In Situ Measurement and Emulation of Severe Multipath Environments

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IN SITU MEASUREMENT AND EMULATION OF
SEVERE MULTIPATH ENVIRONMENTS

A Thesis Presented

by

Stephen DiStasi

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The Faculty of the Graduate College

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In Partial Fulfillment of the Requirements
for the Degree of Master of Science
Specializing in Electrical Engineering

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ABSTRACT

For a variety of wireless sensor network applications, sensor nodes may find their received signal strengths dominated by small-scale propagation effects. Particularly impacted are applications designed to monitor structural health and environmental conditions in metal cavities such as aircraft, busses, and shipping containers. Small changes in each sensor’s position or carrier frequency can cause large variations in this received signal strength, thereby compromising link connectivity. We leverage a technique called Wireless Sensors Sensing Wireless (WSSW) in which wireless sensors act as scalar network analyzers in order to characterize their own environment. WSSW data can enable sensors to react to particularly bad fading, such as hyper-Rayleigh, by switching to a good channel or by implementing other mitigation techniques, such as utilizing a diversity antenna. In this work, the WSSW concept has been extended to accommodate mesh networks and include a spectrum analysis capability for recognizing potentially interfering wireless activity.

The test of mitigation techniques is often problematic since application sites are far from controlled environments and are often difficult to access. To address this problem, we have developed a Compact Reconfigurable Channel Emulator (CRCE) to create a laboratory environment that is configurable to a variety of repeatable fading scenarios. With the CRCE, fading characteristics found at a specific wireless sensor network location may be replicated inside the chamber to discover the connectivity capabilities of the sensors and the effectiveness of diversity schemes (e.g., channel switching or multi-element antenna arrays).
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CHAPTER 1: INTRODUCTION

1.1 Motivation

Within the past decade, wireless sensors have established themselves as being a promising technology to better understand our natural and manmade environments and systems. Existing applications include the use of such devices about airframes for predictive maintenance and non-critical flight systems [1], at active volcano sites for studying patterns in seismic activity to reveal information about volcano structure [2], and on bridges and other civil structures for monitoring structural health [3]. Such wireless systems reduce the cost and weight of installation and also improve long-term reliability over wired systems.

Wireless sensor systems rely on the ability of individual devices to forward data via radio transmissions. If the connection is lost, so is the data; so effort must be made to ensure a consistent wireless link. An often overlooked cause for unreliable links is small-scale fading due to multipath. Multipath refers to multiple waves of a radio transmission arriving with variable delays at the receiver. These additional waves are created by reflections and refractions of the signal off of surrounding objects. The waves may add constructively or destructively depending on relative phase, causing received signal strengths to fluctuate for varying time, position, frequency, and polarization.

These fluctuations in signal strength are referred to as fading, and can sometimes be quite severe. This phenomenon is certainly an issue for mobile applications, such as cell phones, but one which can be mitigated simply by moving to improve reception. For
many sensor systems, however, moving is not an option as sensors are mounted on or within structures. For this reason, understanding the environment encompassing a sensor network and preparing the network to maintain connectivity under varying scenarios is highly beneficial.

1.2 Problem Statement

Recent empirical data collected aboard aircraft [4], helicopters [5] and buses [6] has indicated that it is not uncommon for the multipath fading within these structures to be severe. This result is not unexpected in that these environments are essentially metal cavities. However, the fading statistics within these settings are often found to be more severe than would be predicted using current worst-case (i.e., Rayleigh [7]) fading models. Analytical models for this fading regime, deemed hyper-Rayleigh, were developed and a two-ray model was proposed in [1] to be a new worst-case fading model for this application space. While that work developed a means of categorizing and modeling hyper-Rayleigh fading, presently there are no means to test wireless systems under these conditions in a reliable and repeatable manner. One aspect of the work presented herein is to address this need.

Test equipment such as a vector network analyzer (VNA) may be used to characterize multipath in potential sensor deployment. It is an arduous process, however, moving the VNA, setting antennas in varying positions, and collecting data one location at a time as done in [4, 6]. In addition, many test sites have limited access and so engineers may only get one opportunity to collect all necessary data. As such, there has been work performed toward using sensor nodes themselves to characterize in situ the
channel-selective fading [8, 9] of their environment. These results demonstrated that a sensor node could indeed act effectively as a scalar network analyzer using a method called Wireless Sensors, Sensing Wireless (WSSW). Using sensor nodes for this task saves a tremendous amount of time and effort for an environmental fading analysis, as nodes may already be in place, and are much more easily distributed and configured than conducting network analyzer measurements.

WSSW results to date have demonstrated that a star-network has the means to react to particularly bad fading, such as hyper-Rayleigh, by choosing the best network operating frequency, or by utilizing mitigation techniques such as the diversity antenna presented in [10]. Many wireless sensor networks today, however, are utilizing mesh functionality. In a mesh network, sensor nodes may forward their data to or through neighboring nodes, vastly expanding their communication range and giving them access to network data. Sensor nodes may now make educated in-network decisions without waiting for a central base station to issue commands. Extending WSSW to a mesh network would allow the system to establish low energy, reliable routes for data to pass through the network. In addition, it would highlight unreliable links where additional routing nodes may need to be deployed.

1.3 Thesis Contributions

The work discussed herein addresses such issues of severe fading faced by wireless sensor networks statically placed within enclosed environments. The main contributions of the thesis are as follows:
• **Construction of a chamber capable of creating a wide range of repeatable fading environments through the use of reflecting surfaces.**

This structure, discussed in Chapter 4, will allow engineers to test the connectivity limitations of wireless sensors within harsh time- and frequency-varying fading environments, as well as the effectiveness of mitigation techniques.

• **Construction of a chamber capable of creating a wide range of repeatable fading environments through the use of multiple antennas as well as reflecting surfaces.**

This chamber, discussed in Section 4.5, represents a new technique for creating multipath fading which allows for faster and more controlled time-varying fading environments as well as a wider variety of frequency varying fading environments.

• **Extend WSSW to describe the large and small-scale link effects between nodes of both star and mesh networks over the 16 channels of the 2.4 GHz ISM band.**

The WSSW method has been previously used in star networks in [8], but will be expanded to incorporate mesh networks as presented in Chapter 5. By collecting this data, node or network level decisions may be made to avoid deep fades and potentially high traffic channels.

• **Collecting fading data within chambers using star and mesh wireless sensor networks running the WSSW application.**

This work, shown in Chapter 5, illustrates the usefulness of WSSW and gives a better insight to patterns of fading experienced within wireless sensor networks.
1.4 Thesis Outline

Chapter 1 has presented the growing issue of severe fading encountered by wireless sensor networks placed within enclosed metal structures. Models commonly used to describe these fading environments are discussed in Chapter 2. These models may be stochastic or based on physical phenomena. Chapter 3 briefly covers two structures, anechoic and reverberation chambers, traditionally used for the test of wireless devices. A new chamber design developed specifically for testing wireless sensors in severe fading environments is presented in Chapter 4. The scenarios created within this test chamber emulate those commonly encountered by static deployments within metal cavities. Chapter 5 discusses methods of using sensor nodes themselves to characterize fading environments in situ, allowing them to react to particularly bad fading. This may be accomplished in both star and mesh networks using a technique called wireless sensors sensing wireless (WSSW). Chapter 6 then discusses the results found when placing nodes running WSSW within the new test chamber. Finally, Chapter 7 will conclude the overall significance of the work presented herein.
CHAPTER 2: CHARACTERIZING SMALL-SCALE FADING

2.1 Introduction

As discussed in Chapter 1, wireless communication links often experience large variations in their received signal strengths due to multipath fading. In this chapter, we will present several models developed to characterize multipath environments in order to help systems engineers develop link budgets and understand the limitations of their systems.

Small-scale fading models may be based on physical phenomena or may be stochastic models that have been shown to fit empirical data. Physical models range from Ricean, defined by a strong line of sight link between two communicating antennas, to Rayleigh where there is no line of sight, and then to hyper-Rayleigh, where two strong signal components dominate. Stochastic models include Nakagami and log-normal shadowing.

Since multipath is a random phenomenon, both model types are often represented in terms of their distributions. In particular, the cumulative distribution function (CDF) is often employed to evaluate the probability that certain fades will occur. CDF curves are also useful in displaying the severity of a fading environment and in setting link budgets.

2.2 Physical Fading Models

2.2.1 Multipath Components

Multipath components arrive at a receiver as delayed and attenuated replicas of the original signal. Phase disparity in the multipath waves result in their magnitudes
adding either constructively or destructively. The sum of these signal vectors yields the overall received signal $V_R$ described in the following formula.

$$V_R = \sum_{i=0}^{N-1} V_i \exp(j\Phi_i)$$ (2.1)

From the equation, $N$ is the total number of wave vectors, $V_i$ are the magnitudes of individual waves, and $\Phi_i$ are their corresponding phases. The magnitude and phase components are both assumed statistically independent. The phases are generally treated as independent random variables uniformly distributed between 0 and $2\pi$ [11]. The distribution of the magnitudes is impacted by the severity of the environment.

The impact of multipath is displayed visually in the following two figures, where the left panels show the multipath components received over time, and the right show the corresponding received signal $V_R$ with respect to frequency.

Figure 1. No multipath case: impulse response (left) and frequency response (right)
Figure 1 shows the case where there is no multipath and all received power is result of one incoming wave at time $\tau_0$. Through the Fourier Transform (2.2), we find the corresponding frequency response to be a flat spectrum.

$$H(w) = \int_{-\infty}^{\infty} h(t)e^{-jwt}dt = \int V_0e^{j\phi_0}\delta(t-\tau_0)e^{-jwt}dt = e^{-jwt_0+j\phi_0}$$

$$\Rightarrow |H(w)| = V_0$$  \hspace{2cm} (2.2)

In Figure 2, however, multipath causes several waves to appear at the receiver at delayed intervals and with varying amplitudes and phases. The frequency response in this case shows rapid fluctuations in amplitude; i.e., the amplitude is not constant for all frequencies.

$$H(w) = \sum_{i=0}^{N} V_ie^{j\phi_i-j\omega\tau_i} \Rightarrow |H(w)| \neq K$$  \hspace{2cm} (2.3)

For modeling, it is helpful to group the summation of (2.1) into two different components, a specular component and a diffuse component. The specular component

![Figure 2. Multipath case: Impulse response (left) and frequency response (right)](image-url)
refers to dominating waves, each characterized by its own term, $V_i \exp(j\Phi_i)$, that are independent of the others. We will see later that it is not necessary to consider cases of more than two such waves. The diffuse component is a sum of a collection of independent waves, each with power and phase that is negligible when compared to the total power of the specular component [11].

The received signal strength can thus take the form:

$$V_R = \sum_{i=0}^{N-1} V_i \exp(j\Phi_i) + \sum_{k=2}^{N-1} V_k \exp(j\Phi_k)$$

(2.4)

Specular Component Diffuse Component

In the next section, we analyze the second component of this expression.

### 2.2.2 Rayleigh Fading

The Rayleigh distribution is commonly used to model the worst-case, time-selective fading environment for mobile communication systems [7]. This model represents the situation in which there is no line-of-sight, or other dominant wave, so all received power is from the diffuse component of (2.4). For example, a cell phone operated in an alleyway between two large buildings will likely receive many multipath waves of similar amplitude caused by reflections off the building walls. None of these waves will present a dominant signal, making the specular component of (2.4) nonexistent ($V_1 = V_2 = 0$). This reduces the received signal strength equation to that shown below.

$$V_R = V_{\text{dif}} = \sum_{k=2}^{N-1} V_k \exp(j\Phi_k)$$

(2.5)
The total received power is shown to be the sum of a large number of independent and identically-distributed (i.i.d.) random variables. According to the central limit theorem (CLT), the distribution of this sum approaches the normal or Gaussian distribution. If we consider two such independent normal distributions, \( x \) and \( y \), where \( x \) corresponds to the real part of the signal and \( y \) to the imaginary, we may derive the probability density function (PDF) of the Rayleigh distribution. These PDF’s are shown below, where \( \sigma \) represents standard deviation and \( x \) and \( y \) are two i.i.d. random variables.

\[
p_x(x) = \frac{1}{\sigma \sqrt{2\pi}} \exp \left( -\frac{x^2}{2\sigma^2} \right) \quad (2.6)
\]

\[
p_y(y) = \frac{1}{\sigma \sqrt{2\pi}} \exp \left( -\frac{y^2}{2\sigma^2} \right) \quad (2.7)
\]

Since \( x \) and \( y \) are independent, their joint distribution may be calculated by multiplying the two equations above.

\[
p_{xy}(x,y) = p_x(x) \cdot p_y(y) = \frac{1}{2\pi\sigma^2} e^{-\frac{(x^2+y^2)}{2\sigma^2}} \quad (2.8)
\]

Converting this distribution to polar coordinates allows the magnitude of the fade to be represented by \( r \), as shown in (2.9).

\[
r = \sqrt{x^2 + y^2} \quad (2.9)
\]

The conversion of (2.8) from Cartesian \((x, y)\) to polar \((r, \theta)\) coordinates requires a change of variables, where finding the Jacobian determinant \((dx\,dy = R\,dR\,d\theta)\) is
necessary. Substituting (2.9) into the result of this conversion will yield (2.10), where the
distribution for \( r \) is Rayleigh. The phase distribution for \( \theta \) is uniform (2.11).

\[
p_r (r) = \begin{cases} 
\frac{r}{\sigma^2} \exp\left(-\frac{r^2}{2\sigma^2}\right) & (0 \leq r \leq \infty) \\
0 & (r < 0)
\end{cases} \tag{2.10}
\]

\[
\theta = \frac{1}{2\pi} \quad (-\pi \leq \theta \leq \pi) \tag{2.11}
\]

The cumulative distribution function (CDF) for Rayleigh fading is found by
integrating the PDF, as shown below.

\[
F_r (r) = \int_{-\infty}^{r} p_r (R) dR = \int_{0}^{R} \frac{R}{\sigma^2} e^{\frac{-R^2}{2\sigma^2}} dR = -e^{\frac{-R^2}{2\sigma^2}} \bigg|_{0}^{r} \tag{2.12}
\]

\[
F_r (r) = \begin{cases} 
1 - e^{\frac{-r^2}{2\sigma^2}} & (r \geq 0) \\
0 & (r < 0)
\end{cases} \tag{2.13}
\]

Multipath has either a constructive or destructive effect. We note that these
effects are equally likely when the frame of reference is the median received signal
strength. As such, when plotting the CDF of a data set we normalize the distribution by
the median fade value so all curves pass through the (0 dB, 50%) cumulative probability
point. This median value represents the large-scale fading (loss based on distance from
transmitter). Loss or gain, relative to the median, represents the small-scale fading and is
plotted against cumulative probability. The CDF for the Rayleigh distribution is shown
in Figure 3.
Figure 3. CDF of Rayleigh fading model

Cumulative distribution plots are useful for analyzing the statistical severity of fading environments. As can be seen from the red lines in Figure 3, in an environment characterized by Rayleigh fading, there is a 10% probability of at least an 8 dB fade, and a 1% probability of at least an 18 dB fade occurring. This Rayleigh model has been derived from very physical assumptions. We will now take a look at other physical models describing fading both better and worse than Rayleigh.

2.2.3 Ricean and One-Wave Fading

A Ricean, or Rice, fading scenario is characterized by one dominant signal, such as line of sight, arriving at the receiver accompanied by attenuated random multipath components [7]. For example, the link between a satellite and its ground station will have strong line of sight component and minimal diffuse power as there is little potential for significant multipath vectors. Likewise, a cell phone link to a tower will most likely
have one dominant component, but this dominant component may be a strong multipath wave as opposed to line of sight, and it will be accompanied by highly varying levels of diffuse power. These cases may all be described by the Ricean fading model.

Since there is one dominant wave arriving at the receiver ($V_1 \neq 0$, $V_2 = 0$), the received signal in (2.4) may be simplified to the summation of one specular component and the diffuse component, as shown in (2.14). Note that the diffuse component follows the Rayleigh distribution as discussed in the previous section.

$$V_R = V_1 \exp(j\Phi) + V_{\text{dif}}$$  \hspace{1cm} (2.14)

The ratio of specular power to diffuse power is referred to as the Ricean-$K$ factor. This ratio measures the relative strength of the dominant component to the diffuse component and so is directly related to link variability.

$$K = \frac{\text{Average specular power}}{\text{Diffuse Power}} = \frac{|V_1|^2}{2\sigma^2}$$  \hspace{1cm} (2.15)

As the diffuse component ($\sigma$) decreases, $K$ becomes larger and there exists less possibility of multipath interference. If there is no diffuse component, then $K = +\infty$ and there is no fading, this is considered the One-Wave Model [11]. As the diffuse component increases, or $V_1$ becomes less dominant, $K$ approaches 0. For $K = 0$, all received power is the result of diffuse waves, and we once again have the Rayleigh model. Figure 4 illustrates various Ricean cases with CDF curves.
Figure 4. CDF comparison of One-wave, Ricean ($K=10$ dB), and Rayleigh models

The line representing the one-wave model (no fading) is a step function beginning at 0 dB, showing that there is a 100% chance of the median signal strength arriving at the receiver. As $K$ decreases, the curve is seen to rotate clockwise about the median point representing the greater probability of more severe fades. They continue rotating until $K = 0$, or the Rayleigh model.

2.2.4 **Hyper-Rayleigh Fading and Two-Ray Model**

As noted, the Rayleigh model is considered the worst-case scenario for mobile applications [7], yet there are particularly harsh environments in which hyper-Rayleigh, or worse than Rayleigh, models are necessary for characterizing the fade [1]. Such environments include aircrafts, shipping containers, and other metal enclosures, where wireless sensors may be deployed with no chance of moving or retrieving them once
installed. As with the One-wave, Ricean, and Rayleigh distributions, physical concepts have been developed to describe this hyper-Rayleigh regime.

Returning to (2.4), we will now consider two dominant waves \((V_1 \neq 0, V_2 \neq 0)\) along with a diffuse component. This is referred to as two wave with diffuse power (TWDP) by [11] and is rewritten in (2.16). The two specular components, \(V_1\) and \(V_2\), could encompass a line of sight element and a strong multipath element, or two dominant multipath elements. As before, the phases are assumed to be statistically independent and uniformly distributed between 0 and \(2\pi\).

\[
V_k = V_1 e^{j\Phi} + V_2 e^{j\Phi} + V_{\text{diff}}
\]  

(2.16)

Two parameters \((\Delta \text{ and } K)\) are used to quantify the relative impacts of \(V_1\) and \(V_2\) on the overall received signal strength in relation to the diffuse component [1].

\[
\Delta = \frac{\text{Peak specular power}}{\text{Average specular power}} - 1 = \frac{2V_1V_2}{V_1^2 + V_2^2}
\]

(2.17)

\[
K = \frac{\text{Average specular power}}{\text{Diffuse power}} = \frac{V_1^2 + V_2^2}{2\sigma^2}
\]

(2.18)

\(\Delta\) is seen to vary from 0 to 1, and we note that \(K\) in (2.18) now has two components as opposed to the Ricean formulation seen in (2.15). When \(\Delta = 0\), one or both of the specular components does not exist (Ricean and Rayleigh models, respectively). When \(\Delta = 1\), both of the specular components are equal \(V_1 = V_2\). This case is of particular interest because it results in scenarios more severe than Rayleigh; fading referred to as hyper-Rayleigh [1].
For \( V_1 = V_2 \), if the diffuse power dominates (\( K \to 0 \)) the fading model becomes Rayleigh. However, the probability of deep fades becomes greater as \( K \) increases. A worst case scenario exists when there is no diffuse power (\( K \to \infty \)). There is now the possibility that \( V_1 \) and \( V_2 \) are of phase \( \pm \pi \) from each other and so would sum totally destructively, resulting in a received signal strength of zero. The model for this case (\( K \to \infty, \Delta = 1 \)) is the two-ray proposed as a new worst-case model for static wireless devices, especially for wireless sensors contained with high multipath environments [1]. The PDF [1] and CDF [12] of the two-ray model are shown below.

\[
p(r) = \frac{2r}{\pi \sqrt{4V_1^2V_2^2 - (V_1^2 + V_2^2 - r^2)^2}} \bigg|_{V_1 = V_2 = 1} = \frac{2r}{\pi \sqrt{4r^2 - r^4}} \quad (2.19)
\]

\[
F_r(r) = \int_{-\infty}^{r} p_r(r) dr = \int_{0}^{r} \frac{2r}{\pi \sqrt{4r^2 - r^4}} dr 
\quad (2.20)
\]

\[
F_r(r) = \begin{cases} 
1 - \frac{1}{\pi} \arccos \left( \frac{r^2 - 2}{2} \right) & r \geq 0 \\
0 & r < 0 
\end{cases} \quad (2.21)
\]

The CDF’s for various hyper-Rayleigh cases with \( \Delta = 1 \) and different values of \( K \) are shown in Figure 5. This figure illustrates the severity of the two-ray case as compared to Rayleigh fading. For example, the Rayleigh model would predict a 25 dB fade to occur with probability of \(~0.2\%\), but a two-ray environment would experience such fades with probability of near 2\% (an order of magnitude greater).
2.3 Stochastic Models

2.3.1 Nakagami-\(m\) Model

The Nakagami-\(m\), or \(m\)-distribution, is a statistical model related to the gamma function. This distribution was first used in the 1950’s as an empirical model based on ionospheric and tropospheric rapid fading data [13]. Recently, the Nakagami-\(m\) model has been used for modeling urban multipath channels [14] and in-building ultra-wide bandwidth channels [13]. Its PDF is shown in (2.22), where \(\Omega = E[r^2]\) and \(m\) is an independent variable.
Statistically, the Nakagami distribution is very similar to that seen by the Ricean and TWDP models shown earlier. But it has the convenient characteristic of having just one variable, $m$, which when adjusted allows the distribution to yield different statistical fading models. For example, $m = 1$ results in the Rayleigh distribution, $m > 1$ represents more benign fading than Rayleigh, and $0.5 \leq m < 1$ implies a hyper-Rayleigh fading environment. The worst case scenario exists when $m = 0.5$, which is seen to predict a slightly worse fading condition than that of the two-ray model. This is displayed in Figure 6.

![Figure 6. Nakagami worst-case model [13]](image)

The model predicts a large amount of constructive interference as seen in the upper right corner of the CDF, which is uncharacteristic of hyper-Rayleigh fades [13].
Severe hyper-Rayleigh fading has been attributed to the number of multipath waves approaching two. Yet the greatest sum two waves may yield is double their magnitude, or a 3 dB increase, if they are equal and in phase. To account for large amounts of constructive interference, it is implied that there must exist a large number of multipath waves, which would be more characteristic of Rayleigh behavior.

In addition, this model does not use physical occurrences to describe why its results may characterize a fading environment. The previous models discussed have been derived using physical phenomena such as the number and relative weights of incoming radio waves, whereas the Nakagami-$m$ model is simply an equation that has been conveniently fitted to match the statistical behavior of collected fading data.

### 2.3.2 Log-Shadow Model

The log-shadow model has been widely used to model large-scale propagation effects [7]. The model utilizes a reference, a path loss exponent, $n$, and the zero mean Gaussian distributed fading factor, $X_{\phi}$, which has a standard deviation $\phi$ dB as shown in (2.23) [13]. By viewing the first two components of (2.23) as setting the median received signal strength, and varying the standard deviation of $X_\phi$ (in dB), log-normal shadowing may also be used to model a range of small-scale fading statistics [13]. Example scenarios, with varying $\phi$ values, are shown in Figure 7.

$$PL(d) = PL(d_o) + 10 \cdot n \cdot \log_{10} \left( \frac{d}{d_o} \right) + X_{\phi}$$

(2.23)
Figure 7. Log-shadow models with varying $\sigma$

The shape of the CDF curve for a log-shadow model is different from that of Rayleigh or Nakagami, curving downward instead of remaining linear. We see the model also has the benefit of simplicity, for a constant distance $d$, one only needs to vary the standard deviation to accomplish different levels of multipath severity. Likewise, the standard deviation found from fading data may be used to estimate the severity of multipath. For example, $\sigma < 2.5\,dB$ may be benign, while $2.5\,dB < \sigma < 5.5\,dB$ is Ricean, $5.5\,dB < \sigma < 7.5\,dB$ is approximately Rayleigh, and $\sigma > 7.5\,dB$ is hyper-Rayleigh.

Like the Nakagami model, the log-shadow model predicts a large amount of constructive interference which would be uncharacteristic of hyper-Rayleigh events. In fact, this model predicts that the amount of constructive interference increases as fading worsens. This is the opposite of that predicted by the TWDP model, where severe fades are result of the number of dominant waves approaching two and large amounts of
constructive interference become less possible. Also like the Nakagami model, the logshadow model does not base its derivations from physical features of the environment.

2.4 Using Models to Develop a Link Budget

A link budget presents all the losses and gains of a wireless signal through a telecommunications network. The primary purpose of a link budget is to ascertain the maximum range a transmitter and receiver may be separated. However, the reliability of this link is dependent on the fading environment and thus a fade margin must be included in the budget. This margin is established by the chosen fading model and percent of reliability desired at the edge of coverage.

For example, consider a network characterized by Rayleigh fading, where sensor radios have -100 dBm sensitivity, and it is required that 99% of transmissions at the edge of coverage are successfully received. To find the margin, one must find the point on the Rayleigh curve (Figure 8) where there is a cumulative probability of 1%. In this case, the margin is ~18 dB, meaning that to accomplish 99% reliability at the edge of coverage the expected median signal strength must be -82 dBm or better. If the environment exhibited two-ray fading, the margin would increase to ~33 dB, decreasing the median signal strength to -67 dB and forcing communication links to operate in much closer proximity, or requiring the transmitter to significantly increase its power (by 15 dB!). It is essential that the correct model be used as these are very significant differences. As dependability requirements increase, using an incorrect model may lead to reliability suffering by orders of magnitude.
2.5 Conclusion

Several models have been presented as means for characterizing the statistical behavior of fading in multipath environments. Of these, the One-Wave, Ricean, Rayleigh, TWDP, and Two-Wave models have physical underpinnings which describe their behavior. In these cases, the level of fading is based upon the number and relative weights of specular and diffuse waves. Other models, such as the Nakagami and log-normal shadowing, accurately portray the statistical nature of fading found in the field, yet their results do not attribute physical aspects of the multipath event.

The cumulative distribution function has been introduced as a convenient means of viewing these fading models. Once a model has been selected to fit the projected environment of a wireless system, its CDF may be used by system engineers to set a network link budget. One aspect of the link budget is to determine requirements for
maintaining links at the edge of coverage within a certain percentage of reliability. By miss-choosing the fading model, link reliability could suffer by orders of magnitude, especially when designing a system for high dependability.

In the next chapter, we will discuss two testing structures, the anechoic and reverberation chamber, traditionally used for testing wireless devices. These structures test aspects of wireless devices such as receiver sensitivity and diversity gain, a measure of how well the device mitigates fading. Many results of such testing directly influence the link budget.
CHAPTER 3: CONTROLLED WIRELESS TESTING ENVIRONMENTS

3.1 Introduction

Consistent testing environments are necessary for an accurate characterization of wireless device performance and limitations. These tests are traditionally carried out within one of two testing structures, the anechoic chamber and/or the reverberation chamber. Anechoic chambers are used for creating environments where multipath is minimized or non-existent. Reverberation chambers, however, create high levels of multipath and are most often associated with Rayleigh behavior.

3.2 Anechoic Chambers

Anechoic chambers are designed specifically so that any energy incident on the chamber walls is absorbed and not reflected. The interior surface of the anechoic chamber is made up of RF radiation absorbent material, or anechoic material, responsible for creating this virtually multipath free environment. Chambers are often small- to medium- sized rooms so that test equipment can be easily installed and far field antenna performance may be assessed. These chambers are commonly used for measuring electromagnetic compatibility and interference (EMC and EMI), antenna radiation patterns, and radar cross sections.

The following figure displays a near field antenna test for vehicles. This test features an 18 x 16 x 12 meter anechoic chamber developed by Eccosorb, adequate for frequencies in the range 60 MHz – 40 GHz. Note the pyramidal shaped anechoic
material and relatively large size of the chamber. The chamber exhibits a controlled and repeatable environment, allowing for an accurate comparison of antenna performance.

![Near-field antenna test in anechoic chamber made by Eccosorb](image)

**Figure 9. Near-field antenna test in anechoic chamber made by Eccosorb**

### 3.3 Reverberation Chamber

The reverberation or mode stirred chamber (MSC) is also utilized in EMC/EMI studies. In contrast to anechoic chambers, MSC have highly reflective walls thereby creating a resonant cavity and thus nominally an inhomogeneous field (standing waves) within the structure. To provide a statistically homogeneous environment, the chamber employs one or more rotating, reflective panels (or stirrers), and/or changes the position and/or orientation of the emission source. Reverberation chambers vary in size but tend to be electrically large (e.g., > 60 λ). MSC have been shown to be effective in creating time-varying environments with Ricean characteristics ranging from $K \approx 100$ (i.e., negligible fading) to $K \approx 0$ (i.e., Rayleigh) [15]. This variability in fading is created through the addition or removal, respectively, of anechoic material.
Reverberation chambers have traditionally been very large, highly shielded chambers as in Figure 10. Working like a giant (but low power) microwave oven, RF energy is injected into a corner of the chamber and effectively “cooking” the device under test. The electric field at any point within the chamber is the vector sum of all the reflected waves arriving at that point. These waves are continually perturbed by the rotating tuner seen in the center. This assures that all points within the chamber experience a large array of different electromagnetic field magnitudes which repeat themselves for each rotation of the tuner. The reverberation chamber shown below is specifically used for electromagnetic immunity and shielding testing [16].

Figure 10. Inside Reverberation Chamber at Defense Science and Technology Organization (DSTO) at Salisbury, Australia

More recently, reverberation chambers have been made much smaller for high frequency measurements of small antennas and testing of mobile devices in Rayleigh fading environments. Two such products, made by Bluetest, are shown in Figure 11.
The chamber on the left exhibits strong shielding isolation for accurate receiver sensitivity measurements. The right chamber, however, is most appropriate for passive and radiated power measurements, including their response to a human head. They are suitable for frequencies above 700 MHz and 850 MHz, respectively. Other capabilities of reverberation chambers include evaluating radiation efficiency, gains obtained by use of diversity antennas, channel capacity of MIMO antenna systems, total radiated power, and static and dynamic receiver sensitivities [17].

![Figure 11. Reverberation Chambers by Bluetest](image)

3.4 Conclusion

Two chambers are typically used for the controlled testing of wireless devices in various environments. The anechoic chamber is used for tests requiring line of sight communication, such as antenna range and sensitivity analysis. The reverberation chamber may be used for testing mobile devices used in dynamic environments.
experiencing Ricean or Rayleigh fading. There has been little effort, however, for testing wireless devices in time- or frequency-varying fading conditions as severe as hyper-Rayleigh. In the next chapter, we present a new class of chambers built to create these severe fading environments, and to do so in a repeatable manner which will allow for the controlled test of wireless devices under these conditions.
CHAPTER 4: COMPACT RECONFIGURABLE CHANNEL EMULATOR

(CRCE)

4.1 Introduction

As discussed in the previous chapters, there is a need for a repeatable means of testing wireless devices within hyper-Rayleigh fading environments. To satisfy this need, a compact, reconfigurable channel emulator (CRCE) has been designed and is detailed in this chapter. The CRCE is a chamber that, unlike anechoic or reverberation chambers, is intended to provide non-uniform fading profiles for wireless devices placed within. The CRCE is capable of creating not only Ricean and Rayleigh fading profiles, but also hyper-Rayleigh fading which has been observed in airframes and similar cavity structures.

Herein, we will discuss in detail four CRCE chambers built to date. Each chamber takes a new step in design, materials, and capabilities for use as a testing structure. The first was used for proof of concept testing, discovering the potential of an electrically small chamber used to create severe multipath environments. The second and third chambers gain functionality in creating a discrete number of such events, the third being a much more manageable and repeatable design. The fourth chamber experiments in using multiple transmitting antennas to create a larger and more controlled selection of hyper-Rayleigh scenarios.

4.2 Design Overview

The following is a list of features and constraints necessary for the CRCE:
1. **Chamber must be mobile—lightweight and sized to fit through doorways.**

The size of the chamber is predominately dictated by what will fit conveniently in the lab and be easily transferable to other locations. For this reason, a maximum width of 3½’ will be instituted to assure that the chamber may pass through doorways.

2. **Adequate size for 2.4 GHz and 5 GHz ISM bands.**

These unlicensed ISM (Industrial, Scientific, and Medical) radio bands and are of current and upcoming interest for wireless systems, encompassing the widely used IEEE standards 802.11 for WLAN (Wireless Local Area Network) and 802.15 for WPAN (Wireless Personal Area Network). Previous size-limited reverberation chambers have used dimensions of just a few wavelengths in each direction [18]. For example, the Standard RT reverberation chamber made by Bluetest is 0.79 x 1.85 x 1.24 meters. This chamber is utilized for testing using frequencies down to 870 MHz, at which chamber dimensions correlate to 2.29λ x 5.36λ x 3.59λ. Our frequency range of interest, 2.4 GHz, has a shorter wavelength than 870 MHz (0.125 m verses 0.345 m). Using the same dimensional ratio as the Standard RT, the CRCE could feasibly be reduced as small as 0.286 x 0.67 x 0.449 meters (0.938 x 2.20 x 1.47 feet).

3. **Highly reflective walls to assure multipath.**

Steel, aluminum, and copper-mesh have all proven themselves to be capable selections for creating radio reflections. All are conductive and exhibit reasonably high reflection coefficients. Of them, aluminum is the lightest, while copper-mesh is the most expensive and least supportive. The material may remain as thin as structurally possible.
4. *Stirrer similar to that of reverberation chamber.*

To create discrete frequency-varying scenarios and time-varying changes, it will be necessary to alter the multipath environment in a controlled manner. A reflective blade rotated by a stepper motor will achieve this task.

5. *Large door for easy installation/removal of anechoic material.*

It is likely that the addition/subtraction of anechoic material will be required for creating a wide range of fades. The sizes of anechoic sections must be minimized, especially in thickness, to prevent cluttering the chamber. For this reason, anechoic performance may be sacrificed in place of flat (non-pyramidal), space-efficient designs. The door, however, must be sized appropriately to allow for this installation.

6. *No gaps in chamber walls to prevent electromagnetic leakage in or out.*

Gaps in the chamber walls will allow signal contamination, compromising the repeatability of fading scenarios. For this reason, effort must be made to assure that the chamber, especially at corners and the doorway, is effectively shielded with reflective or anechoic material.

### 4.3 CRCE-I: Proof of Concept

The first step was to construct a proof-of-concept CRCE in order to demonstrate that Rayleigh and hyper-Rayleigh environments could indeed be created within a relatively small chamber. This CRCE was built with minimal cost and precision in February, 2007. The design of which is shown below in Figure 12.
The chamber was 4’ x 4’ x 3.5’ and consisted of a steel frame and walls made of particle board. The latter dimension was chosen simply to allow it to pass through doors. Two 4’ x 2’ sections were connected by hinges to create a barn door at the front of the chamber. To create reflections, thin aluminum sheeting was secured to the inner walls and a manually adjustable steel paddle was placed in the center. Antennas were mounted on platforms on opposite walls of the inner chamber. As illustrated in Figure 13, these antennas were connected with a vector network analyzer (VNA) which swept a frequency range, providing $S_{21}$ data for the band of interest (2.40-2.48 or 5.00-5.08 GHz). Data was pulled from the VNA to a custom Labview graphic user interface (GUI) on the PC, where its CDF was calculated and displayed. The realization of this design and captured data are shown in the figures below. Data is displayed as in-band (left) and CDF (right), and has been taken in the 2.4 GHz ISM band.
Figure 13. CRCE-I, used for proof of concept. Outside (left) and inner (right).

Figure 14. CRCE-I Ricean Fading. Inband (left) and cdf (right).

Figure 15. CRCE-I Rayleigh Fading. Inband (left) and cdf (right).
Figure 16. CRCE-I hyper-Rayleigh Fading. Inband (left) and cdf (right).

The data above displays the large range of fading environments accomplished through the positioning of the antennas and reflective blade, as well as the addition and subtraction of anechoic material. The chamber is able to create scenarios ranging from Ricean ($K \approx 100$) to beyond the two-ray model and maintain these scenarios until the environment is disturbed. The most severe fades were collected when reflective material was added as a sort of false floor, leading us to believe that the higher amplitude multipath waves resulting from a smaller chamber have a greater potential for creating harsh fading environments. The results of CRCE-I, proof of concept testing, confirmed that there was potential for using such a chamber as a testing structure, and so allowed for the continuation and advancement of the project.

### 4.4 CRCE-II and III

#### 4.4.1 Design

The 2\textsuperscript{nd} and 3\textsuperscript{rd} CRCE chambers were of similar design and behavior and so are discussed together. After the results of CRCE-I, we decided to continue with the slightly smaller dimensions of 3’ x 2’ x 3’ to facilitate transportation. At 2.4 GHz this
corresponds to $7.3\lambda \times 4.8\lambda \times 7.3\lambda$ (still exceeding the Bluetest chamber values). This updated design is illustrated below in Figure 17.

![Figure 17. CRCE-II & III block diagram](image)

The CRCE was utilized in conjunction with an Anritsu MS2036A VNA Master which sweeps the frequency and provides $S_{21}$ data for the band of interest (e.g. 2.40-2.48 or 5.00-5.08 GHz). Since the CRCE is relatively small, we added the ability to add fixed coaxial delay lines to emulate strong reflections off a distant object. In addition, interference sources are also provided ports in order to conduct susceptibility testing. Finally, a reflecting blade attached to a stepper motor provides discrete control to a fixed number of fading scenarios. The blade may also be attached to an adjacent DC motor for high rate temporal variations.
4.4.2 Construction

CRCE-II (Figure 18) was built in the summer of 2007 and was utilized at Goodrich Aerospace in Vergennes, VT through December 2007. This CRCE was built with a steel frame and all walls made of ¼” plywood lined on the inside by copper mesh. Care was taken to assure there were no gaps on the inner wall where RF leakage (in or out) could contaminate the multipath environment. The chamber was not equipped with a DC motor and instead utilized a metal oscillating fan to emulate higher rate temporal variations (>25 Hz) found in, for example, rotor craft environments. Functionality of this chamber was excellent, but it was heavy, the copper was expensive, and it was not a very manufacturable design.

CRCE-III (Figure 19) was built in the UVM machine shop and is constructed with thin aluminum walls. It features all the functionality of CRCE-II in a much lighter, inexpensive, repeatable design. The DC motor used in this structure is capable of rotating the reflective blades at about 10 Hz. This speed is slower than that of the metal oscillating fan, but is directed through the Control GUI leading to more repeatable testing. A detailed description of all the parts, circuitry, and data acquisition equipment used are presented in Appendix A. Control and data for the CRCE-II and III chambers is presented in the next section.
CRCE-III was delivered to Goodrich in December 2007 and is currently being utilized as part of the wireless testing protocol. Based on the CRCE-III design, two new chambers were built. One chamber, CRCE-IV, resides at UVM while the other was sent to our collaborators at the University of South Florida (USF). These chambers are being
configured with the additional feature of an electrically configurable multi-element antenna array, used for generating the multipath scenarios. CRCE-IV will be discussed further in Section 4.5.

4.4.3 Control Station

The stepper motor along with data acquisition and analyses for the CRCE chambers are controlled through a PC utilizing the Labview based GUI (shown in Figure 20).

![Figure 20. Labview based GUI for controlling the CRCE](image)

This GUI remotely configures the scan attributes for the VNA (i.e., start/stop frequency). Data can be collected in one of two scan modes, frequency- or time-varying, for which the user selects a frequency range or specific frequency for testing, respectively. Sweeps are captured from the VNA and a cumulative distribution function
(CDF) of the data along with other statistical information (median, standard deviation, max, and min) are calculated and displayed.

The GUI is also utilized to control the rotation and position of the rotating blade. The blade can be rotated continuously at speeds varying from 0.1 to 2.0 Hz for the time-selective scan, or positioned at specific angles for the frequency-selective scan. For accurate repeatability of the fading environments, it is essential that the precise angle of the blade be known. Therefore, all angle positions are relative to a known “Home” position, which the stepper motor can be sent to at any time. Each 7.2° step made by the stepper motor generates a unique fading environment, resulting in 50 unique measurements. This same fading environment can be recreated whenever the blade is sent back to that specific angle.

An “AutoScan” feature allows the system to capture and record VNA data for each position of the stepper motor. When complete, the user can view each fading scenario accomplished one at a time, or all at once. The program will appropriately position the stepper motor to recreate any of these scenarios, if selected. This eliminates the need to view each fading response one at a time while looking to create a specific environment. However, if anything is moved within the chamber (antenna or addition/subtraction of anechoic material) the accurate recreation of previous fading environments is unlikely.

The AutoScan feature may also be utilized for spatial selective fading. In this case, the rotating blade is replaced with an L-shaped blade, and the transmitting (or receiving) antenna is placed on the flat portion of the ‘L’, about 9” away from the shaft.
Now, when AutoScan is selected the antenna will be rotated to 50 locations around 360°, collecting frequency selective data for each, as illustrated in Figure 21. Since the motor is stepping 7.2° at a time, each transmission location is ~1.13”, or 0.229 λ at 2.4 GHz, from the previous location. In one rotation, the maximum distance between two measurement points is ~18” (~1.5 λ at 2.4 GHz). When the scan is complete, one may select “Spatial Scan” under the “Scan Type” on the GUI and select a specific frequency in which to view the spatially-varying fading.

![Figure 21. CRCE IV. Spatial Selective Scan.](image)

### 4.4.4 Results: Frequency-selective fading

Three fading environments captured from the CRCE-III are shown in Figure 22 to illustrate the versatility of the chamber. The captured data is compared to CDF’s of the
theoretical worst-case multipath scenarios of Rayleigh fading (for mobile systems) and two-ray fading (for static systems).

Figure 22. Frequency-selective fading exhibiting hyper-Rayleigh, Rayleigh, and Ricean characteristics. In-band (left) and CDF (right).

The green record in Figure 22 (left) shows an almost benign environment, with an inband variation of only 3 dB across the 2.4 GHz ISM band. In Figure 22 (right), we see this corresponds to high-$K$ Ricean fading. The blue line shows an inband variation of 26 dB and statistical behavior resembling that of the Rayleigh model. The most severe fading data is represented by the red record. Here the inband variation exceeds 35 dB across the ISM band, and the statistical behavior closely resembles that of the two-ray model proposed in [1]. Note that the GUI in Figure 20 shows a scenario in which the probability of deep fades is between those predicted by the Rayleigh and two-ray models, in the region considered hyper-Rayleigh. This large range of fading scenarios is accomplished through the position of the antennas and reflecting blade, and the
addition/subtraction of anechoic material. The influence of the anechoic material on fading will be further discussed later in this section.

AutoScan allows the user to gather data at all 50 positions of the stepper motor. As long as nothing is moved within the chamber, the user may go back and recreate any of these scenarios as desired. Figure 23 shows the results of one such test, where antennas were placed on opposite sides of the blade (no LOS), and no anechoic material was added.

![Figure 23. Frequency-selective data collected at 50 stepper positions. In-band (left) and CDF (right)](image)

Figure 24 shows the results for the same test, but with a 2’ x 2’ section of anechoic material positioned in front of the door. For the first case, the chamber is very reflective and so there will be a large number of multipath waves; while for the second test multipath should be minimized.
Figure 24. Frequency-selective data collected at 50 stepper position. Anechoic material present. In-band (left) and CDF (right)

As predicted by the physical fading models presented in Chapter 2, cases in which multipath waves are prevalent result in Rayleigh-like scenarios. Figure 23 (left) shows that these environments are all unique in where and how deeply they fade, yet Figure 23 (right) displays that all exist within a narrow range of statistical variability. The fading results range from about Rician ($K < 10\text{dB}$) to TWDP ($K < 10\text{dB}$), with just a few outliers on either end.

The case in which multipath is minimized using anechoic material yields results ranging from benign environments all the way up to the two-ray model. Figure 24 (left) shows smooth changes in in-band response over the frequency range for each position. In addition, each in-band response is very similar in shape, yet highly variable in fade depth. This behavior is likely the result of having just one or two prevalent waves, which fluctuate in amplitude along with the diffuse component. Figure 24 (right) confirms this
prediction by exhibiting CDF’s distributed from Ricean (high \( K \)) up to the two-ray model. Results from both cases seem to validate ideas presented by the physical models.

Table 1 presents the overall impact of anechoic foam on CRCE performance. The high multipath case, created through lack of foam, resulted in Rayleigh-like behavior with equal probability of Ricean and hyper-Rayleigh cases. The range, however, is limited as there are virtually no cases of benign or two-ray scenarios. When anechoic foam was included, multipath became limited and the majority of fading environments was Ricean. The probability of Rayleigh and hyper-Rayleigh decreased, but there are now more extreme fading profiles available.

**Table 1. Percentage of cases produced by CRCE**

<table>
<thead>
<tr>
<th>Case Description</th>
<th>No anechoic foam</th>
<th>With anechoic foam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benign (&lt;5 dB fade)</td>
<td>&lt;1%</td>
<td>6%</td>
</tr>
<tr>
<td>Ricean</td>
<td>20%</td>
<td>55%</td>
</tr>
<tr>
<td>Rayleigh</td>
<td>60%</td>
<td>25%</td>
</tr>
<tr>
<td>hyper-Rayleigh</td>
<td>20%</td>
<td>10%</td>
</tr>
<tr>
<td>two-ray</td>
<td>&lt;1%</td>
<td>4%</td>
</tr>
</tbody>
</table>

To test the repeatability of fading environments created during an AutoScan, the stepper was sent back to locations and compared with the original scans. Results consistently yielded almost identical scans. One such comparison is shown in Figure 25 below. This Rayleigh-like data not only shows similar statistical data, but also fades at the same frequency and depth as the original. Small variations do exist, but may be minimized by allowing more time between stepping the motor and reading a scan, as to avoid amplitude fluctuations due to small movement. Note that the VNA is a highly
sensitive instrument and power measurements presented here are being made over three orders of magnitude.

Figure 25. Proof of repeatability. In-band (left) and CDF (right)

4.4.5 Results: Time-selective fading

With the stepper motor we can also introduce temporal variations in the environment with repeatable low rates (< 2.0 Hz). The DC motor may be utilized for higher rate temporal effects (~25 Hz). Operating either of these time-varying devices results in time-selective fading data that has been seen to exhibit fades of ~20 dB (Figure 26, left). Statistically we find this data to exhibit Rayleigh-like fading (Figure 26, right). This result is not surprising for the CRCE is operating in a mode very much like a MSC. However, we are able to achieve these fading results in a physical design that is significantly smaller than a typical MSC. A drawback, however, is that the MS2036A VNA will not read more than 551 points for a given measurement. With the VNA sampling at ~275 Hz (its slowest rate), the maximum capture time is 2 seconds. This is a major limitation in capturing long time-varying fades.
4.4.6 Results: Spatial-selective fading

As described in the previous section, spatial-dependent fading may also be examined. Frequency-sweep data was collected for 50 locations of the transmitting antenna around a 360° rotation. By selecting a specific frequency, the spatial-selective data (50 points) may be presented. The statistical behavior of this data is highly varying depending on the position of TX antenna, and on the selected frequency. Figure 27 shows three fading profiles from the same scan, each representing a different frequency. The green line displays Ricean fading, the blue Rayleigh, and the red hyper-Rayleigh.

This is a significant result because it emphasizes the non-uniformity of the CRCE. Over space or time, the chamber will produce a great range of results. In this, it truly differs from reverberation chambers, where results over time and space are statistically consistent.
In addition, the spatial-varying fading results have revealed insight into signal changes over a very short distance. Altering the position of a transmitting or receiving antenna by less than \( \frac{1}{4} \lambda \) may yield highly differing levels of fading. Wireless sensors placed in high multipath environments, such as aircraft, may thus be expected to exhibit such variable behavior based on slight changes of position, antenna orientation, or objects in the environment. While our work thus far has utilized test equipment to measure the channel effects, the only valid approach in attaining accurate fading measurements of a sensor node’s environment would be to use the wireless sensor itself.

![Figure 27. Spatial-selective fading showing Ricean, Rayleigh, and two-ray fading. In-band (left) and CDF (right).](image)

### 4.4.7 Anomalous Fading Data

While the propensity of our data conforms with the physical models discussed in Section 2.2, we have seen a very few instances of data that does not conform with the arguments presented against the Nakagami and log-normal shadowing models. For example, as illustrated in the right panel of Figure 28, we see an instance of constructive
interference exceeding what would have been predicted by our physical models. In examining the fading data we find the result to have a median value of -50.3 dBm while the trace itself is seemingly bi-modal. However, as noted, cases such as these are very rare in our experience and thus we contend to not validate the use of either the Nakagami or log-normal shadowing model for severe fading environments.

![Graph](image)

**Figure 28.** Fading data illustrating large amounts of constructive interference. In-band (left) and CDF (right).

### 4.5 CRCE-IV: Electrically Controlled Multi-antenna Multipath Emulation

CRCE-IV was built in order to test a new method of creating multipath events. This method utilizes the existing method of mechanical perturbation achieved by the previous chambers in conjunction with the added capability of electrical perturbation, which will be accomplished by use of multiple transmitting antennas. This feature vastly increases the total number and range of fading scenarios available to the user, thus decreasing the need to open the chamber and alter the environment. In addition, time-varying fading will be much better controlled, raising the repeatability of tests, and will
increase obtainable cycle rates by two orders of magnitude (up to thousands of Hertz).

The design for CRCE IV is presented in Figure 29.

Figure 29. CRCE-IV block diagram

The chamber was built in the UVM machine shop and is identical in structure to CRCE III. The difference is that the chamber now contains a 1:4 power splitter and four switching devices (Figure 30), controlled by the PC, and which directly activate and deactivate their respective transmitting antennas. These circuits are discussed further in Appendix A.
In addition to the choice of four separate transmitting locations, antennas may be activated simultaneously, creating multiple sources of specular waves. With four antennas, this allows 15 separate active modes of transmission, each of which has been shown to create its own unique environment. 15 modes times 50 stepper positions yields 750 separate fading scenarios. Figure 31 and Figure 32 show results from fading data collected using 7 active antenna modes at the 50 stirrer locations (350 scenarios); the latter figure with anechoic foam added and the former without anechoic material. These results reinforce those represented in Table 1, where high levels of multipath yield mostly Rayleigh-like scenarios, while less multipath yields a large range of sloping curves.
Figure 31. 350 Fading Scenarios creating using 7 active antenna modes at 50 locations. No anechoic material. In-band (left) and CDF (right).

Figure 32. 350 Fading Scenarios creating using 7 active antenna modes at 50 locations. Anechoic material added. In-band (left) and CDF (right).

By switching through the active antennas modes, a controlled form of time-varying multipath is created. Figure 34 shows antennas cycling through the 7 combinations, switching modes every 100 ms giving a frequency of 1.43 cycles/s ($f = 1 / (7 \times 100 \text{ms})$). The result is 7 clearly repeating, discrete levels of amplitude. Figure 34 shows the same scenario increased by 5 times ($f = 7.14 \text{ Hz}$). Expectantly, the CDF
curves for both sets of data are equal and also show 7 steps. Adding more active antenna combinations would increase the number of amplitude levels and smoothness of the CDF curve.

Figure 33. Seven antenna combinations creating seven discrete signal amplitudes. 500 samples over ~2 seconds (left) and cdf (right).

Figure 34. Seven antenna combinations creating seven discrete signal amplitudes. 500 samples over ~2 seconds (left) and cdf (right).
The frequency of time-varying changes may be increased to the limit of the analog output board. In our case, output pulses are skew limited to 10 kHz. As mentioned earlier, however, the VNA is only sampling at \( f_s = 275 \) Hz. This is our present constraint on the maximum rate of antenna switching if time-varying measurements within the chamber are to remain consistent.

Utilizing the switching antennas in conjunction with the rotating blade creates an aperiodic time-varying environment shown to exhibit Rayleigh-like behavior, as shown in Figure 35. This result is similar to that of operating two asynchronous spinning devices, as with the metal oscillating fan and rotating blade in CRCE-II.

Figure 35. Aperiodic time-varying fading exhibiting Rayleigh behavior.

4.6 Using the CRCE

After setting up a range of known frequency-selective fading environments, or a desired time-varying scenario, wireless devices may be connected to the RX and TX antenna ports and tested for performance under various and repeatable fading conditions.
Scenarios under which transmissions fail may reveal limitations of the device under test (DUT) and compared to those of different hardware or software configurations. The relatively small size of the chamber will likely require that an attenuator be used to reduce the median RSS to a desired level. Presently, Goodrich Corporation’s Aerospace Utility Systems Group of Vergennes, VT is using CRC III to test wireless devices for their relative susceptibility to multipath fading.

4.7 Conclusion

We have presented a design for a compact chamber that enables the generation of a wide range of fading phenomenon. In particular, this work demonstrates the ability to create frequency-selective fading profiles that lie in the Ricean, Rayleigh, and hyper-Rayleigh regimes (Figure 22) in a repeatable manner (Figure 25). The CRCE also enables time-selective fading at repeatable low rates (< 2.0 Hz), periodic high-rates (~25Hz), and of aperiodic nature. In addition, a method of using electrical perturbation has shown potential for creating time-selective fading at rates of hundreds of Hertz and in a very repeatable manner.

The significance of this work is that now desktop testing of hardware may be conducted where these channels are emulated at the physical layer. This aspect will thus enable controlled testing of radios, antennas, and methods of fade mitigation, such as new diversity antennas designed to mitigate the severest fading cases.

Diversity techniques rely on the ability of a wireless device to sense the fading severity of its own environment. In the next chapter, we will discuss the technology and
work accomplished to enable these techniques, as well as new work developed to advance the technology to accommodate star and mesh networks of wireless sensors.
CHAPTER 5: WIRELESS SENSORS SENSING WIRELESS (WSSW)

5.1 Introduction

Previous chapters have addressed the issue of multipath fading experienced by wireless sensors within metal enclosures. To mitigate severe fades, sensors may make use of one of several diversity techniques. Whether the diversity methods are to be employed from a node or a network level, it is first necessary for environmental fading data to be collected.

The objective of this work is to demonstrate that the sensor nodes themselves can effectively be used to characterize in situ the fading behavior for all links of a wireless sensor network. In particular, the work leverages the frequency agility and received signal strength indication (RSSI) capabilities of the wireless chipset to ascertain the frequency dependent, propagation characteristics of the links. This technique has been referred to as wireless sensors, sensing wireless (WSSW) and has previously been demonstrated for characterizing point-point links of a star networks [8, 9].

The work presented herein extends this approach to mesh networks. A mesh network involves the communication of wireless sensors with not only a base station, but also its neighboring nodes (Figure 36). In such a system, nodes may share data or forward packets through each other, vastly extending the network size. A changing environments often requires that these networks dynamically recalculate the best path for their data to take to a given destination.
5.2 Motivation

Our motivation for this work is threefold. First, employing the WSSW method enables the system operator to understand the link performance as a function of operating frequency (i.e., channel). As we have discussed, for statically deployed networks where nodes are located near or embedded within surfaces, the received signal strength may vary greatly as a function of small scale changes in position or frequency. For example, Figure 37 illustrates the WSSW signal strength data collected from three nodes of a mesh network.
For this deployment, all nodes were located in an office environment and spaced equidistant. However, one link clearly shows a significantly worse fading response than the other two. Having such data enables the system designer to properly select channels which benefit all links and thereby improving overall network reliability and potentially lifetime if power control is utilized. Other network level decisions may include routing data around potentially unreliable links in a multi-hop system.

Collecting link strength data as a function of frequency is effectively using wireless sensor nodes as scalar network analyzers. This technique may also be utilized for site surveys conducted at network deployment sites. The alternative to WSSW involves an arduous process of collecting data from a network analyzer at numerous positions of a deployment site [4, 5]. This process is not only time consuming, but costly, deployment sites are often difficult to access, and the validity of such testing is questionable. By employing WSSW, the sensors characterize their own fading environments in a fashion that is faster, less costly, more representative as it shows what the nodes are actually experiencing, and may be conducted over the lifetime of the deployment.

Our second motivation for characterizing channel fading is to enable sensor nodes themselves the means to mitigate such fades. It has been shown that reconfigurable, low-complexity diversity antennas can be effectively integrated with wireless sensor hardware [10]. These antennas make use of multiple spatial, pattern, or polarization options to mitigate the deepest of fades. In mesh networks, the configuration of these antennas
would potentially change depending on the particular link being utilized. Incorporating WSSW in the design would provide the data to enable this configuration.

Finally, leveraging the link variability data from WSSW will provide insight on the environment itself. The phenomena that cause variability over frequency (i.e., multipath) will likewise cause variability over space. For example, if a link exhibits relatively benign channel characteristics (e.g., the dashed line of Figure 37), one can expect similar statistical behavior from nodes placed elsewhere in proximity. In contrast, if a link exhibits wide fluctuations across channels (e.g., the straight line of Figure 37), we would expect like behavior for the node (or additional node) placed in that vicinity. Thus, the link variability can be utilized as criteria for future node placement either to avoid harsh channel conditions or to improve redundancy in regions where fading is severe.

5.3 Hardware

WSSW was originally introduced utilizing the MicroStrain V-Link hardware, limited to the configuration of a star network [8]. The signal strength monitoring was shown to accurately duplicate data captured using a network analyzer. These results indicate that WSSW provides an alternative method for conducting RF site surveys. To extend WSSW to a mesh network, the work herein makes use of the Zigbee compliant Freescale 13192 evaluation board, shown in Figure 38.

As noted, to enable the WSSW technique, the radio chipsets must support both frequency agility and signal strength (RSSI) measurement. The Freescale hardware
utilizes the MC13192 radio transceiver designed for operation in the 2.4 GHz ISM band. The MC13192 allows frequency tuning in 5 MHz increments, complying with the IEEE 802.15.4 standard. For signal strength, the MC13192 is capable of monitoring a range from approximately -5 dBm to -97 dBm [12]. To implement WSSW on the Freescale hardware, custom firmware has been developed and is detailed later in this chapter.

As illustrated in Figure 36, WSSW for a Star Network involves the link between a base station node (Base 1) and a node within transmission range (e.g. Node A). A command, containing a particular node address, is initiated by a CPU and directed to the base station via serial cable. This command is broadcast by the base station, and received by any sensors within range and operating on the same frequency. The sensor with the appropriate node address then transmit “pings” on each of the 16 radio channels defined

**Figure 38. Freescale 13192-EVB evaluation boards**

**5.4 WSSW for Star Networks**

As illustrated in Figure 36, WSSW for a Star Network involves the link between a base station node (Base 1) and a node within transmission range (e.g. Node A). A command, containing a particular node address, is initiated by a CPU and directed to the base station via serial cable. This command is broadcast by the base station, and received by any sensors within range and operating on the same frequency. The sensor with the appropriate node address then transmit “pings” on each of the 16 radio channels defined
by the IEEE 802.15.4 standard. These pings are received by the base station, and corresponding RSSI values are directed back to the CPU for viewing and analysis.

The GUI illustrated in Figure 39 is used to initiate the WSSW event and present the resulting fading data. Four graphs are illustrated in this figure.

<table>
<thead>
<tr>
<th>Frequency Selective Fading</th>
<th>Time Varying Fading</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Graphs of frequency selective fading data" /></td>
<td><img src="image" alt="Graphs of time varying fading data" /></td>
</tr>
<tr>
<td><strong>CDF for Frequency Selective Data</strong></td>
<td><strong>CDF For Time Varying Data</strong></td>
</tr>
<tr>
<td><img src="image" alt="CDF graph" /></td>
<td><img src="image" alt="CDF graph" /></td>
</tr>
</tbody>
</table>

**Figure 39. WSSW GUI for star network**

The graphs on the left are associated with frequency-selective fading data (across channels). The top-left graph shows received power (RSSI) versus channel and the lower-left shows the cumulative distribution function (CDF) for the fading statistics. The two reference curves are for Rayleigh fading and two-ray fading, the latter, as discussed earlier, being proposed as a worst-case scenario for some wireless sensor applications [1].

The graphs on the right illustrate the time-selective fading for one particular frequency
channels. The upper-right graph presents the received power over time while the lower-right shows the CDF of the fading statistics.

The GUI screenshot displays WSSW data collected in an office environment. The two communicating nodes were placed a few feet apart and with no line of sight. It can be seen that 2 of the 16 channels experience deep fades of about 20 dB (top left). This frequency-selective environment may be categorized as hyper-Rayleigh (bottom left). The rapidly varying signal strength over time (top right) for a single frequency, exhibits Rayleigh behavior (bottom right), as would be expected for a link with no line of sight.

5.5 WSSW for Mesh Networks

WSSW for a mesh network extends the previous approach to include multiple nodes as illustrated by Nodes D, E, and F of Figure 36. As with a star network, the WSSW command initiates at a CPU and is directed to the base station (Base 2). The base station then transmits the “Sweep” command to all nodes within range. Contained in this packet is a list of the node addresses of all the wireless sensors in the area. All nodes tune to Channel 11 and the node whose address comes first begins transmitting small “ping” packets containing its address. Other nodes listen for a ping from the correct source, and once received, store the corresponding RSSI value in a table. They then switch to the next channel and wait. The transmitting node switches to the next channel and commences with transmitting pings. This continues until all 16 channels, defined by IEEE 802.15.4, have been swept, at which time the nodes re-initiate back to Channel 11 and the next node in the list becomes the transmitter. Once every node on the list has
performed its own transmission sweep, fading tables are collected by the base station node and presented through a GUI. Flowcharts in Appendix B illustrate this progression.

Viewing inband data for more than $N = 3$ nodes will quickly become confusing as the number of links rises with increasing number of nodes (5.1).

$$\text{# of bidirectional links} = \binom{N}{2}$$  \hspace{1cm} (5.1)

For this reason, two graphics have been developed to display the relative quality and variability of each link within the network. Figure 40 illustrates the GUI, configured for a WSSW mesh system of $N = 5$ nodes placed within an office environment. The figure presents link loss data (upper left) along with a topological representation (upper right) in which the relative median link strength is indicated through a four level color code. The figure also presents the fading statistics both as a cumulative distribution function (lower left) and pictorially with one of four color codes on the network topology graph (lower right). This presentation enables the system designer to separate large-scale effects from small-scale. For example, median signal strength (illustrated in the top panels) can be used to determine \textit{in situ} the path loss exponent for the environment (a large-scale effect). This information may be used at the network level to determine the nominal spatial densities for additional node deployments. In contrast, the fading statistics (illustrated in lower panels) captures the impact of small-scale effects. This information can be utilized by the system designer to differentially favor locations in the network with more consistent links or used by the nodes to autonomously implement diversity schemes to mitigate fades.
Figure 40. WSSW GUI for mesh network of \( N = 5 \) nodes

Table 2: Four color code representing relative link strength

<table>
<thead>
<tr>
<th>Level</th>
<th>RSSI Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>RSSI &gt; median + 5 dB</td>
</tr>
<tr>
<td>Average</td>
<td>median - 5 dB &lt; RSSI &lt; median + 5 dB</td>
</tr>
<tr>
<td>Low</td>
<td>median - 15 dB &lt; RSSI &lt; median - 5 dB</td>
</tr>
<tr>
<td>Poor</td>
<td>RSSI &lt; median - 15 dB</td>
</tr>
</tbody>
</table>

The four level color codes representing the relative median link strengths (upper left) of the WSSW GUI are shown in Table 2. Link quality is presented with green being a ‘good’ link having an average RSSI value greater than the median of all records by 5 dB. Yellow represents a moderate link, with RSSI ± 5 dB about the median. Orange is a relatively low quality link, 5 to 15 dB below the median, and red represents a ‘poor’ link with average RSSI values more than 15 dB below the median.
<table>
<thead>
<tr>
<th>Color Code</th>
<th>Fading Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benign</td>
<td>$\sigma &lt; 2.5$ dB</td>
</tr>
<tr>
<td>Ricean</td>
<td>$2.5$ dB $&lt; \sigma &lt; 5.5$ dB</td>
</tr>
<tr>
<td>Rayleigh</td>
<td>$5.5$ dB $&lt; \sigma &lt; 6.5$ dB</td>
</tr>
<tr>
<td>hyper-Rayleigh</td>
<td>$\sigma &gt; 6.5$ dB</td>
</tr>
</tbody>
</table>

The four level color codes representing fading profiles (lower right) of the WSSW GUI are shown in Table 3. The fading profiles are based on the standard deviation of collected RSSI values across the given frequency band. As indicated by the log-shadow model in Chapter 2 (Figure 7), standard deviation may correlate to physical fading models. In our case there are only 16 data points (one for each available channel) making up a frequency sweep, yielding CDF curves with a minimum cumulative distribution of $1/16$ (.0625). Figure 41 displays a constrained version of Figure 7, emphasizing the range in which our representative log-normal curves characterize the physical fading regimes.

![Figure 41. Log-normal CDF curves with varying $\sigma$, compared to Rayleigh and two-ray models.](image-url)

65
For small standard deviations (0 to 5.5 dB), the fading statistics are Ricean, with the lowest deviations (0 to 2.5 dB) being relatively benign. For moderate standard deviations (5.5 to 6.5 dB), the fading statistics are approximately Rayleigh. And for standard deviations beyond 6.5 dB, the fading exhibits hyper-Rayleigh fading.

5.6 Other Uses for and Limitations of WSSW

In addition to the scalar network analyzer functionality, WSSW can also provide spectrum analysis in order to monitor the wireless environment as presented by other systems. Figure 42 illustrates this spectrum analysis functionality of WSSW. In the figure, a node is monitoring activity across the 2.4 GHz ISM band which is also utilized by WiFi systems. Channels 14-16 are found to exhibit little interference in comparison to, for example, Channels 21-23 and thus would be more appropriate for utilization by the sensor network.

![WSSW spectrum analysis functionality](image)

Figure 42. WSSW spectrum analysis functionality, monitoring spectral activity across channels (left) and activity over time for a single channel (right).
The work performed herein allows for collection of fading data describing many links of a mesh network. This network, however, is limited to the range of the base station, which initiates the WSSW command and collects the resulting data. For this method to be utilized in a true multi-hop network, a means for forwarding commands and data through intermediate nodes must be developed. Also, memory limitations will require that fade tables be stored on nodes’ onboard flash drive as opposed to RAM.

5.8 Conclusion

In this chapter we discussed the use of wireless sensors nodes to characterize in situ the frequency-selective channel fading conditions for all links in a star or mesh network. This information may be used to select channels of operation that decrease the total energy cost of transmissions throughout a WSN and/or improve the link quality throughout. This information can also be leveraged for the avoidance of unreliable links, and/or utilization of diversity methods. In addition, the information may provide insight to the network’s overall environment and thus additional nodes may be deployed at locations to improve overall system reliability. The next chapter will explore results found from running the WSSW application within the CRCE chamber.
CHAPTER 6: WSSW IN THE CRCE

6.1 Introduction

Chapters 3 and 4 introduced a wireless test chamber (CRCE) whose purpose it is to create a wide variety of severe fading environments. Chapter 5 then demonstrated a method (WSSW) of using wireless sensors themselves to characterize fading in situ. In this chapter, we further demonstrate the capabilities of WSSW by using the CRCE as a representative environment for a sensor network deployment. In doing so, we will demonstrate the ability of the CRCE to create unique fades between many transmitting and receiving locations for the 16 channels employed in our WSSW implementation. Additionally, we will be testing WSSW for measurement consistency in such a high multipath environment.

6.2 Setup

Figure 43. WSSW for five nodes inside CRCE-IV
Five Freescale sensors running WSSW firmware had their external antenna ports connected to the antenna ports of the CRCE as illustrated in Figure 42. The sensors thus sit together *outside* the chamber while transmitting and receiving data from fixed antenna positions *inside* the chamber. For the work presented herein, the antennas were maintained in the same position for each of the experiments.

### 6.3 Results

WSSW data was collected and analyzed using the custom Labview GUI discussed in Section 5.5. The results displayed below illustrate cases with (Figure 45) and without (Figure 44) anechoic material.

![Graphs and diagrams showing frequency selective fading and relative link strength](image)

**Figure 44.** WSSW for 5 node network, performed within the CRCE. No anechoic material present.
Figure 45. WSSW for 5 node network, performed within the CRCE. Anechoic material added.

The first thing to notice from the frequency selective fading (top left) of the GUI screenshots is that each link exhibits unique fading. This reinforces results from Section 4.4.6, where spatial-selective testing within the chamber also exhibited this non-uniformity. Sensor measurements were not totally consistent over time for these tests. While their fade shapes remained similar, particular measurements sometimes varied as much as 3 dB. Since the conditions in the CRCE were static throughout the test, this variability is most likely due to limitations of the Freescale transceiver hardware in performing RSSI measurements. However, averaging as few as four RSSI measurements for each channel reduced this variability to less than 1 dB.

The next thing to notice is the difference in data collected with and without anechoic material installed in the chamber. Figure 44 (no anechoic) shows in-band data...
with almost equivalent medians, and fades of about 10 dB for each link. The in-band results of Figure 45 (with anechoic), however, exhibit highly varying data, with fades exceeding 20 dB for two of the ten links and median values differing by as much as 12 dB. This outcome is similar to data presented throughout Chapter 4, where fading data collected with anechoic foam displayed a much higher level of statistical variability than when the material was left out, reinforcing the physical underpinnings of the Rayleigh and TWDP models presented in Chapter 2.

6.4 Conclusion

Chapter-IV demonstrated large fades being created within the CRCE chamber as measured by a vector network analyzer (VNA). The VNA obtained these results by scanning over 550 frequency channels. Wireless sensors complying with the IEEE 802.15.4 standard, however, are limited to just 16 channels in the 2.4 GHz ISM band. By running WSSW software within the CRCE as performed in Chapter-VI, we have shown that large fades are also apparent over this reduced selection of frequencies. In addition, we have demonstrated a method in which sensor hardware may be attached and tested within the chamber. This method assures that transmit and receive locations remain consistent while software or hardware are exchanged in order to accurately compare their relative impact on performance.
CHAPTER 7: CONCLUSION AND FUTURE WORK

In this work we have presented new means of measuring and emulating severe wireless communication channels as might be seen by sensor networks. We conclude this thesis by summarizing the significant contributions and by identifying avenues for future work.

7.1 Significant Contributions of Work

- A compact, reconfigurable channel emulator (CRCE) has been built with the ability to create a wide range of repeatable fading environments.

The CRCE has been built to produce fading over time, frequency, and space. Controlled and repeatable fading scenarios ranging from Ricean (high $K$) to the two-ray model may be created within the chamber, providing a means for testing wireless devices in such environments. The design, construction, and performance of the CRCE have been detailed in Chapter 4.

- Developed an enhanced CRCE feature in which multipath events are created using multiple transmits antennas.

Multiple transmit antennas may be activated simultaneously as an additional method of creating multipath diversity within the CRCE. By switching the array of activated antennas, time-varying fading events may be better controlled and operated at high rates. This development was discussed in Section 4.5.

- Have revealed insight to the physical nature of multipath events.
Fading data collected inside the CRCE for severe multipath cases with and without anechoic material (Section 4.4.4) has revealed insight into the physical nature of multipath. High levels of multipath resulted in fading data within a narrow range of statistical variability about the Rayleigh model, whereas limiting multipath in the chamber resulted in widely varying levels of statistical variability. These results reinforce the nature of the physical models discussed in Chapter 2.

- *Expanded WSSW to encompass mesh networks.*

In Chapter 5, WSSW was demonstrated to be an effective method of collecting fading data between all links of a mesh network. In doing so, we have provided a tool for fast data collection during site surveys, set the framework for employing network and node level mitigation techniques, and created a means for in-network environmental analysis for planning additional unit deployments.

### 7.2 Continuing Work on CRCE

Work presented in Chapter 5 demonstrated that four transmitting antennas may be utilized by the CRCE to create 15 discrete levels of received signal amplitudes, or 15 times more frequency-selective fading scenarios than the previous CRCE. This is an enormous increase for the number of frequency-selective modes, but 15 signal amplitudes for time-varying fading still does not offer much variability or real-world practicality. The University of South Florida (USF) is continuing this work by installing 8 transmitting antennas into a CRCE. 8 transmission antennas will increase the total
number of active transmit modes to 255, vastly increasing the number of frequency-varying scenarios and number of discrete values during time-varying event.

As the total number of available frequency-selective fading environments increases, a means of categorizing such fades will become a valuable tool. If implemented, test engineers could select a range of fading severity and the CRCE would choose the appropriate scenarios from its available package to reproduce. This method of self configuration would make for fast, relevant testing, without unnecessary redundancy.

7.3 Continuing Work on WSSW

The work presented in Chapter 6 expanded the concept of wireless sensors, sensing wireless to incorporate link measurements between multiple neighboring nodes. Collecting this data was the main focus of the work, and it has demonstrated that nodes in a mesh network exhibit severe and unpredictable frequency- and time-selective fading in office environments as well as metal shells.

The next step is to use WSSW as a foundation for executing node and network level mitigation. Expanding the fade mitigation strategies developed by Ketcham [10] to utilize the 2-D fade table provided by WSSW will increase the nodes’ ability to maintain all their links within a mesh network. In addition, control algorithms may be developed to expand Galbreath’s work in frequency allocation strategies in star networks [8] to incorporate WSSW data for mesh networks. For example, channel selection to improve overall network life.
7.4 Final Comments

Engineering corporations, such as Goodrich Aerospace, are gearing the design of aircraft and other such systems to one day incorporate wireless sensors in areas where wired sensors still dominate. These sensors perform non-critical tasks, such as regulating cabin lighting, as well as more critical roles, as carried out by those deployed in landing gears and fuel tanks. Wired sensors impose design and safety issues to these systems, including space requirements, difficult installation, maintenance, adding weight where weight is critical, and conducting lightning strikes. Integrating wireless sensors into aircraft design overcomes these issues, but as with any new technology adds problems of its own. Before wireless sensors are permitted to replace their wired counterparts, they must first prove that they are at least as reliable.

One issue concerning the reliability of communication links within a wireless sensor network is that of multipath fading. There has been little effort, however, in testing wireless sensors within fading environments as severe as would be encountered within enclosed metal structures, such as an aircraft. In fact, the traditional chambers in which wireless testing is conducted (anechoic and reverberation) are not even capable of producing such environments.

Detailed in Chapters 4 and 5 are the design and capabilities of a compact, reconfigurable channel emulator (CRCE) built specifically to create a wide range of frequency- and time-selective fading scenarios. Test engineers may utilize the chamber for testing different hardware/software configurations under specific fading environments, or under a wide range of environments, in an effort to discover their
relative performance. More specifically, the CRCE will discover the ability of these systems to maintain communication links when submitted to severe fading channels.

Mitigating deep fades is accomplished through the use of diversity techniques, such as the application of a diversity antenna. In order to use such devices effectively, the sensors must actively characterize the link strengths of their communication channels. This process has been enabled by a technique called wireless sensors, sensing wireless (WSSW), as outlined in Chapter 6. In addition to facilitating diversity methods, WSSW has provided a tool for fast data collection in sensor deployment characterization, and created a means for in-network environmental analysis for planning additional unit deployments. This work has identified opportunities to enable one to characterize channels in situ and to emulate them in a laboratory setting.
BIBLIOGRAPHY


APPENDICES

Appendix A: CRCE components

The following is a list of instruments, parts, and circuitry used in conjunction with the reflective chamber to make up the CRCE.

**Vector Network Analyzer:**

The vector network analyzer used for collecting $S_{21}$ data is the Anritsu MS2036A VNA Master. It is portable, functional in both the 2.4 and 5 GHz ISM bands, and easily controlled by Labview via an Ethernet cable.

![Figure 46. Anritsu MS2036A VNA Master for $S_{21}$ data collection](Image courtesy of Anritsu)

**Data Acquisition:**

For CRCE-II and III utilize National Instrument’s USB-6008, a 12-Bit, 10 kS/s Low-Cost Multifunction DAQ. The USB-6008 supports 8 analog inputs (12-bit, 10
kS/s), 2 analog outputs (12-bit, 150 S/s), 12 digital I/O, and a 32-bit counter. This DAQ interfaces simply through USB, is easily controlled by Labview, and has all the ports necessary for running the stepper motor and reading data from an infrared sensor.

Figure 47. NI USB-6008 for stepper motor and sensor control  
(Image courtesy of National Instruments)

CRCE-IV requires fast control of four control switches, as well as stepper motor and sensor control. For this reason, the CRCE utilizes the NI PCI-6723 analog output card, for 13-bit static and waveform output on up to 32 channels. This card features 800 kS/s per channel for one channel or 45 kS/s per channel for 32 channels operating at once. The channels are slew rate limited to 10k Hz in wave output mode. In addition, this DAQ device maintains 8 digital input/output ports which may be used to control the stepper motor and reach from the infrared sensor. Like the previous DAQ, the PCI-6723 is simple to set up, and easily controlled through Labview.
Reflective blades:

The reflective blades were built at the University of South Florida (USF). They are constructed of steel and are built to hang vertically from motor shaft. Their design assures unique reflective characteristics through 360° of rotation.
**Stepper Motor and Control:**

The 12 VDC, 20 ohm, unipolar stepper motor is capable of 1.8° full steps. The motor mounts to a bracket on the ceiling of the chamber, and suspends the reflective blades from its shaft. Four wires (A1, A2, B1, and B2) control stepper operation through the driver circuit shown in Figure 51, where on the right is the stepper motor, and on the left is the link to the translator or DAQ device. The center taps (A and B) are linked to a 12-V power supply. The coil activation sequence used for operating the motor is shown in Figure 52, where the CRCE has employed the higher torque option.

![Figure 50. Stepping Motor, Mfg # 57BYG084-R.](Image courtesy of Jameco Electronics)

![Figure 51. Stepper motor driver circuit](Image courtesy of Jameco Electronics)
Infrared Sensor and Control:

An optical detector is utilized for sensing black-to-white transitions on the CRCE stirrer shaft to measure rotation speed. The sensor uses an infrared emitted diode combined with an infrared phototransistor to detect the reflected infrared signal.

Figure 53. Optical Sensor
(Image courtesy of SparkFun Electronics)
**Splitter and Switches:**

The 1:4 power splitter takes the RF Out line from the VNA and splits it into four identical signals. These signals then travel to one of four switches, which when activated output the signal through an antenna. When not activated, the signal terminates at a 50 ohm load, limiting reflections back to the splitter. Both power splitter and switch operate at frequencies up to 5 GHz. The splitter requires both positive and negative voltage references, $V^+ = 5\, \text{V}$ and $V^- = -5\, \text{V}$, and TTL control port (0 or 5 V).

Figure 54. ZN4PD1-50 power splitter (left) and ZASWA-2-50-DR switch (right)  
(Image courtesy of Mini-Circuits)
Appendix B: WSSW operation flowcharts

The following flow charts describe the stream of operations performed by the Freescale EVB boards during WSSW for mesh networks.

Figure 55. Flow chart for WSSW in mesh network—“Sweep Command”
Figure 56. Flowchart for WSSW in mesh network—“Get Data” command