Wireless Data Communication in Substations

Final Report

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Preface

The PSerc, National Science Foundation Industry/University Collaborative Research Center, sponsors this research project titled “Power System Monitoring Using Wireless and System-Wide Communications”. This project consists of two parts:

Part I. Wireless data communications in substations
Part II. Mobile Agent Solution

This is the final report of the first part of the project on “Wireless Data Communication in Substations”, which outlines the research project activities carried out by Electrical Engineering Department of Texas A&M University.

The following TAMU personnel have participated in this project:

- Dr. Mladen Kezunovic, Eugene E. Webb Professor, Principal Investigator
- Alireza Shapoury, Graduate Research Assistant

We also thankfully acknowledge the active contribution of FreeWave Technologies and Alvarion Ltd in providing us the required provisions to conduct some measurements using their products.

Texas A&M University, October 15, 2002
Executive Summary

This report concerns wireless application in substation environment for monitoring purposes. Software, firmware, hardware, and the transmission media have significant bearings on the performance of the ensemble system-wide wireless communication. We have elaborated in this report mainly on the physical layer characteristics, since this layer is the most differentiating part between this application and other well-addressed applications.

The first part of this report characterizes the particular transmission media of the substation environment based on the previous measurements as well as the assumptions and analysis, which are found in the standards and technical literature. Then we investigate the corresponding probable impacts on main Spread Spectrum modulation techniques. Based on this review, we conclude that realistic impacts on these modulation schemes can be determined by a comprehensive measurement campaign. Several scenarios have been considered for measurement part. The desired measuring statistics were identified for each test run and the required measurement devices, configurations and operation modes were carefully selected, programmed and modified accordingly to serve the purpose of the project. The actual field tests have subsequently been conducted in several substation yards and the recorded data were acquired for post-processing.

Our statistical analysis suggests that the widely used classical distributional analysis is not appropriate unless incorporated with time series analysis.

We investigated the potential impacts of substation slow varying and fast varying electrical and environmental processes on wireless link quality and presented general recommendations for the wireless system candidates at the end of the report. As an example, we noticed that signal level variations have a strong dependency on the location of the substation (e.g. in rural or industrial regions) rather than the variations on the substation power delivery. Furthermore, this report implicitly presents a methodology for wireless site survey, which can be adopted for other relevant power system applications.
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Texas A&M University, October 15, 2002
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 followings 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 of data acquisition and I/O (large scale operation)

Substation switching operation, corona effect, and gap discharge breakdown are among major causes of high frequency electromagnetic interferences, which directly impact the wireless connection quality. Furthermore, the radio wave propagation influences wireless communication in substations in several ways. Antenna gain, size and electrical isolation and grounding are among 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 yet feasible wireless solution 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 of the detrimental effects of switching transient fields on the VHF or UHF and other radio band channels ([1], [2] and [4]). This project tries to offer the most appropriate wireless strategy for substation environment. Equipment layout, metallic bodies of obstacles, multipath propagation, antenna displacement, robustness and security are among major issues, which call for a separate analysis for this special application with respect to other widely considered wireless system environments. To our knowledge, no specific experiment has yet been done about the detrimental effects of impulsive power station noises on the Industrial, Scientific and Medical (ISM) frequency band wireless channels, which are dedicated by FCC for such purposes.
To perform an accurate comparison analysis among different wireless implementations, measurement and inspection of a wide spectrum of modulation, coding and implementation techniques are required. 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 adopted approach in this project. We first improve our understanding of the noise profile in substation environment as well as the wireless channel behavior. Then we tried to develop realistic models, and validate them. We try 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, which are used in the off-the-shelf devices. We have contacted several vendors that supply the wireless devices and also traced other similar activities 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 a place/time to another. Several measurements have been comprehensively conducted since 35 years ago in this regard [4]. On-going technological changes, channel utilizations, atmospheric impacts and other parameters necessitates frequent and updated measurement and comprehensive analysis campaign. This analysis might suggest considerable changes to the man-made noise model, which is presently used in radio link design. Proximity, power settings, number of the wireless devices in the network and even choosing 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 would not improve the link quality, while power setting is a crucial factor in noise-limited channels [6] (If we double the transmission power level from all wireless devices, they will cause twice as high 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 particular strategy for analysis of wireless link for substation applications. In this part we shall introduce some basic knowledge about the so-called man-made noises and their 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 has been explained in the third part of the report. In this section, first few key parameters that we shall use in our analysis have been introduced then the available methods of measuring these parameters have been proposed and the appropriateness of deploying these methods are investigated. In the fourth part of the report, the empirical results have been presented and analyzed. Based on the post processing in this subsection, a generalized methodology for wireless survey in substation environment has been 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 basically 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, we have investigated the impact of the transient noises 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, which is discussed in the next section. The measurement helps us understand the detrimental impact of these noises on selected modulation schemes.

2.2. FCC Regulations Regarding ISM Frequency Band Usage

The Federal Communication Commission’s (FCC) has allocated three frequency bands in Part 15 of the FCC Regulations to operate on a secondary basis. The primary users are government systems and industrial, scientific, and medical (ISM) users. While 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. 30dBm) 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 half a mile. Non-spread spectrum devices in this frequency range are limited to approximately 0.07 watts of output, which 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.
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 impulsive 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 impulse noise, hits, and jitter.

![Figure 1 A simple base-band model of impulsive noise](image-url)
2.4. Noise Sources In Substations

We refer to term noise as an undesired disturbance within the frequency band of transmission. In radio transmission we specially are 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. Cautions 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 the impact of which is stronger.

There are two main types of radiated radio noise sources in substations: [3]

a) Gap breakdown
b) Line conductor corona

Gap discharge radio-noise is produced by a rapid flow of electric current in the air gap existing 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. Basically in power-line applications random noise (often considered Gaussian), is a component of the total noise caused by the discharge[11].

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 sources 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) [4].

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 here normalized the transmission time slots to one). We assume that the pulse width is greater than $T_b$. This is however a valid assumption for data communication in ISM frequency bands.
Calculating the bit error probability results in [6]:

\[ P_b = \rho \cdot Q\left( \sqrt{\frac{2E_b}{N_j}} \right) \]

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

\[ N_j = \frac{J}{W} \]

In which \( J \) is the total time-average power of the transient noise in the bandwidth frequency of our spread spectrum transmission \( W \). The detailed calculation can be found in [6].

For data devices BER should be typically less than \( 10^{-5} \). Proper source coding usually decreases this amount. According to the above formula, to achieve a low BER we can do the followings:

1- Increasing \( E_b \): FCC set certain limitations on increasing the signal power.

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

**Figure 2** Variation of BER with respect to \( \rho \) in DSSS

Differentiating the above equation with respect to \( \rho \), the value of \( \rho \) that maximizes the bit error probability is calculated as follows:
Figure 3 Comparison between a constant power noise $\rho=1$ and worst-case high power transient noise $\rho=\rho^*$.

Figure 2 shows the distinct difference between a constant power noise $\rho=1$ (which is often the case for calculating the performance of the DSSS) and our worst-case high power transient noise $\rho=\rho^*$.

It is worth noting the 40dB difference in the signal-to-noise ratios (SNRs) between these two cases. This apparently shows that high power transients can do a lot of 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 the power line switching activities).

2.5.2. FHSS

Like for the 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 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.

Bit error probability calculation for FHSS results in:

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

Figure 3 shows the impact of the partial-band noise on bit error rates versus different signal to interference ratios.

![Figure 3](image)

**Figure 3** Variation of BER with respect to \( \rho \) in FHSS

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

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

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

Texas A&M University, October 15, 2002
2.5.3. Crude Comparison of DSSS and FHSS

A true efficiency tradeoff between FHSS against 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. It is worth mentioning in here that FHSS uses a sort of nonlinear modulation from the implementation perspective and consumes less, 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.

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. Note the difference in the definition of the fraction $\rho$ 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 the performance. The combination of these two types of noises, given constant noise power, would give the same result as for the partial-band noise alone.

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

Texas A&M University, October 15, 2002
2.6. Scenarios In Which Spreading The Spectrum Is Inefficient

In 5.6 of this report, it is noted that one can use tetherless batteries to 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 [7]. Although 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, but then 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 less power is injected to the wireless channel, the more capacity is available for the wireless network. Fortunately nowadays 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 the DSSS indicates approximately 5dB 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. This can not only result in practical preferences in selecting one of these modulation schemes, but also reveals the capacity bounds for 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 here we narrow down our survey to substation noise impacts on 900MHz ISM and 2.4GHz frequency bands. (ISM stands for the Industry, Scientific, and Medical).

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 [9]. 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, and it determines fundamental quantities such as transmitter power requirements, coverage areas, and battery life. Time dispersion arises due to 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 ($\tau$) 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 $\tau$, $\sigma(\tau)$, 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, which constitutes the object of the particular reception and is conveyed over the wireless link. Furthermore in here, the generally used term “noise” addresses the 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 dominancy of substation noises, we ignore the (slow/fast) fading components in this application. Furthermore in power-line applications the random noise is considered a component of the total noise caused by discharge [11]. We expect to observe three types of noises in substation applications; background noise, incidental impulsive noise and unwanted signals.

We define the background noise 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 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 (peak detectors) for long runs and recording the receptions during tripping, investigating the seasonal effects and climate impacts.

Most wireless devices interpret the signal levels using RSSI values, which is 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 vendor companies usually provide the RSSI to dBm conversion table instead. New devices have the ability to report the signal levels in dBm format. RSSI is basically defined by the firmware design and different companies calculate the RSSI for their devices differently. In here we convert the values to dBm values and then to voltage levels as our analysis 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 seasonal trend. The sources of these trends are weather cycles, seasonal interferences from other devices using the same frequency bands, diurnal variation of electrical power consumption (which may lead to noise variations), etc.

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

The goodness of measurements is quantified in terms of bias, short-term variability or instrument precision, day-to-day or long-term variability and uncertainty. The continuation of goodness 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 characterization 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
the 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,
which are basically designed for a drive-in type measurement.

3.4. Testing Practices

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

For the reader, who is more interested in various measuring instrument, we
have provided Appendix B, where we listed a few typical measuring
instruments, which we believe, are appropriate for the purpose of this project.
We manage to record empirical data from two of these experiments while the
other two resulted in our further hand-on knowledge about the most appropriate
and yet available measurement procedure and setup for 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
resulted 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, which 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 still lift up the veil of the few transmission impairments, these methods are unable to detect digital modulation impairments. For example in spread spectrum technology, the 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. Especial tools are required to measure quality parameters such as signal to interference ratio, bit or packet error rates, pilot pollution, etc.

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

First lets review SIGTEK ST-515 channel sounder, which was available to us, to get more acquainted with 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. 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. 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.”

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1 The technical description and corresponding figures of ST-515 set are excerpted from SIGTEK, the software radio company (Tech Brief Using the ST-515 Save Snapshot and Bulk Processing Features, by Heidi Pohlhaus), with slight modifications.

Texas A&M University, October 15, 2002
Figure 7 SIGTEK ST-515 typical bulk processing display (www.sigtek.com)
As can be seen, the characteristics of the device offer strong capabilities. In our first try, we setup 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 reposition of the device for each measurement run. As a general rule of thumb, the testers should avoid long cable runs for receiver power supply or use the battery operated portable power supplies (UPS), deploy poly-phase surge arrestors for antenna protection and 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 345KV yard. Conducting 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). 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 obeying the clearance from the overhead power-lines, sometimes make line-of-sight links impractical. So practically 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 is placed in a stationary position near the control room, where the base unit is more likely to be located, while the receiver will be 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 here, 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 has been chosen since it is almost located in the middle of the ISM band. Generally speaking channel 1, 6, and 11 are used since these channels produce the least interferences 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)](image)

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

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2 Berkley Varitronics Systems, Grasshopper manual version 1.9

Texas A&M University, October 15, 2002
to aid in finding the proper disposition of the hub and access points throughout the network. The device is capable of 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.

![IEEE802.11b Access Point (AP)](image)

**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.

![Grasshopper device, measurements are taken behind the metallic cubicles at different locations](image)

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

The gathered data is then incorporated to the model, which is 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 $X (\sigma)$ 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, which 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 the fact that shadowing may occur at some locations and not others, etc.

Introducing a new random variable for taking the physical features of the propagation environment improves our model. We call it $X_e$. Hence the path loss model becomes:

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

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

Obviously 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 substations works for another substation, even if they are similar in layouts. Having said that, we attempted to work out the problem with linear regression method and resulted in too many outliers to maintain the model conformity. As to the above setbacks, we skip reflecting 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. –75dBm by manufacturer recommendation of the testing instrument).
3.4.3. 900MHz Long-Term Site Survey

Although the Spread Spectrum Modems are not the best fit for our application, we use as much hardware and software features available as possible to get more active acquaintances with the wireless channel.

Fortunately the diagnostic kit of FreeWave® modem devices has become available to us, which allows long-term field surveys in our test sites. Thanks to the active cooperation and technical feedbacks from of the vendor, we managed to program and configure a setup to meet our measuring 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 time observation of the “signal-to-noise” variations.

The setup consists of wireless modems, data devices and a processing unit. The modems operate at 900MHz. The processing unit fetches the wireless quality parameters from the modems. We programmed the setup in such a way to

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, which we call here 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. 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, which records the received data. This data is juxtaposed 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 to the substation. The repeater radio is placed at the farthest circuit barker away from the slave and from the master radio (i.e. next to the control room). The reason that we used a repeater radio is to gather as much data as we can from our measurement to have bigger statistics. Note that 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 slave radio by this layout.
The problem with the above setup is the requirement for proper ventilation and air conditioning for the slave data device.

Figure 15 shows the revised setup plan, which relaxes the requirement for having a data device (Notebook or laptop 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 the slave radio.

This measurements need to be performed for different voltage-level substation and the test runs for continuously for few days.

The average signal and noise levels for modem devices can help us understand the power requirements, error probability and the noise profile in substation environment.

The observation of the probable variation of noise level during the day is 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, are investigated.

Unfortunately delay-spread cannot be measured by this setup and needs other measuring instruments.
3.4.3.2. Actual Measurement Setup

Two laptops were deployed and programmed to emulate the continuous data communication to the virtual circuit breaker 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 inappropriate in this case [9]. 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 (34.5KV, 138KV 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 902 to 928MHz frequency spectrum (Each reading is about a 20 ms and the sample interval is approximately 5 seconds.) If multiple samples are taken at the same frequency in the time period, the most recent sample is most significant with a
weight of 256 and a value that had been sampled 255 samples back will have a weight of one. The average noise was calculated and recorded each one-minute using the above procedure. Hence there are more than 20,000 observations per our dataset. 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 and our readings. The instruments have negligible or no correlation to the temperature deviation within the nominal range [5].

The resulting data of this setup have been used for 900MHz analysis part of the rest of the project.

Figure 16 Master radio data device and the diagnostic computer
3.4.4. 2.4GHz Long-Term Site Survey

We conducted a similar setup plan for 2.4GHz 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 far end of the substation attached to the circuit breaker metallic structure. The Radios use 79 channels within 2400 to 2483.5 MHz frequency
range using 9 hopping sequences per each hopping set. A program has been designed to peek continuously the link quality data from the radios, seeing that this feature was not a built-in function in the device. These data then was transferred and gathered and recorded each second. Specific provisions made to avoid data congestion while polling the data from the radios.

The bandwidth occupancy of 2.4GHz frequency band is lower than that of 900MHz; hence we expect to experience less interference from other radios in this spectrum. We skip explaining the installation details, as it was pretty similar to the previous setup plan. The measurement runs implemented in two 14-days periods, one in 138KV yard and the other in 345KV yard of the substation. These testing periods are chosen 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 basically 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. Further to this, 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, which was provided by the vendor company. The recorded data from this experiment have been utilized for 2.4GHz analysis part of the rest of 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 in the previous part. Wireless channels are in general hard to analyze since the dynamism of the propagated signals are constantly changing by time and position. The communication medias for one yard to the other yard of even the same substation are not the same. Surfaces of the metallic and non-metallic structures in the substation contribute to the amount of the 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. It is worth noting that 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 pick just one data set achieved from our measurement and proceed with the analysis in this report, unless we specifically point out the non-conformity of the other data sets for this analysis. This is done to maintain the flow of our reasoning. For the reader who is interested in the results of each data set, we provide Appendix C, in which we echoed the outcomes of other data sets.

4.2. Methodology

There are basically three popular data analysis approaches that we can adopt here: Classical, Bayesian and Exploratory Data Analysis. The difference among these approaches which all yield to 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 a Bayesian analysis, data-independent distribution is imposed on the parameters of the selected model according to the engineering knowledge of the analyst. The analysis thus consists of formally combining both the prior distribution on the parameters and the collected data to jointly make inferences and/or test assumptions about the model parameters. Finally, for Exploratory approach, the data collection is not followed by a model imposition; rather it is followed immediately by analysis with a goal of inferring what model would be appropriate.

Many of the radio engineers adopted the Bayesian approach, as there already exist 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 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 is defined by experience and theoretical conjecture for 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 methodology as mentioned before an a-priori (distributional) model is defined before the analysis. In our case, nonetheless, it is basically hard to identify a hypothetical distribution in the first place, which copes with the empirical data. A suggested noise distribution of a typical substation is discussed in [2]. The suggested statistics depends 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 practically intricate to define an all-round 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 normal distribution of the observation 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 normal a distribution.
Figure 18 Run Sequence Plot of Noise Voltage
Figure 19 Sample Autocorrelation Plot (900MHz measurement setup)

Figure 20 Sample Autocorrelation Plot (2.4GHz measurement setup)

There are other tests, which 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 explicit form of nor the value of certain parameters in distribution model. These tests 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 [10] has been considered to be the most appropriate tool for our scenario among other non-parametric tests. This is the method, which has been suggested by IEEE [9]. Statisticians however prefer to use the modified K-S test; the Anderson-Darling (A-D) test [15]. A-D gives more weight to the tails than does the K-S test. The A-D test makes use of the specific distribution in calculating critical values. This has the advantage of allowing a more sensitive test and the disadvantage that critical values must be calculated for each distribution. Tables of critical values are already available and are usually applied with a statistical software program.

4.4. Statistical Confidence of the Results

IEEE recommendation for site survey suggests using Kolmogorov-Smirnov method to calculate the statistical confidence of the measurement. This approach works only when the Cumulative Distribution Function (CDF) is reasonably continuous.

In practical measurement, we do not have always the luxury of having both a high-resolution measuring device and a large dynamic range, which is 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 Cumulative Distribution Function. The other way to work around the problem is to use Moving Average technique to make a practically continuous cumulative distribution. Fortunately, our measurement setup allows long duration survey and consequently large size for our data set (more than 14000 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 21 shows the Cumulative Distribution Function of 345KV substation yard.

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

This is a measure of the confidence in our data sampling and the results are independent on the form of the distribution function which characterizes the observe data [9]. Table 1 gives the calculated confidence percentage 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.

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 part we will show that unfortunately there are some fundamental problems that makes this analysis in question. We still keep this part as an effort to follow IEEE recommendations on the site survey.

![Cumulative Distribution Function (CDF) of the measured data](image)

**Figure 21** Cumulative Distribution Function (CDF) of the measured data

Texas A&M University, October 15, 2002
### Table 1 Expected Deviation With Respect To Confidence Levels For 900MHz Measurement

<table>
<thead>
<tr>
<th>Confidence Level</th>
<th>%80</th>
<th>%90</th>
<th>%99</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected Deviation from the median</td>
<td>$5.37 \times 10^{-4}$</td>
<td>$6.12 \times 10^{-4}$</td>
<td>$8.18 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Let’s now probe our data to see if the results basically suggest the use of distributional measures discussed above. Randomness is one of the key assumptions in determining if the statistical process is in control. If the assumptions of constant location and scale, randomness, and fixed distribution are reasonable, then the univariate process can be modeled as:

$$Y_i = A_0 + E_i$$

Where $Y_i$ is the observed variable $A_0$ is source data and $E_i$ is an error term.

If the randomness assumption is not valid, then a different model needs to be deployed. This will typically be either a time series model or a nonlinear model (with time as the independent variable).

Figure 18 shows the run sequence plot. It indicates that the data do not have any significant shifts in location or scale over time (hence stationary).

Autocorrelation plots [13] are commonly used for checking randomness in a data set (The formula, which is used in [13], is in autocovariance sense). This randomness is ascertained by computing autocorrelations for data values at varying time lags.

The sample autocorrelation (autocovariance) plot (which is Figure 19 for 900MHz and Figure 20 for 2.4GHz measurement setup) 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 since determining the distribution of the data is only meaningful when the data are random. The plot exhibits an alternating sequence of positive and negative values, which are mildly decaying to zero. Figure 22 indicates the lag plot of the data, which further shows the presence of a few outliers in our data set. The above plots reject an appropriate distribution model for our dataset.
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, meanwhile 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 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 parts we will attempt to fit an appropriate model based on the data structure.
Figure 23 Recorded Noise Values For Typical Days of These Two Weeks
4.5.1. Ambient Temperature Independency

To better investigate the probable relationship between the parameters, scatter plot has been deployed. Scatter plot is a useful diagnostic tool for determining association. This is a simple probe to rule out the causality, if there exists no association between the data set.

However if such association exists, the plot may or may not suggest an underlying cause-and-effect mechanism. In other words, causality implies association however the presence of association may not necessarily proves cause and effect mechanism.

Figure 24 shows the scatter plot of the measured noise level versus the ambient temperature. The lack of predictability in determining the noise level from any given value of temperature, and the associated amorphous, non-structured appearance of the scatter plot, leads to conclusion that there is no relationship (or correlation) between the temperature and the noise signal level, hence we rule out a dominant causality of the temperature on the noise level.

![Figure 24 Scatter plot of the noise level versus the ambient temperature](image)

Figure 24 Scatter plot of the noise level versus the ambient temperature
4.5.2. Substation Load Pattern Impact on 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 25 shows the variation of the load pattern in substation during a typical day.

![Figure 25 Transformer Load versus the Noise Variation in 2.4GHz](image-url)
It is a trivial fact that the load pattern per se follows a time-series process. Hence in here we juxtapose the time series run sequence of the load pattern with the run sequence of our radio quality. Figure 26 shows the scatter plot of these two parameters.

![Figure 26 Scatter Plot of 138KV Transformer Loading versus the Noise Level at 2.4GHz Frequency band](image)

* 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 we the units have been taken off from this axis.

As it is seen from the graph although in the early morning there is a negative correlation between the transformer loading, this correlation disappears during the daylight. Hence in sum, the transformer loading does not show any contribution to the noise level.

Figure 27 and Figure 28 verifies the same reasoning for 900MHz frequency band.

For both 900MHz and 2.4GHz frequency bands, we analyzed the instantaneous ingoing/outgoing voltage values, power factors, ambient temperatures as well as transformer temperatures and have found no obvious
correlations of these parameters to the variation of the noise average in long-term survey.

It is worth noting that the variations of the average of the noise have been focused in this part and not the real-time noise levels.

![Transformer Load versus the Noise Variations in 900KHz](image)

**Figure 27** Transformer Load versus the Noise in 900MHz Frequency band
Figure 28 Scatter Plot of 138KV Transformer Loading versus the Noise Level at 900MHz 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 from this axis.

4.6. Univari ate Time Series

A common assumption in many time series techniques is that the data are stationary. If the time series is not stationary, we can often transform it to stationarity and stabilize the variance across time. Although seasonality also violates stationarity, this is usually explicitly incorporated into the time series model. In our case, run sequence shows almost constant location and scale and 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) [12], hence we adopt ARMA modeling approach. Based on the 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 shall inspect the residual to ensure that it has a Gaussian distribution. This would justify the goodness of our fit.
Box and Jenkins [13] popularized an approach and developed a systematic methodology for identifying and estimating ARMA models. We shall deploy Box-Jenkins systematic approach to model our dataset. The next step is to determine the order of the autoregressive and moving average terms in the Box-Jenkins model. After fitting the model, we should validate the time series model. The primary tool for validating the model is residual analysis.

4.6.1. Model Identification

The autocorrelation plots (Figure 19 and Figure 20) 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 29) 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 is to fit an AR(8) model. Model validation rejects this model since the resulting residuals fail to have a random Gaussian distribution. On the other hand the presence of peaks and trough in the run sequence plot suggest ARMA models as another potential fit. We adopt this more generalized model here from now on.

First, we use Akaike’s Information Criterion to find a full AR model [12]. We use readymade statistical software for this purpose. An AR (27) model will fit our data best.
Second, we use stepwise ARMA method to look for subset AR and obtain the alpha coefficient.

It suggest an AR(21) model with AIC=-4744.27 to be a better fit than full AR model. Third, we use stepwise ARMA method to look for a subset ARMA model we achieve p=36 q=24 (i.e. the orders of our ARMA model) having an AIC=-4812.06, which is less than full AR model. Now we need to estimate our model’s parameters and find the residuals. We use the Marquardt algorithm to calculate the MLE for the parameters of our model [12]. We get -1.0174, 0.6803, -0.3740, 0.0726, -0.0306, -0.0377, -0.3446, -0.9222, and 0.3474. These are our alpha1, alpha2, alpha3, alpha17, alpha29, alpha36, beta3, beta21 and beta24.

4.6.2. Model Verifications

Now we have to check the residuals of our model, if these residuals are white noise, then the chosen model is judged to be a proper fit. Using Q-test we got p-value of 0.0736. Hence we don’t have significant evidence rejecting the hypothesis that the residuals are white noise. Hence ARMA (36,24) is our final model. If we fail to receive a residue of Gaussian noise, we shall redo the procedure afresh to achieve better ARMA model.

4.7. Conclusion

The characteristics of the dataset 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 statistic software. The observation and analysis of the measured data suggest (time sensitive) site-specific wireless design for this application.
5. Identifying Reliable System Characteristics

5.1. Introduction

Here we try to identify the needed specifications for a wireless system regarding this project. For this purpose we have to set general bounds on some system parameters. For instance, when using proper modulation, increasing the power results in decreasing the error rate, but the output power of the devices should meet the 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 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 300ns. Such buildings are limited to data rates of a few hundred kilobits per second without equalization. This is what we also expect 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 consider in this project. In practice, using bit and block level codings, the achievable BER would be yet 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 performing control for substation applications, the data transmission should not be the 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 us to use the directional antennas. We considered using 0-dB omnidirectional antennas (without any amplifiers) during our measurement process and we think that given the proximity of the devices this type of antenna suffices.

In practical applications utilization of other types of high-dB antennas (i.e. high gain antennas) in the substations is often impractical since these types of antennas are usually taller and thus prone to being struck by lightning 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, which is 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 grounding conductor. The power supply should be equipped with solid-state surge arrestors and wherever possible, the tetherless devices are preferred to using batteries for direct supply of their electronics. If the technology trends allow battery usage for wireless devices for this application, then spreading the spectrum becomes in question as described in section 2.6 of this report. Worth reiterating is that in this recent case, 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 could prevent unauthorized interception of signals and data. Nowadays, even data security of IEEE802.11 is in question. One solution is using non-standard schemes for those applications, which demand higher, network security. The importance of this issue for our application also requires a close investigation.
Conclusion

We have first identified the noise sources and their statistical behaviors in a substation environment. Given these noise profiles, the initial 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 5dB superior to that of FHSS. However, assessment 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 can not only affect the practical preferences in selecting one of these modulation schemes, but also reveals the capacity bounds for the wireless network.

In here we have focused on a few key issues we believe are important for consideration when implementing a wireless network. One set of the measurements is conducted using FreeWave Modems. The setup is equipped with the diagnostic kit, which is used for the communication network assessment in laboratories. Many modifications, verifications and programming have been performed in the system to enable us to hit our measuring 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 the measurements is conducted utilizing BreezeNet IEEE802.11-based radios. Quality parameters of the latter setup were recorded in one-second intervals.

The characteristics of the dataset 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 statistic software. The observation and analysis of the measured data suggest (time sensitive) site-specific wireless design for this application. Considering this a-priori knowledge, the wireless system analyst can optimize the best time of the day/week for on-site wireless network analysis.
References


Texas A&M University, October 15, 2002

A Quick Evaluation of the Existing Wireless Candidates

In here we try to categorize the existing off-the-shelf wireless devices according to their present or potential capabilities for substation usage. We do not indicate the superiority of one specific device over the other. According to the authors' knowledge, no theoretical analysis or accurate performance measurement has been conducted for these devices in substation environment. This part is just an “application-oriented” study of the existing devices, based on the available specifications provided by the vendor companies.

Controlling and Monitoring Considerations

Taking various methodologies into account, one can categorize the devices, based on their connectivity requirements, as follows:

I) Devices that need continuous communication link (e.g. continuous logging of voltages or currents of the network, for remote analysis, fault diagnosis and troubleshooting)
   (a) Devices having step like values (e.g. on, off, warning, excitation or controlling commands)
   (b) Devices that should transmit (digitized) analog data (e.g. the current or the voltage of the network)

II) Devices that needs periodical connectivity: These devices often monitor or control non-critical data and information (e.g. the oil level or gas pressure of circuit breakers). These devices may send a burst of information during their connecting time.
Our Requirements

A) Optimum data throughput for this application
The size of the information transmitted for our application is not large.

B) Connectivity
The connectivity is the most critical issue. The system should be robustly connected and any failure in devices should be detectable by the central computer (housing at the base station). This can be done by synchronous or asynchronous polling method or any other means.

C) Protocol
The device should be IP compatible. The transport protocol should allow real-time monitoring (e.g. RTP/IP)

D) Added Features
The availability of each of the following features is an advantage:
Allowing different Antenna mounting options to suit installations
Roaming across subnets

E) Measurements
We are interested in measuring the following parameters.
- Power output table or graph
- Receiver sensitivity
- Receiver delay spread (multipath)
- Measurements of overrun packets
- Measurements of Fragmentation Threshold
- Measurements of duplicate packets

F) Regulations
The device shall meet FCC requirements.

The following pages categorize the off-the-shelf wireless solution based on their technologies.
Cellular Digital Packet Data (CDPD) Technology

CDPD is a two way digital packet-switching technology that allows carriers to transmit packetized data at speeds up to 19.2 Kbps. This technology already supports TCP/IP addressing and also it supports packet switching, which means that the channel is not necessarily occupied all the time. Each channel stream can support up to 30 users at the same time. As data such as e-mail arrives, it is forwarded immediately to the user without a circuit connection having to be established.

Although no companies have as yet recommended this technology for power industry applications, it can be properly installed and used.

Costs
1) Tariff (3-5 cents per packet)
2) 300-500$ for each device

Advantages
1) Real-time
2) Cellular (so that if a device is in the network, it can be accessed or can access every device in cellular network)
3) Sufficient baud rate for our telemetric requirements (monitoring and control)
4) Ability of contentious connection
5) On-demand occupation of the channels
6) Charged for the amount of data sent
7) TCP/IP addressable

Disadvantages
1) Limited coverage in the United State (See http://www.goamerica.com/coverage/cdpd.html for coverage map)
2) Not much development
3) Although the bandwidth is sufficient for our application, the industry is not throwing its weight behind this technology due to limited baud rate

Service Providers
AT&T, Verizon
Cellular Control Channel Transceivers

Within a cellular telephone system, several of the channels are assigned as 'control' channels. Each control channel set consists of a forward control channel and a reverse control channel. The forward control channel is used to send general information from the cellular base station to the cellular telephone. The reverse control channel sends information from the cellular telephone to the base station and the cellular system.

Cellular Control Channel Transceivers use these control channels for data communication. The provider company makes the devices to be IP addressable.

Costs
1) Tariff (5-10$ /month for one call per day)
2) 125-150$ for each device

Advantages
1) Good coverage in the United State (See http://www.remoteconnection.com/cell_map.htm for coverage map)
2) Already used by industry for monitoring

Disadvantages
1) Latency (15 Sec.)
2) Low data capacity (just 15-25 digits)
3) High Tariff rates

Service Providers
Aeris Microburst Systems, Cellemetry Co. Telemetric
## WLAN 802.11

The IEEE 802.11 Working Group presented a standard for Wireless Local Area Networks (WLANs), allowing for peer-to-peer communication. There are few specifications in the family such as 802.11a and 802.11b operating at different speeds but all of them specify the use of CSMA/CA (carrier sense multiple access with collision avoidance). IEEE 802.11 can be used either in ad hoc network or client/server networks. Ad hoc networking is used between multiple stations while the client/server networking uses access points. Access points are used to handle traffic from the mobile radio to the backbone of the client/server network. The backbone can be wireless, wired or fiber optic. A large LAN can consist several Access Points (APs).

General Electric Power Management (GE) already used WLAN for monitoring and control in substations. Although their use of Ethernet is just limited to providing a communication link among the controlling cubicles inside the control room, they maintain that this technology is applicable to the whole substation area. To our knowledge they have not yet done any practical inspection on the reliability of Ethernet use in substation area.

### Costs
1. No monthly fee for frequency occupancy (It works in ISM frequency band)
2. 300-700$ for each access points

### Advantages
1. Fast data transmission (the data communication speed is fast enough to avoid any latencies caused by data collision and channel occupancies)
2. Easily expandable
3. Almost instantaneous connection time.
4. Cellular architecture, allowing several wireless devices
5. TCP/IP addressable
6. Industrially accepted protocol
7. Working over ISM free frequency bands, provided that the system meets FCC power regulation

### Disadvantages
1. No technical inspection on the effect of substation noises on WLAN applications
2. Need for Internet connection for Inter-substation applications
3. Inadequate insecurity

### Service Providers
Lucent, Cisco, Young Design, Inc (YDI), etc.

Texas A&M University, October 15, 2002
Non-standard Spread Spectrum Modems

There are a few spread spectrum products that use ISM frequency band. The major advantage of these devices is their free usage of the frequency band for their transmission. Some of these devices have more networking features and can be programmed to be used as slaves, masters or repeaters. One of the problems with these devices is the incompatibility of different vendor products.

Costs
1) No monthly fee for frequency usage (It works in ISM frequency band)
2) 500-900$ for each access points

Advantages
1) Working over ISM free frequency bands, provided that the system meets FCC power regulation
2) Ability of continuous data transmission up to 11500 bits per second
3) Expandable architecture, allowing connecting several wireless devices
4) TCP/IP addressable

Disadvantages
1) No technical data on the effect of substations noises on these modems
2) Latency in connection (not a proper mean for control applications)

Service Providers
Data Comm for Business, Inc. (DCB), Young Design, Inc (YDI), FreeWave Technologies, etc.
Appendix B

Evaluation of the Appropriate Measuring Instruments for the Project

Unfortunately, the complexity of the setup makes the measurement difficult. Assembling the components of the setup for the purpose of the measurement is hard even for a one-shot measurement. Small movement of the connecting wires would cause the setup to deviate from the correct calibration. There are few compact measurement devices for this purpose in the market, which are basically designed for a drive-in type measurement. An introduction to the features of these devices, vendors and the results of the correspondences with the vendor companies are given in this report.

Device: 8960 wireless communications test set

Company: Agilent Headquarters
395 Page Mill Rd. P.O. Box #10395 Palo Alto, CA 94303
Phone: 650 752 5000
800 452 4844

WEB: wireless.agilent.com

Main purpose: GSM, GPRS, W-CDMA, cdma2000, IS-95, DCS1800, PCS1900, TIA/EIA-136, and AMPS mobile phone testing

Features: RSSI, BER, BSIC, SAT, Channel Number, Ec/Io, Data Throughput

Tuning Range: Covers 900MHz and 2.4GHz

Price: Unknown

Renting Policy: Unknown

This device cannot be used as stand-alone. It requires additional Antenna and measuring instruments for calculating the noise figure.
Device: SIGTEK ST-515 channel sounder

Company: SIGTEK INC.
9075 Guilford Road Suite C-1
Columbia, Maryland 21046

Email: info@sigtek.com
Phone: (410) 290-3918
Fax: (410) 290-8146

WEB: www.sigtek.com

Main purpose: Wireless Channel Sounder

Features:
- Path Loss and Delay Spread Measurement
- Interference Spectrum
- Amplitude Distribution Measurement
- Simple Calibration
- Direct Excel Spreadsheet Data Log
- MATLAB friendly

Resolution: 30 ns

Tuning Range: 2.4-2.483 GHz
- Not proper for ISM 900MHz measurements

Price: Unknown (product discontinued)

Renting Policy: Unknown
Device: Combo (SitePlanner, WaveSpy, Infeilder)

Company: Wireless Valley Communications, Inc.
104 Hubbard Street
PO Box 10727
Blacksburg, VA 24062
Phone: (540) 552-8300
Fax: (540) 552-8324

WEB: www.wirelessvalley.com

Main purpose: Wireless design and archiving environment
Scanning receiver
Site-specific measurement

Features: RSSI, BER, BSIC, SAT, Channel Number, Ec/Io, Data Throughput
Neighbor Lists
Pseudorandom Noise (PN) Code
MATLAB friendly

Tuning Range: 2.4-2.483 GHz

Price: >15000$ (according to options)

Renting Policy: Not provided from the vendor
Device: 8714ET RF Vector Network Analyzer (T/R)

Company: Agilent Headquarters
395 Page Mill Rd. P.O. Box #10395 Palo Alto, CA 94303
Phone: 650 752 5000
          800 452 4844

WEB: wireless.agilent.com

Main purpose: RF component manufacturing, inspection and maintenance.

Features: Narrowband and broadband detection
          100 dB dynamic range
          Real-time sweep speeds (40 ms/sweep)
          Integrated T/R test set
          Synthesized source with 1-Hz resolution
          Standard LAN interface
          Standard Internal Agilent Instrument BASIC (IBASIC)
          Standard 2, 6, and 12-port switching test sets available
          Optional fault-location and SRL measurements

Tuning Range: 300 kHz to 3 GHz

Price: 16,820 USD

Renting Policy: Unknown

This device cannot be used as stand-alone. It requires additional Antenna and measuring instruments for calculating the noise figure.
Indirect Measurement

Device: FreeWave Spread Spectrum Modems with diagnostic kit

Company: FreeWave Technologies
1880 S. Flatiron Court
Suite F Boulder, CO 80301
Phone: (303) 444-3862
Fax: (303) 786-9948

WEB: www.freewave.com

Main purpose: Spread Spectrum Modems

Features: Signal to Noise measurements at each frequency hop
Packet error measurement

Tuning Range: 900MHz (2.4GHz is also available)

Price: Unknown

The device cannot differentiate the multipath component from the transient noises (The multipath component is related to the physical architecture and substation layout).
Device: YBT250 * Y350C Transmitter and Interference Analysis

Company: Tektronix Inc.
Phone: 800 8339200 Option 1
buy@tektronix.com

WEB: www.tektronix.com

Main purpose: Digital and Analog Transmitter Verification for GSM, IS-136 and CDMA

Features:
- Interference Analyst Option
- Power Measurement
- Installation Tx Checks
- MATLAB friendly
- Field Rugged

Tuning Range: 30-2500MHz

Price: 11795.00USD

Renting Policy: Unknown

- It also needs a transmitter set to send digital data (The device then does the interference analysis on the received signal.)
Device: Duet Measurement Instrument

Company: Berkeley Varitronics Systems, Inc.
Liberty Corporate Park, 255 Liberty Street,
Metuchen NJ 08840 USA
Voice (732) 548-3737
Fax (732) 548-3404

WEB: www.bvsystems.com

Main purpose: CDMA Multipath Measurement

Features:
- Multipath and Fast-Fade Analysis
- PN Scanner
- Out-of-network Testing
- In-network testing
- Data Logging Option
- Measurement of Sync Data
- Measurement of Paging Data
- Measurement of Pilot Hole
- Measurement of Pilot Pollution

Resolution: 40-50 ns

Tuning Range: 2.4-2.85 GHz

- Good for ISM 2.4 GHz but not proper for ISM 900MHz measurements

Price: Approximately 80,000 USD

Renting Policy: Approximately 10,000 USD per month, two month minimum
Appendix C

Data Results From All Measurements

The conformity of the analysis and the methodology, which is presented in this report have been examined for each individual data set but were not echoed in the main body of the report to avoid unnecessary repetitions and probable distraction from the core project goal.

The graphs in the next pages show noise voltage and ambient temperature variation versus time in separate yards of different substations (for 900Mhz frequency spectrum). The temperature is depicted as a color bar under the graphs. The darker the color indicates the higher ambient temperature. It can be easily noticed that almost all data sets have distinct characteristics of there own family.

We dropped the vertical axis units since our noise analysis concerns the variations of the received noise by a fixed radio device rather than the absolute value of the noise.
Noise Voltage Variation
(After taking the Moving Average of degree 3)

And

Ambient Temperature
(indicated by color density bar)

Versus Time (34.5KV Yard)
Noise Voltage Variation
(After taking the Moving Average of degree 3)

And

Ambient Temperature
(indicated by color density bar)

Versus Time (34.5KV Yard)
Noise Voltage Variation
(After taking the Moving Average of degree 3)

And

Ambient Temperature
(indicated by color density bar)

Versus Time (34.5KV Yard)
Noise Voltage Variation
(After taking the Moving Average of degree 3)

And

Ambient Temperature
(Indicated by color density bar)

Versus Time (138 KV Yard)
Wireless Data Communication in Substations

Texas A&M University, October 15, 2002

**Noise Voltage Variation**  
(After taking the Moving Average of degree 3)

**And**

**Ambient Temperature**  
(Indicated by color density bar)

**Versus Time (138 KV Yard)**
Noise Voltage Variation
(After taking the Moving Average of degree 3)

And

Ambient Temperature
(Indicated by color density bar)

Versus Time (138 KV Yard)

Texas A&M University, October 15, 2002
Noise Voltage Variation
(After taking the Moving Average of degree 3)

And

Ambient Temperature
(Indicated by color density bar)

Versus Time (345KV Yard)
Noise Voltage Variation  
(After taking the Moving Average of degree 3)

And

Ambient Temperature  
(Indicated by color density bar)

Versus Time (345KV Yard)
Noise Voltage Variation
(After taking the Moving Average of degree 3)

And

Ambient Temperature
(Indicated by color density bar)

Versus Time (345KV Yard)
Noise Voltage Variation
(After taking the Moving Average of degree 3)

And

Ambient Temperature
(Indicated by color density bar)

Versus Time (345KV Yard)
Noise Voltage Variation
(After taking the Moving Average of degree 3)

And

Ambient Temperature
(Indicated by color density bar)

Versus Time (345KV Yard)
Wireless Data Communication in Substations

Noise Voltage Variation
(After taking the Moving Average of degree 3)

And

Ambient Temperature
(Indicated by color density bar)

Versus Time (345 KV Yard in a Non-Residential Region)

Texas A&M University, October 15, 2002
Noise Voltage Variation
(After taking the Moving Average of degree 3)

And

Ambient Temperature
(Indicated by color density bar)

Versus Time (345 KV Yard in a Non-Residential Region)
Noise Voltage Variation
(After taking the Moving Average of degree 3)

And

Ambient Temperature
(Indicated by color density bar)

Versus Time (345 KV Yard in a Non-Residential Region)
Wireless Data Communication in Substations

Noise Voltage Variation
(After taking the Moving Average of degree 3)

And

Ambient Temperature
(Indicated by color density bar)

Versus Time (345 KV Yard in a Non-Residential Region)
**Noise Voltage Variation**
(After taking the Moving Average of degree 3)

And

**Ambient Temperature**
(Indicated by color density bar)

**Versus Time (345 KV Yard in a Non-Residential Region)**
Noise Voltage Variation
(After taking the Moving Average of degree 3)

And

Ambient Temperature
(Indicated by color density bar)

Versus Time (345 KV Yard in a Non-Residential Region)
Noise Voltage Variation
(After taking the Moving Average of degree 3)

And

Ambient Temperature
(Indicated by color density bar)

Versus Time (345 KV-138 KV Yard in a Residential Region)
Noise Voltage Variation
(After taking the Moving Average of degree 3)

And

Ambient Temperature
(Indicated by color density bar)

Versus Time (345 KV-138 KV Yard in a Residential Region)
Wireless Data Communication in Substations

**Noise Voltage Variation**
(After taking the Moving Average of degree 3)

And

**Ambient Temperature**
(Indicated by color density bar)

**Versus Time (345 KV-138 KV Yard in a Residential Region)**

Texas A&M University, October 15, 2002
Noise Voltage Variation
(After taking the Moving Average of degree 3)

And

Ambient Temperature
(Indicated by color density bar)

Versus Time (345 KV-138 KV Yard in a Residential Region)

Texas A&M University, October 15, 2002
Noise Voltage Variation
(After taking the Moving Average of degree 3)

And

Ambient Temperature
(Indicated by color density bar)

Versus Time (345 KV-138 KV Yard in a Residential Region)
Noise Voltage Variation
(After taking the Moving Average of degree 3)

And

Ambient Temperature
(Indicated by color density bar)

Versus Time (345 KV-138 KV Yard in a Residential Region)