 10^{-7}. Maximum BER of data devices should be less than 10^{-5}. This is the value that we chose in this project. In practice, using bit and block level codings, the achievable BER would be even smaller than this value, but for modulation analysis, we consider this value as a hard limit.

5.4 Necessary Response Time for the Wireless Device

Although monitoring is not as critical as controlling for substation applications, the data transmission should not be bottlenecked by the response time of the wireless device. Hence, the wireless transmission speed and its response time should not restrict the maximum data rate and minimum response time of the data acquisition devices.

5.5 Antenna

The gain of the antenna depends on the size of the antenna, the operating radio frequency and the efficiency with which it focuses the radio waves. It is expressed (theoretically) relative to the performance of an isotropic antenna that radiates equally in all directions. By definition, the isotropic reference antenna has a gain of 1 or 0 dB. Directional antennas are used in the applications where coverage over a sector by separate antennas is desired. Point-to-point links also benefit from directional antennas.

In our application, however, the physical structure of substations does not always allow the use of directional antennas. We considered using 0 dB omni-directional antennas (without any amplifiers) during our measurement process. Given the proximity of the devices, we think that this type of antenna would have been sufficient. In practical applications, utilization of other types of high-dB antennas (i.e., high gain antennas) in substations is often impractical since these types of antennas are usually taller and, therefore, prone to being struck by lightening in such high-voltage environments.

Antenna diversity can also be used to combat the multipath and delay spread impacts on wireless channels. This will also improve the performance (decrease the packet error rate) of the system. There are a number of solutions on the market utilizing this low-cost diversity benefit. The physical separation between the antennas defines the delay spread tolerance needed for optimal communication.

5.6 Power Supply and Galvanic Isolation

Traveling waves and unstable grounds can damage the susceptible wireless solution. Proper galvanic isolation and grounding should be implemented to avoid these probable damages. The antenna should be grounded via a grounding conductor. The power supply should be equipped with solid-state surge arrestors and, wherever possible, tetherless devices are preferred to using batteries for direct supply of their electronics. If technology trends allow battery usage for wireless devices for this application, then using spread spectrum communications may be questionable, as described in section 2.6 of this report. As noted previously, the radios can still operate within the ISM license-free spectrum.

5.7 Adequate Data Security

The present commercial wireless systems do not offer features that prevent unauthorized interception of signals and data. Even data security of IEEE802.11 is in question. One solution is to use non-standard schemes for those applications that demand higher network security. The importance of this issue for our application also requires detailed investigation.

6. Conclusion

We have first identified the noise sources and their statistical behaviors in a substation environment. Given these noise profiles, the assumed conditions under which regular wireless systems are designed, may not hold true anymore. To investigate this, we considered the worst-case (i.e., worst noise) analysis for these two core modulation formats: Direct Sequence Spread Spectrum (DSSS) and Frequency Hopping Spread Spectrum (FHSS). According to this worst-case analysis, given the same noise power, the performance of the DSSS is approximately 5 dB superior to that of FHSS. However, assessment of the likelihood of the occurrence of these worst-case situations in a substation requires field measurements of the noise profile. The result of the measurement cannot only affect the practical preferences in selecting one of these modulation schemes, but also reveals the capacity bounds for the wireless network.

In this project, we have focused on a few key issues we believe are important for consideration when implementing a wireless network. One set of the measurements was conducted using FreeWave Modems. The setup was equipped with the diagnostic kit used for communication network assessment in laboratories. Many modifications, verifications and programming were performed in the system to enable us to hit our measurement targets. Diagnostic capability of these devices allows us to perform a few measurements (such as signal and noise power levels, packet loss, temperature and daily/weekly noise variation) in one-minute time intervals. Another set of measurements were conducted utilizing BreezeNet IEEE802.11-based radios. Quality parameters of the latter setup were recorded in one-second intervals.

The characteristics of the data set that we gathered from the substation site survey indicates that the classical distributional analysis is not an appropriate approach for prediction. The measured data has a strong non-random component with long-time memory and a stationary internal structure, which calls for time series analysis. This structured can be modeled with an ARMA model according to the Wold’s decomposition theorem. Although the order of the ARMA model might become ultimately high, prediction can be easily calculated by off-the-shelf statistical software. The analysis of the measured data suggests that wireless communications design should be site-specific for substation applications. Considering this a-priori knowledge, the wireless system analyst can optimize the best time of the day/week for on-site wireless network analysis.

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