Modeling Environmental Effects on Directionality in Wireless Networks

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Abstract—**Realistic radio modeling is crucial for accurate simulation of wireless networks. This paper examines the effect of using directional antennas in real environments with non-trivial multipath effects. We find that the actual variation in signal strength as a function of antenna direction differs appreciably – sometimes dramatically – from what the antenna power (gain) pattern alone would suggest. We quantify and analyze this difference across several antenna types and environments, and provide a generalizable parametric model to support more realistic planning, simulation and analysis.**

I. INTRODUCTION

Increasingly, wireless networks are using *directional* antennas to improve throughput and reach [1]. These networks are frequently studied in simulation to evaluate the design of new protocols. A more recent development is the use of electronically steerable directional or phase array antennas [2]. These antennas provide better network performance by controlling the radiation pattern of the antenna, thereby increasing the gain (strength of the transmitted and received signal).

As is the case throughout networking, much of the research and design for wireless networks is conducted using simulation and analytical models. As a result, accurately modeling the the physical layer is essential because it will have a significant influence on the behavior of the entire network stack.

We argue that the *effective power pattern* – the observed variation in signal strength as a function of antenna direction – is a result of both antenna directivity and the environment. Without a significant environmental influence, the effective power pattern would be equivalent to the antenna's *power pattern* [3]. However, in many cases, the two differ dramatically. This has been observed before [4], but no better models have been proposed.

This paper presents a measurement-based approach to modeling the effective power pattern of a range of antennas in a variety of environments. We show that this model primarily captures the effect of the environment, and consequently that the results obtained with one antenna are generally applicable to many different directional antenna types. Indeed, in a separate paper we show that this model can be used as the basis for improved simulation of wireless networks [5]. Using parameter values for similar environments from Section IV-D, and *without prior modeling of the test locations*, the new simulation process performed between 1.6 and 10 times better than state-of-the-art wireless networking simulators at predicting the performance of a propagation-sensitive application.

Additionally, we evaluate and calibrate laptops with commodity wireless networking cards and show that they provide sufficient accuracy to be used for environmental modeling, while being far less expensive and more portable than standard signal generators and analyzers.

In the next section, we discuss how directional antenna gain is modeled in current simulators, which motivates our work in creating a new model. Section III describes the measurements performed and provides analysis of the interesting features in this data. Our new model for the *effective power pattern* is presented in Section IV, and in Section V, we conclude.

II. BACKGROUND AND RELATED WORK

Although there has been much research done on radio propagation models (see [6]–[8] for excellent surveys of this work) the simulators commonly used in networking research do not consider antenna directionality and radio propagation as interacting variables. This paper considers three widely-used simulators: *OpNet*, *QualNet*, and *NS-2* [9]–[11]. Each one supports several models of radio propagation (path loss and possibly fading), but they all follow the same general model with regard to antenna gain: For any two stations i and j, the received signal strength is computed according to the general form of equation 1:

$$P_{rx} = P_{tx} * G_{tx} * |PL(i,j)| * G_{rx} \tag{1}$$

The received power P_{rx} is the product of the transmitted power P_{tx}, the transmitter's gain G_{tx}, the magnitude of the path loss between the two stations, and the receiver's gain G_{rx}. The transmitter and receiver gains are modeled as constants for omnidirectional (effectively isotropic in the azimuth plane) antennas. For directional antennas, gain is a function of the antenna pattern and the relative angle between the transmitter and receiver.

For some given zenith ϕ, azimuth θ, and an antenna-specific characterization function $f_a()$, the power transmitted in that direction is given by equation 2:

$$\text{Gain in direction}(\phi, \theta) = f_a(\phi, \theta) \quad (2)$$

$$\text{Combined gain} = f_a(\phi, \theta) * f_b(\phi', \theta') \quad (3)$$

Correspondingly, the receiver gain is modeled by a (potentially different) function $f_b()$ of the direction from which the signal is received. Equation 3 considers the combined effect. What this model omits is the effect of secondary paths between the sender and receiver. In free space, the straight-line primary path is the only path between sender and receiver, so the antenna angles relative to that line are the only ones that matter. In some cases, such as the two-ray model, the path loss model includes signal reflected off the ground as a special case, but no other objects are considered. However, in environments with significant multipath, *the gain cannot be determined based solely on a single direction*. In reality, the transmitter's power is radiated in all directions, and the receiver aggregates power (be it signal or noise) from all directions. Imagine for example that a transmitter has a null pointed directly at a receiver, but also has its main lobe pointed at a surface which reflects the signal toward the receiver. It is the significance of these secondary paths which causes the effective power pattern to differ from the that of the antenna alone.

III. MEASUREMENTS

In this section we will describe the datasets we collected and the normalization procedure, and give some high-level statistical characterization of the data.

A. *Experiments Performed*

Label	Location	LOS	Dist. (m)	Samples	Loss (%)
Para-Out-A	Urban Field	Yes	30.48	214471	24.81
Para-Out-B	Open Plain	Yes	30.48	258876	7.05
Para-In-A	Office 1	Yes	12.19	267092	2.21
Para-In-B	Office 2	Yes	60.96	268935	10.41
Para-In-C	Office 2	No	15.24	283104	5.12
Para-Ref	Open Plain	Yes	30.48	219	N/A
Patch-Out-A	Urban Field	Yes	30.48	455952	12.44
Patch-Out-B	Open Plain	Yes	30.48	278239	4.99
Patch-In-A	Office 1	Yes	12.19	290030	2.21
Patch-In-B	Office 2	Yes	60.96	265593	7.40
Patch-In-C	Office 2	No	15.24	278205	2.65
Patch-Ref	Open Plain	Yes	30.48	219	N/A
Array-Out-A	Urban Field	Yes	30.48	475178	N/A
Array-In-A	Office 2	Mixed	Varies	2672050	N/A
Array-In-B	Office 2	Mixed	Varies	2708160	N/A
Array-Ref	N/A	N/A	N/A	360	N/A

TABLE I: Summary of data sets

In order to derive an empirical model that better fits real world behavior, we collected data in several disparate environments with three different antennas. A high level summary of these datasets is in table I. The three antenna configurations were: (1) a 24dBi parabolic dish with an 8-degree horizontal beam-width, (2) a 14dBi patch with a 30 degree horizontal beam-width, (3) and a 8-element uniform circular phased array pattern with a main-lobe beam-width of approximately 52 degrees. This phased array functions as a switched-beam antenna and can form this beam in one of 16 directions (on 22.5 degree increments around the azimuth).

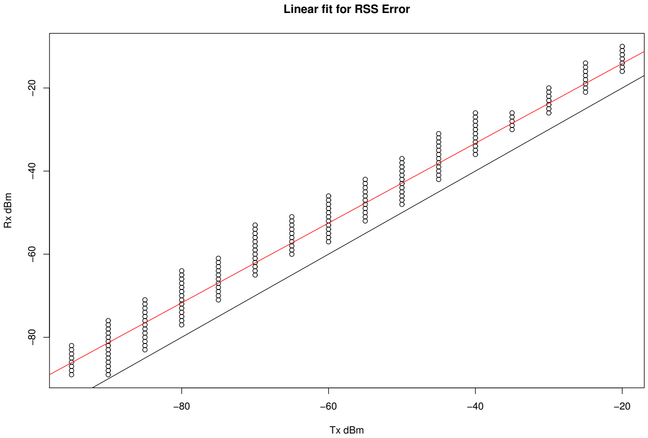

Fig. 2: Linear fit for RSS measurements of commodity 802.11 radios

Data sets were collected using both high-precision measurement and test equipment as well as calibrated laptops. The laptops were used both for convenience and to demonstrate that the measurements required can be conducted with inexpensive, widely-available equipment. We use two laptops with one acting as a receiver and the other as a transmitter. Each is equipped with an Atheros-based radio. The receiver is connected to a 7 dBi omnidirectional antenna on a tripod approximately 2 meters off the ground. The antenna being modeled is also mounted at a similar height on a tripod, and is connected to the transmitting laptop. With the equipment in place, the procedure is as follows: For each 5 degree position about the azimuth, the transmitter sends a volley of packets and the receiver records their apparent signal strength.

In the process of collection, some packets will be dropped due to interference or poor signal. In our experience, the percentage of dropped frames *per angle* is very small: the maximum lost frames per-angle in our datasets is on the order of 5%, with less than 1% loss being more common (the mean is 0.01675%). Moreover, the correlation coefficient between angle and loss percentage is -0.0451, suggesting that losses are uniformly distributed across angles. There were 4000 samples in each direction (500 packets $* 8$ MAC-layer retries each) for our configuration), so noise due to packet loss is negligible.

To ensure that the commodity 802.11 radios reported trustworthy signal strength values, the received signal strength (RSS) measurements of each card were calibrated using an Agilent E4438C vector signal generator (VSG) to transmit 802.11 frames at a range of known power levels. The reported signal strengths had some absolute error, but there was an excellent (adjusted $R^2 = 0.989$) linear fit between the true and report values. Figure 2 plots the measurements and fit. This fit was used to correct all measurements made using these cards.

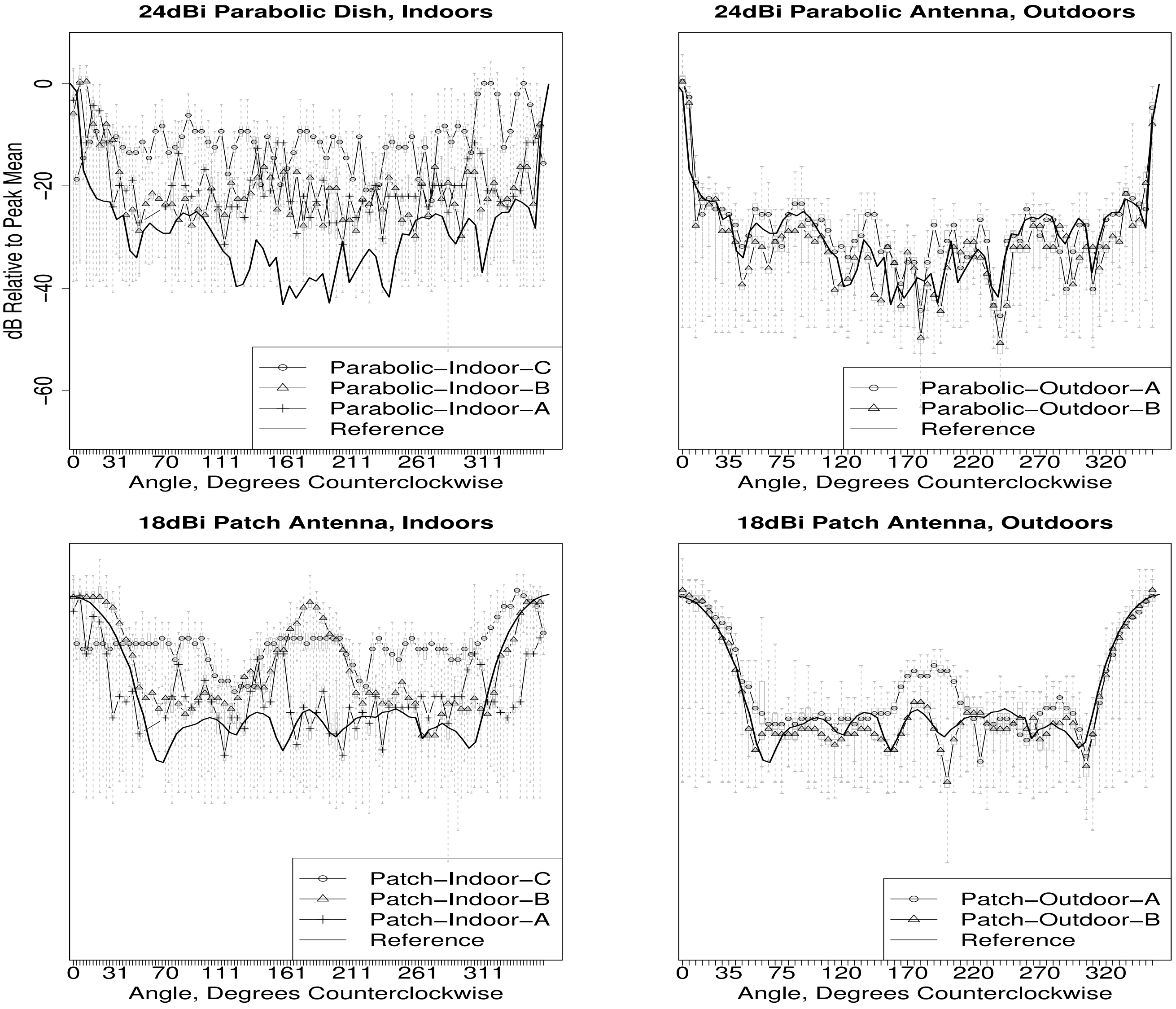

Fig. 1: Comparison of signal strength patterns across different environments and antennas.

In addition to the in-situ experiments, we have a "reference" data set for each antenna. The Array-Reference data set was provided to us by the antenna manufacturer. Because the other manufacturers could not provide us with data on their antennas, Parabolic-Reference and Patch-Reference were derived using an Agilent 89600S vector signal analyzer (VSA) and an Agilent E4438C VSG in a remote floodplain[1].

The following is a brief description of each of the experiments. More detailed information is available in [12].

- **Parabolic-Out-A, Patch-Out-A, Array-Out-A** – An open field on our university campus was used for these experiments. The urban field was roughly 152.4 meters on a side and surrounded by brick buildings on two of the four sides.
- **Parabolic-Out-B, Patch-Out-B** – These measurements were taken in the aforementioned floodplain. The floodplain was flat, recessed, and free from obstruction for at least 500 meters in all directions.
- **Parabolic-In-A and Patch-In-A** – The directional transmitter was positioned approximately 12 meters from the receiver in a walkway between cubicles and desks. This was our most cluttered environment.
- **Parabolic-In-B, Parabolic-In-C, Patch-In-B, and Patch-In-C** – A different 25x30 meter indoor office was used for this set of tests. Two receivers were used here: one with line of sight and one without line of sight, placed amidst desks and offices.
- **Array-In-A and Array-In-B** – Seven phase array antennas were deployed in the same indoor space used for Parabolic-In-B, Parabolic-In-C, Patch-In-B, and Patch-In-

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[1] We were unable to acquire access to an anechoic chamber in time for this study, but plan to make use of one for even cleaner reference measurements.

C. These data sets represent two of the seven antennas.

- **Parabolic-Reference and Patch-Reference** – The antenna under test was connected to a VSG outputting a 25 dBm signal and rotated in 5-degree increments in the azimuth. An Agilent VSA was connected to the receiver and made a 10-second running average of power samples at the 2.412 GHz frequency. Three consecutive averages of both peak and band power were recorded for each direction. The measured noise floor (-59.62 dBm) was subtracted from the power measurements to give an estimate of the signal's power.

B. Normalization

Our first task in comparing data sets is to come up with a scheme for normalization so that they can be compared to one another directly. For each data set, we find the mean peak value which is the maximum of the mean of samples for each discrete angle. This value is then subtracted (division in a linear domain) from every value in the data set. The net effect is that the peak of the measurements in each data set will be shifted to zero.

C. Characterization

1) Error relative to the reference: Figure 1 shows the normalized measured in-situ patterns and their corresponding (also normalized) reference patterns. It can be seen that there is much variation in the measured patterns and also in how much they differ from the reference. As we would expect, the measurements in outdoor environments differ less, due to less clutter, but still deviate from the reference on occasion. As a further confirmation that our measurement process works well, notice how well Parabolic-Out-B and Patch-Out-B in figures 1 correlate with the reference pattern[2].

2) Distribution of Error: Our foremost question in characterization is: *is there a straight-forward explanation for error*? Figure 3 provides a cumulative density function (CDF) of all error for each antenna. The antennas provide similar error distributions, although offset in the mean. The Array data is the most offset, possibly because of error in the reference pattern, and exhibits some bimodal behavior. The Patch data is closest to the reference, showing a large kurtosis about zero.

Clearly, the antennas have different error characteristics. However, within each antenna, and within each data set, it might be that the error in a given direction is correlated with that in other directions – if this were true, we could use a single or small set of probability distributions to describe the error process in a given environment, with a given antenna.

We use a Shapiro-Wilkes test on the per-angle error for each data set to determine if it fits a normal distribution. The resulting p-values are well under the $\alpha = 0.05$ threshold, indicating that error is not normally distributed; this means that standard statistical tests (and regression models) that assume normality can not be used.

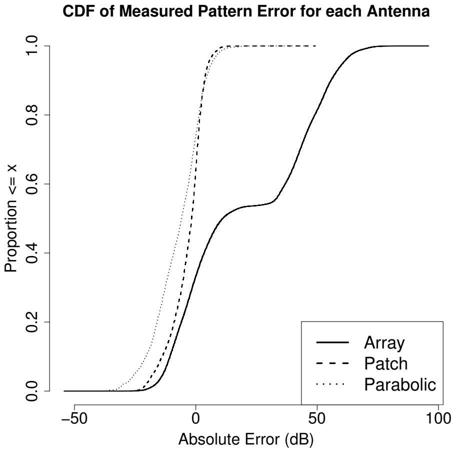

Fig. 3: CDFs for the error process (across multiple traces) for each antenna.

A pairwise Mann-Whitney U-test can determine which pairs of samples grouped on some criterion (in our case angle) are drawn from the same distribution. All of our traces show similar trends: in the majority of pairs we find that the per-angle error for each data set is not drawn from the same distribution. However, there is one exception: for angles near zero, we are unable to make this conclusion. This observation, that *measurements where the main-lobe of the directional antenna is pointed at the receiver may exhibit correlated error processes*, motivates another series of tests.

To further explore "possibly well behaved" error processes about the main lobe, we applied a Kruskal-Wallis rank-sum test to two scenarios: (1) For angles near zero, are batches with the same antenna but different environments equivalent? (2) For angles near zero, are batches with the same environment but different antennas equivalent?

For (1), the null hypothesis is rejected for all combinations. In fact, the maximum p-value found is 1.990343e-40. For (2), the results still point strongly towards rejection (mean p-value = 0.0082), however there is one outlier in the office 1 environment for which the p-value is 0.2097. One outlier, however, does not undermine the overwhelming evidence that neither antenna configuration nor environment alone is sufficient to account for intra-angle variation in error - even in the more well-behaved cone of the antenna main-lobe.

There are several qualitative points which are worth bringing out of this data: (1) In the indoor environments, none of the measured traces track the reference signal closely; (2) In all environments, there is significant variation between data sets; (3) The maximum signal strength is generally realized in *approximately* the direction of maximum antenna gain, but directions of low antenna gain often do not have low signal strength. This means that *one can not safely rely on pre-determined antenna patterns for null-steering in many environments*.

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[2] Recall that these experiments were done in the same location as the reference

IV. MODELING EFFECTIVE DIRECTIONALITY

We began this paper with the observation that path loss and antenna gain are typically regarded as orthogonal components of the power loss between transmission and reception (Equations 1 - 3). In this section, we evaluate the *best case* accuracy of this approach, and suggest a new model based on the limitations identified.

A. Limitations of Orthogonal Models

This subsection formalizes the orthogonal antenna gain / path loss model and analyzes the error associated with it. If transmit power and path loss do not vary with antenna angle, the received power relative to antenna angle can be modeled as:

$$\widehat{P_{rx}} = \beta_0 * f(\phi, \theta) \tag{4}$$

β_0 is a constant combining the path loss – however calculated – and the gain of the non-rotating antenna. f is a function describing the gain of the other antenna relative to the signal's direction (azimuth θ and zenith ϕ). Without loss of generality, we will assume that the antenna being varied is the receiver, and that the zenith, ϕ, is fixed.

To evaluate the accuracy of this model, we start by finding the estimate b_0 for β_0, which minimizes the sum of squared error (SSE). In effect, this is assuming the *best possible path loss estimate*, without specifying how it is determined. If the function f correctly describes the antenna, and if path loss and antenna gain are in fact orthogonal components of the received signal strength, then the remaining error should be *randomly* distributed about 0.

The path loss value used for each data set was the lowest-error fit for that specific data, and the antenna patterns (f) for the patch and parabolic antennas were measured using the antenna in question. Note also that error patterns differ between environments; One could derive an ex post facto f to eliminate the error in a single data set, but it would not be applicable to any other.

The magnitude and *systematic nature* of the error suggests that the orthogonal model has inherent limitations which cannot be alleviated by improving either the antenna model or path loss model separately.

B. An Integrated Environment-Directivity Model

This subsection describes a new model for the interaction of antenna direction and the RF environment. This integrated model addresses the systemic errors discussed above, and is sufficiently simple to use in analysis and simulations.

We address the environment-specific, direction-specific error shown in figure 4 with the following environment-aware model, given in eq. 5. The expected received power $\widehat{P_{rx}}$ is given by a constant β_0, the antenna gain function f, and a yet to be determined environmental offset function x:

$$\widehat{P_{rx}} = \beta_0 * f(\phi, \theta) * x(\phi, \theta) \tag{5}$$

As with the orthogonal model, we assume a constant zenith and consider f and x with regard to the azimuth θ. Equation 5 can be converted to a form that lends itself to least-squares (linear regression) analysis in the following way: First, we rewrite eq. 5 as addition in a logarithmic domain, and second we substitute a discrete version for the general x. In the discrete x, the range of angles is partitioned into n bins such that bin i spans the range $[B_i, T_i)$. Each bin has associated with it a boxcar function $d_i(\theta)$ defined to be 1 if and only if the angle θ falls within bin i (eq. 6) and an unknown constant *offset value* β_i. These transformations yield the model given in eq. 8.

$$d_i(\theta) = \begin{cases} 1, & B_i \leq \theta < T_i \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

$$x(\theta) = \sum_{i=1}^{n} d_i(\theta)\ \beta_i \tag{7}$$

$$f(\theta) - \widehat{P_{rx}} = \beta_0 + \beta_1 d_1(\theta) + \beta_2 d_2(\theta) + \cdots + \beta_n d_n(\theta) \tag{8}$$

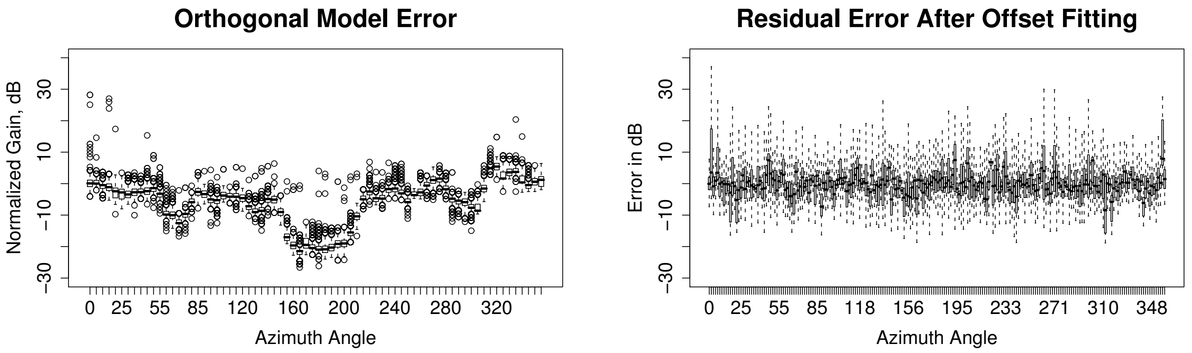
If x is discretized into n bins, the model has $n+1$ degrees of freedom: One for each bin and one for β_0, the signal strength without antenna gain. For any given signal direction, exactly one of the $d_i()$ functions will be 1, so each prediction is an interaction of two coefficients: β_0 and β_i. Consequently, β_0 could be eliminated and an equivalent model achieved by adding b_0's value to each b_i. Mathematically, this means that there are only n independent variables in the SSE fitting, and the full set is collinear. In practice, we drop the constant b_n, but this does not mean that packets arriving in that bin are any less well-modeled. Rather, one can think of bin n as being the "default" case.

The azimuth can be divided into arbitrarily many bins. The more finely it is divided, the more degrees of freedom the model offers, and thus the more closely it can be fitted to the environment. To investigate the effect of bin number, we modeled every data set using from two to twenty bins. Figure 5 shows the residual standard error as a function of bin count. The grey box plot depicts the mean and interquartile range for all of the data collectively, and the foreground lines show values for links individually. In general, there appears to be a diminishing return as the number of bins increases, with the mean remaining nearly constant above 16 bins.

In discussing parameters for this model, we will use the 16-bin case specifically. We find the same patterns across other numbers, though the actual coefficients are bin-count specific. One result of note with regard to bin count is this: Several environments exhibit a "sawtooth" pattern in which the odd bin counts do better than the even ones, or vice-versa. This appears to be an effect of the *alignment* of the bins relative to environmental features, rather than the *number* of bins.

C. Accuracy

This model has significantly less error than the orthogonal model: Across all data sets, the mean residual standard error is 4.0 dB, *(4.4dB indoors)* compared to 6.15 dB *(7.312 dB indoors)* for the orthogonal model. More importantly, the error remaining in the discrete offset model is largely noise: The mean error is almost exactly zero for several ways of grouping



(a) Error for Patch-Indoor-B

(b) Error for all data sets

Fig. 4: Differences between the models and reality in dB.

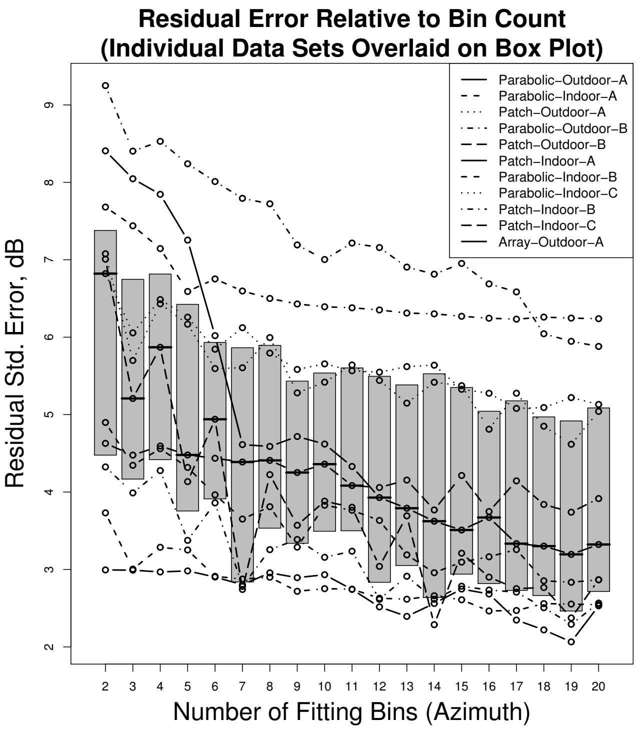


Fig. 5: Effect of increasing bin count (decreasing bin size) on modeling precision.

the data. Figure 4 shows the angle correlation for both models. While the outliers reveal some direction-correlated effect that is not accounted for, this model is much better for the bulk of the traffic. Over 99.9% of the traffic *at every angle* falls within the whisker interval.

D. Describing and Predicting Environments

The environmental offset function x, or its bin-offset counterpart, models the impact of a particular environment combined with a particular antenna. This can serve as an after-the-fact description of the environment encountered, but it also has predictive value: If one knows the offset function for a given environment, it is possible to more accurately model wireless systems in that environment. We are not aware of any practical way to know the exact spatial RF characteristics of an environment – and thus its offsets – without actually measuring it. However, our results suggest that it is possible to identify parameters generating the *distribution* from which the offset values for a *class of environments* are drawn.

Data Set	**Factor**	**Coeff.**	**P-value**
Parabolic-Outdoor-A	Antenna Gain	0.185	1.02e-87
	Obs. Angle	0.00301	5.1e-06
Patch-Outdoor-A	Antenna Gain	0.146	6.4e-50
	Obs. Angle	0.00744	1.14e-17
Array-Outdoor-A	Antenna Gain	0.41	2.03e-206
	Obs. Angle	-0.0271	5.36e-188
Parabolic-Outdoor-B	Antenna Gain	0.0377	8.68e-05
	Obs. Angle	-0.00323	5.95e-05
Patch-Outdoor-B	Antenna Gain	0.00919	0.0492 [3]
	Obs. Angle	-0.00198	3.08e-06
Parabolic-Indoor-A	Antenna Gain	0.33	4.6e-102
	Obs. Angle	0.00463	1.91e-05
Patch-Indoor-A	Antenna Gain	0.258	1.22e-122
	Obs. Angle	0.00894	3.09e-24
Parabolic-Indoor-B	Antenna Gain	0.378	2.2e-134
	Obs. Angle	0.00971	1.97e-16
Patch-Indoor-B	Antenna Gain	0.372	1.1e-81
	Obs. Angle	0.014	3.87e-18
Parabolic-Indoor-C	Antenna Gain	0.668	1.39e-234
	Obs. Angle	-0.0146	4.15e-36
Patch-Indoor-C	Antenna Gain	0.703	0
	Obs. Angle	-0.0154	2.63e-48

TABLE II: Factors influencing fitted offset values, 16-bin case.

We analyzed a range of possible determining factors for the fitted offsets, across all traces and a range of bin counts. A linear regression fit and ANOVA test found significant correlation with two factors: The nominal antenna gain $f(\theta)$ and the observation point; none of the other factors examined were consistently significant. The observation angle was always statistically significant, but the coefficient is constantly near zero. For each factor, the regression coefficient describes the

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[3] Marginally statistically significant.

correlation between the fitted offset and the factor. That is, the coefficient shows how much the actual signal strength can be expected to differ from the orthogonal model, for any value of that factor. For example, the antenna gain coefficients of 0.668 and 0.703 for Parabolic-Indoor-C and Patch-Indoor-C mean that in those data sets for every dB difference in antenna gain between two angles, *the-best fit difference in actual signal strength is only* $\approx$ *0.3 dB*. Table II summarizes these results. Recall the model from equations (5) – (8):

$$\widehat{P_{rx}} = \beta_0 * f(\phi,\theta) * x(\phi,\theta)$$

The environmental $x(\cdot)$ function for any *given* environment can be approximated by a fitted discrete log-domain form, with residual std. error S_{ss}:

$$x(\theta) = \sum_{i=1}^{n} d_i(\theta)\ \beta_i$$

$$f(\theta) - \widehat{P_{rx}} = \beta_0 + \beta_1 d_1(\theta) + \beta_2 d_2(\theta) + \cdots + \beta_n d_n(\theta)$$

The regression analysis and ANOVA in this section provide a basis for describing the $\beta_{1,\cdots,n}$. The β_i are *predicted* by eq. (9) with residual std. error S_{off}, where θ_i is the center angle of bin i:

$$\widehat{\beta_i} = f(\theta_i) * K_{gain} \tag{9}$$

Therefore, if K_{gain}, S_{off}, and S_{ss} are given, expected (log) signal strength can be modeled by equation (10), where β_0 is the estimated gain (loss) from other aspects of the system, ϵ_1 is a random variable with 0 mean and standard deviation S_{ss}, and ϵ_2 is a random variable with 0 mean and standard deviation S_{off}.

$$\begin{aligned}\widehat{P_{rx}} =& P_{tx} + \beta_0 + f(\theta) + \epsilon_1 \\ &+ \sum_{i=1}^{n} d_i(\theta) * (f(\theta_i) * K_{gain} + \epsilon_2)\end{aligned} \tag{10}$$

There are two key results pertaining to the antenna gain regression coefficient: First, the coefficients for different antennas in the same environment are very close. Second, the coefficients for distinct but similar environments are fairly close. Coefficient ranges are summarized in Table III. The column K_{gain} shows the antenna gain regression coefficients; S_{off} shows the residual standard error *of the best offsets* relative to what would be predicted using the regression coefficients; and S_{ss} shows the residual standard error *of the per-packet signal strengths* relative to the estimated offsets. These results suggest that classes of environments can reasonably be characterized by their associated coefficients. In [5], we show that a simulation process using a model based on equations (8) and (9), and the coefficients in table III produces substantially more accurate results than the current state of the art.

Environment	K_{gain}	S_{off}	S_{ss}
Open Outdoor	0.01 - 0.04	1.326 - 2.675	2.68 - 3.75
Urban Outdoor	0.15 - 0.19	2.244 - 3.023	2.46 - 2.75
LOS Indoor	0.25 - 0.38	2.837 - 5.242	2.9 - 5.28
NLOS Indoor	0.67 - 0.70	3.17 - 3.566	3.67 - 6.69

TABLE III: Summary of Regression Results: Gain-offset regression coefficient (K_{gain}), offset residual std. error (S_{off}), and signal strength residual std. error (S_{ss}).

V. CONCLUSION

Wireless signal and interference propagation in the directional setting is more complicated than common previous models have acknowledged. In this paper, we have presented an empirical study of the way different environments and antennas interact to affect the directionality of signal propagation. The three primary contributions of this work are:

1) A well-validated method for surveying propagation environments with inexpensive commodity hardware.
2) A characterization of several specific environments ranging from the very cluttered to the very open.
3) New, more accurate, techniques for modeling and simulating directional propagation in wireless networking.

In addition to being described in this paper, the collected data sets and simulator code implementing our model will be released to the research community[4].

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