Modeling Directionality in Wireless Networks

[Extended Abstract]

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ABSTRACT

The physical-layer models commonly used in current networking research only minimally address the interaction of directional antennas and radio propagation. This paper compares the models found in popular simulation tools with measurements taken across a variety of links in multiple environments. We find that the effects of antenna direction are significantly different from the models used by the common wireless network simulators.

We propose a parametric model which better captures the effects of different propagation environments on directional antenna systems. We believe that adopting this model will allow more realistic simulation of protocols relying on directional antennas, supporting better design and more valid assessment of those protocols.

Categories and Subject Descriptors

I.6.5 [**Computing Methodologies**]: SIMULATION AND MODELING—*Modeling methodologies*; C.2.1 [**Computer Systems Organization**]: COMPUTER-COMMUNICATION NETWORKS—*Wireless communication*

General Terms

Experimentation, Measurement, Verification

Keywords

Modeling, Directional, Antenna, Propagation, Wireless, Networking

1. INTRODUCTION

Increasingly, networks are using fixed or steerable *directional* antennas to improve throughput and reach [3, 2, 1]. In most analytical models, networking researchers use a very simplified model for directionality, typically a conic section. The common network simulators model antennas with varying degrees of fidelity, but all follow the same pattern, which we refer to as the *orthogonal model*: Path loss and antenna gain are calculated independently, based respectively on nodes' positions and relative angles, and the two values are added together. We find that *there are major interaction effects between the antenna and the propagation environment*, and that any model which only accounts for the two separately, *no matter how precisely*, will produce significant errors.

We propose an empirical model for these interactions, and argue that it is applicable to a wide variety of antennas and environments.

2. MEASUREMENTS

Our data were collected using eight-element uniform circular phased array receivers and "omni-directional" dipole transmitters. The receivers were kept stationary, while the transmitters were moved for some experiments to measure the impact of different locations and angles. Every receiver was configured with 16 directional states, each having a 3dB beam width of approximately 52 degrees and a peak to side lobe ratio of 10-15dB. Figure 1a shows the expected antenna pattern in the azimuth-plane based on manufacturer measurements. The receivers were continuously cycled through these states so that 16 effective antenna orientations were measured per receiver for each physical combination of transmitter and receiver positions.

We collected data in two very different environments: One data set was collected in an open field on the University of Colorado campus. A single receiver was placed approximately 100 feet away from a single transmitter; both remained in the same location throughout the experiment. The receiver was physically rotated in 10-degree increments with the transmitter sending a volley of packets in each position. This data is most representative of an uncluttered, but urban, outdoor environment. The other was collected in an office building where seven receivers were deployed in a 25x30m area. Two mobile transmitters were moved throughout the building, sending packets from known locations. All of the receivers and transmission points were on the same floor, but in a variety of rooms. Figures 1b and 1c plot the observed signal strengths relative to antenna angle for these data-sets.

3. MODEL: PER-DIRECTION OFFSET

Even with very good antenna pattern models and a fitted (error minimizing) path loss estimate, the standard models have significant error. Moreover, this error is not randomly distributed, but rather varies with angle.

We propose a new model, given in equation 1: The expected received power is given by a constant path loss β_0, the antenna gain function $f()$, and a new environmental impact function $x()$.

$$\widehat{P_{rx}} = \beta_0 * f(\theta) * x(\theta) \tag{1}$$

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This can be converted to a form that lends itself to least-squares (linear regression) analysis in the following way: First, we rewrite equation 1 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 $d_i(\theta)$ to be 1 iff the angle θ falls within bin i (equation 2) and an unknown constant β_i. These transformations yield the model given in equation 4.

$$d_i(\theta) = \begin{cases} 1, & B_i \leq \theta < T_i \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

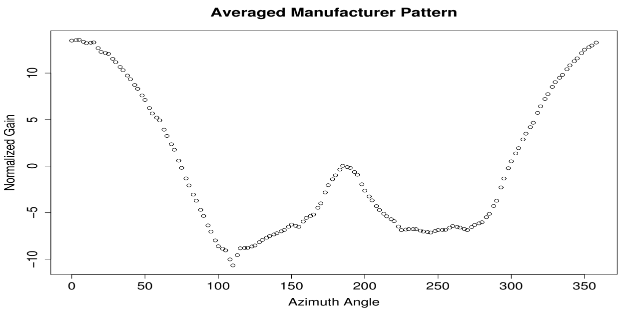
$$x(\theta) = \sum_{i=1}^{n} d_i(\theta)\ \beta_i \tag{3}$$

$$f(\theta_i) - \widehat{P_{rx}} = \beta_0 + \beta_1 d_1(\theta) + \beta_2 d_2(\theta) + \cdots + \beta_n d_n(\theta) \tag{4}$$

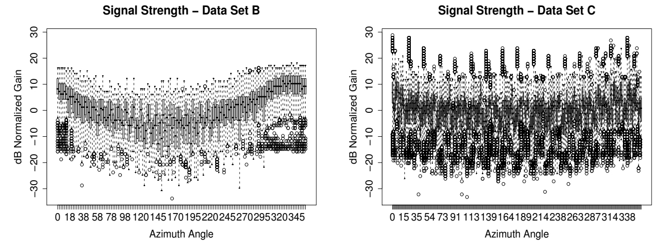
For this data, we discretized $x()$ into 16 bins because our receivers provided that many distinct patterns, and thus it was the greatest angular resolution available for any fixed observation point. This model has 17 degrees of freedom: One for the each pattern and one for β_0, the signal strength without antenna gain. For any given packet, only one of the $d_i()$ functions will be 1, so each prediction is an interaction of exactly two coefficients b_0 and b_i. Consequently, b_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 16 independent variables in the Sum of Square Error (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.

This model has about half the error of the orthogonal model: Across all observation points, the mean residual standard error is 4.1 dB, *(5.1 dB indoors)* compared to 7.6 dB *(8.9 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 the data. Figures 1d and 1e depicts the error (predicted value minus observed value). 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% of the traffic *at every angle* falls within the whisker interval.

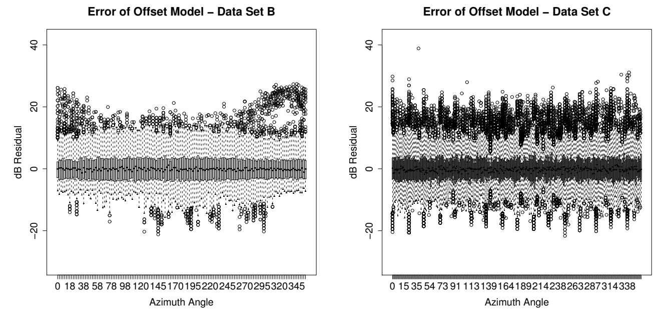
Figure 1b gives the impression that the orthogonal model overestimates the signal strength in high-gain angles and underestimates in low. This is borne out in analyzing the fitted offset values: A linear regression fit and ANOVA test found significant correlation between the offsets and two other factors: the nominal antenna gain $f(\theta)$ and the observation point. These correlations are specific to the environment, and can be used as parameters to generate offset values for similar simulated environments.



(a) Reference Pattern



(b) Outdoor Measured Signal (c) Indoor Measured Signal



(d) New Model Error: Outdoor (e) New Model Error: Indoor

Figure 1: Reference pattern, measured signal strengths, and *new (offset) model* residual errors.

4. CONCLUSION

In this paper, we have identified significant errors in the commonly-used signal strength models which consider path-loss and antenna pattern separately. To correct these errors it is necessary to account for the effects the environment has on signal directionality; they persist even with ideal path loss and antenna gain models. We offer a new measurement-driven model which largely addresses these shortcomings, while remaining simple enough for practical use.

5. REFERENCES

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