Modeling Signal Attenuation in IEEE 802.11 Wireless LANs - Vol. 1

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Abstract

Path loss models are used to approximate signal attenuation as a function of the distance between transmitters and receivers, being an important building block for both research and industry efforts. In this paper we present experimental data that validates the use of the *log-distance model* both inside and outside a standard office building. Our measurements were performed using off-the-shelf IEEE 802.11b hardware and with distances varying from 1 to 50 meters. The values found for the path loss exponent agree with previously published results ($\alpha = 4.02, 3.32$). Moreover, linear regression produced models with acceptable standard deviations (< 8 dB) and suggest the occurrence of *log-normal shadowing*, as the deviations from the mean (in decibels) closely follow a Gaussian distribution.

1 Introduction

The ability to predict the signal strength provided by access points in a wireless LAN (WLAN) is not only useful to researchers but is also a convenient capability in practice. For instance, it gives operators an idea of the coverage provided by a set of access points (APs) based only on their locations, possibly eliminating the need for site surveys when provisioning the network. Moreover, it allows the network to more accurately implement services such as device localization, transmission power control, and interference prediction.

The standard way of estimating signal strength across an environment is by means of a *path loss model*, usually found empirically [9]. Simple models estimate the mean signal strength between transmitters and receivers based solely on the distance between them, while more accurate (and complicated) models use extra information about the environment, such as building blueprints, wall materials, and location of obstacles. Due to scattering, reflection, and diffraction of waves, path loss models are strongly environment-dependent. Moreover, while free space propagation dictates that signal attenuates as a function of the square of the distance, measurements have shown higher attenuation in practice, both inside and outside office buildings [8, 5, 9].
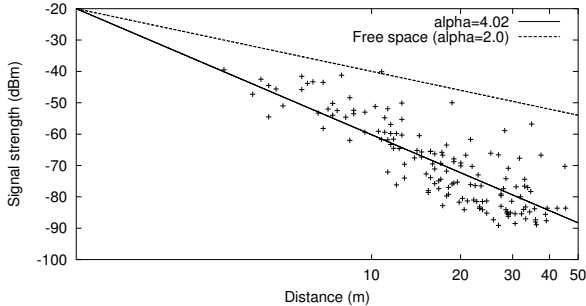
In this paper we demonstrate the applicability of the *log-distance model* to predict signal strength within and around a standard office environment. This model has been chosen for its simplicity and its effectiveness at modeling signal propagation over several frequencies [10, 9]. Our effort differs from previously published ones in several ways:
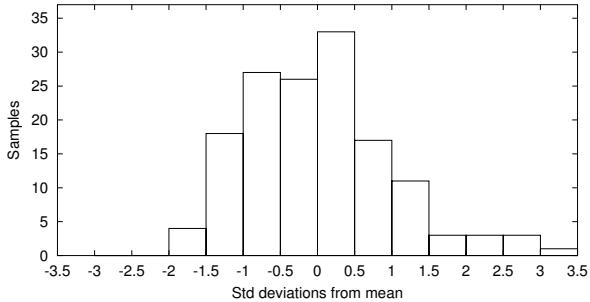
No spatial averaging. It is common practice to represent a given location L by the average signal strength over an area around L, usually in the order of several wavelengths [10, 7]. Such spatial averaging is performed to remove outliers, reducing the effects of small-scale fading and producing values more representative of large-scale path loss. Despite better modeling results, such procedure has a couple of disadvantages. First, as clients are usually stationary [6, 3], the values generated through spatial averaging may produce incorrect statistics. Second, it increases the costs associated with modeling an environment. For instance, access points can autonomously create signal strength samples in overprovisioned networks, relieving operators from unnecessary time-consuming experiments. Such autonomous *calibration* is viable only if spatial averaging is not necessary.

Off-the-shelf IEEE 802.11 hardware. Instead of using pole-mounted antennas and spectrum analyzers, we employ regular 802.11b hardware to collect samples. We believe such setting to produce results more representative of real installations for a set of reasons. First, signal strength estimates may be noisier, as they are generated by standard PCMCIA client devices during frame reception. Second, standard cards do not produce exact omni-directional transmission patterns, which also affects signal attenuation in practice. Finally, the use of such hardware allows our measurements to benefit from techniques implemented to improve reception quality. For instance, most 802.11 devices today implement antenna diversity, which reduces some effects attributed to small-scale fading (e.g. sudden drops in signal strength) [9].

Standard setting. We modeled signal propagation within and around the Gates Computer Science Building at Stanford University. Indoors, 41 locations were sampled within a 66m×24m area in the fourth floor, with measurements taken in corridors and inside offices, with

Figure 1: Measurement locations in the 4th floor of the Computer Science Building.

transmitter-receiver separation ranging from 1 to 50 meters. Outside, we sampled 40 locations with distances varying between 1 and 31 meters from the building's external wall. In both cases, the experiments were performed using the installed IEEE 802.11b wireless infrastructure.

Our results suggest that the log-distance model can be used successfully both indoors and outdoors. First, the values found for the path loss exponent (α) agree with previously published numbers: 4.02 and 3.32 for indoor and outdoor attenuation, respectively. Second, our measurements produced models with acceptable standard deviation values: 7.36 dB inside and 3.1 dB outside the building. Finally, the deviations from the mean (in decibels) could be closely approximated by Gaussians, what is usually referred to as *log-normal shadowing*.

2 Log-distance Path Loss Model

In order to predict received signal strength between clients and access points, in this paper we employ the log-distance path loss model [9]. In this model, received power (in dBm) at a distance d (in meters) from the transmitter ($Pr(d)$) is given by:

$$
\begin{aligned}
Pr(d) &= \overline{Pr}(d) + X_\sigma \\
Pr(d) &= Pr_0 - 10\alpha log(d) + X_\sigma \quad (1)
\end{aligned}
$$

where Pr_0 is the signal strength 1 meter from the transmitter, α is known as the path loss exponent, and X_σ represents a Gaussian random variable with zero mean and standard deviation of σ dB [9]. In the equation above, $\overline{Pr}(d)$ represents the mean (expected) signal strength d meters from the transmitter, while $Pr(d)$ denotes a random outcome. This model takes into account the different obstacles present in multiple transmitter-receiver paths with the same separation, this phenomenon referred to as *log-normal shadowing*.

The parameters (α, σ) define the statistical model and are viewed as heavily dependent on the environment.

Measurements in the literature have reported empirical values for α in the range between 1.8 (lightly obstructed environments with corridors) and 5 (multi-floored buildings), while values for σ usually fall into the interval $[4, 12]$ dB [9]. For example, Seidel *et al.* report the results of modeling two office buildings at 914MHz, with best fits $(\alpha, \sigma) = (3.27, 11.2)$ and $(3.25, 5.2)$ for single-floor measurements [10]. Other installations that have also been shown to follow this model can be found in [9, 8, 5].

3 Modeling Attenuation Indoors

We performed experiments using a subset of the deployed wireless infrastructure in the Computer Science building at Stanford University. We concentrated our indoor measurements at one of the wings in the fourth floor, as depicted in figure 1. As shown, 41 locations were sampled within a 66m×24m area. From these, 13 were located inside offices (5.2m×3.2m), 15 inside conference rooms (at least 8m×4.7m), and 13 in corridors. Such a mix allows for the resulting model to be representative of the whole floor.

A total of four access points were employed, their locations being represented by triangles in figure 1. All access points are Cisco Aironet 1200, operating at 2.4 GHz (802.11b), and mounted close to the ceiling. These APs are provisioned with two antennas and were configured to transmit at 20 dBm [2].

Our client device is a Cisco Aironet 340 PCMCIA card, which is used in our experiments as a receiver. The card has a receive sensitivity of -90 dBm when operating at 1 Mbps, is able to transmit at 15 dBm, and is provided with an integrated internal antenna with diversity support [1]. In order to collect signal strength statistics we employed a modified Linux driver, that recorded power in dBm for received frames.

For each of the 41 locations shown in figure 1 we measured the quality of the signal relative to each access point. In total, 146 AP-client associations were used, as

(a) Average signal strength as a function of distance.

(b) Deviation distribution as a function of σ.

Figure 2: Modeling propagation inside the building.

some locations were covered by only two or three of the access points. In all locations, the laptop was positioned in the same orientation, facing the left wall in figure 1.

In each location and for each AP, the following procedure was executed:

1. **force association between client and the desired access point**. This was done to avoid hand-offs during the experiments. Additionally, the card was configured to transmit at 1 Mbps.

2. **generate incoming traffic (AP to client)**. The client sends 30 ICMP ECHO request messages (`ping`) to a computer in the local network and estimates the signal strength for each ECHO response received. A delay between 300 and 1000 ms was used between `ping` messages.

Figure 2(a) presents the 146 signal strength samples (in `dBm`) as a function of the separation (in meters) between AP and client. Each sample consists of the average signal strength at that location, while the distance values were found using a blueprint of the building.

The best model (equation 1) that fits this experimental data was found through linear regression using a log-log scale (signal strength in `dBm` versus $\log(distance)$). We fixed Pr_0 at -20 `dBm`, the expected signal power 1 meter from the receiver assuming free-space propagation. An estimate for α is found using the slope of the line that best fits the data, while the sample standard deviation is used as an estimate for σ. Our experiments yielded $\alpha = 4.02$ and $\sigma = 7.36$ `dB`, represented by the solid line in figure 2(a).

These values agree with previously published results, which have found values such as $\alpha \in [3, 4]$ and $\sigma \in [4, 12]$ `dB` for office environments. As expected, attenuation is much higher than predicted by free-space propagation, where signal is expected to decay as a function of the square of the distance ($\alpha = 2$ in equation 1; dotted line in figure 2(a)). Due to the simplicity of the log-distance model, the attenuation induced by walls, doors, windows, and other obstacles is aggregated into the pa-

rameter α, thus yielding higher values.

Our dataset also suggests that the deviations from the mean (X_σ) closely follow a log-normal distribution (normal distribution in `dBm`), as other researchers have proposed [9]. Figure 2(b) shows the number of samples as a function of the deviations from the mean (in terms of multiples of σ). The deviations closely follow a Gaussian distribution, with 70.5% of the samples within 1 standard deviation from the mean, 95.2% within 2 deviations, and 99.3% within 3 standard deviations (the expected values are respectively 68%, 95%, and 99.7%).

For clients in close range to access points (up to 10-15 meters), the path loss model found for a given environment can be used to provide an approximate lower bound on signal strength. From all 19 samples with distances smaller or equal to 8 meters, 14 (73.7%) are located above the fitted line. For distances smaller than 12 meters, the same is true for 32 out of 43 samples (74.4%). Moreover, of all 11 samples falling below the line, only 2 are more than 5 `dB` from the predicted value. Such lower attenuation in close range has also been perceived by other researchers, even justifying the construction of so called "breakpoint" models, which employ lower values for α for small transmitter-receiver separations [9].

4 Modeling Attenuation Outdoors

Despite the smaller volume of literature compared to the studies of the indoor wireless channel, several papers suggest that a model similar to equation 1 can be used to predict signal penetration into buildings. In this case, the signal strength detected by an access point inside a building relative to a device located outside can be approximated by:

$$Pr(d) = Pr_0 - 10\alpha \log(d) - W + X_\sigma, \quad (2)$$

the main difference to equation 1 being W (wall attenuation factor, in `dB`), which accounts for the attenuation caused by the external walls. Durgin *et al.* used this model to approximate propagation into homes at

<div align="center">(a)   (b)</div>

Figure 3: Measurement locations outside the Gates building.

5.85 GHz for distances varying between 30 and 210 meters [4].

We equation 2 to model the attenuation of 802.11 signals outside the Gates building. As transmitter, we used an access point located 9 meters from the building's external wall. Figure 3 depicts our measurement configuration: overall, we sampled 40 locations over 4 straight lines going out of the building at a $90°$ angle and spaced approximately every 2 meters. The measurements were performed in front of large windows (6ft$\times$7ft each), with separations varying between 2 and 22 meters (11 to 31 meters to the access point).

Our measurements indicate that the modified log-distance model given by equation 2 closely approximates attenuation outside the building. In each of the 40 locations, between 30 and 75 RSSI samples were collected, with average signal strength values shown in figure 4(a). The solid line shows the model instance found through linear regression; it produced $W = 4.8$dB and $\alpha = 3.32$ with a standard deviation of 3.1 dB. Despite the lower attenuation rate compared to the measurements inside the building ($\alpha = 4.02$ vs. $\alpha = 3.32$), signal still degrades much faster than predicted by the free-space model (dotted line in figure 4(a)).

As with our indoor measurements, the deviations from the mean can be closely approximated by Gaussian random variables. Figure 4(b) shows the number of samples as a function of the number of standard deviations from the mean. As shown, 70% of the samples within 1 standard deviation from the mean, 95% within 2 deviations, and 100% within 3 standard deviations.

5 Conclusion

Based on experiments with off-the-shelf 802.11 hardware, we have shown that the log-distance path loss model with log-normal shadowing can be used to estimate signal attenuation both inside and outside an office building with moderate accuracy. Inside the building, our measurements produced a model with a path loss exponent (α) of 4.02 and a standard deviation of 7.36 dB, values which agree with previously published results [9]. Fitting a log-distance model to the measurements performed *outside* the building produced a lower path loss exponent ($\alpha = 3.32$) and a standard deviation of 3.1 dB, after deducting 4.8 dB for the attenuation caused by the external wall.
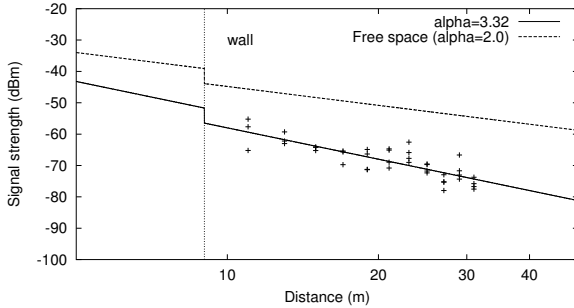
Both indoor and outdoor models produced deviations in decibels that closely follow a log-normal distribution (Gaussian distribution in a logarithmic scale such as dBm). Indoors, 70.5% of the samples were within 1 standard deviation from the mean, 95.2% within 2 deviations, and 99.3% within 3 standard deviations. For the measurements performed outside the building, these percentages were respectively 70%, 95%, and 100%. These values are all less than 3% from the theoretical percentages associated with a Gaussian distribution.

Finally, our experiments suggest that signal strength in close range tends to be higher than predicted by the model. Over 74% of the samples collected less than 12 meters from access points followed this trend. This result agrees with previously published papers, many of which support the use of so-called breakpoint models that employ lower values of the path loss exponent close to the transmitter.
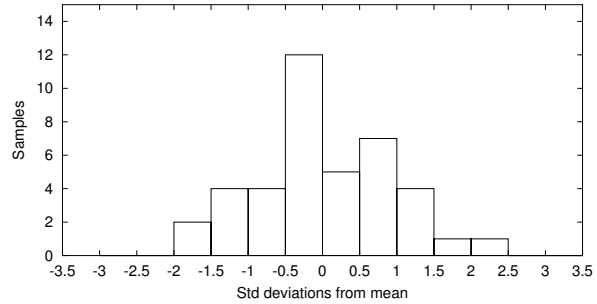
These results demonstrate that signal strength can be predicted using simple models even when employing off-the-shelf IEEE 802.11 hardware. Consequently, it can be of valuable use to both research and industry efforts as a first evaluation step for new wireless services.

References

[1] Cisco Aironet 340 Series Client Adapters. Product Data Sheet. Cisco Systems, Inc., 2000.

(a) Average signal strength as a function of distance.

(b) Deviation distribution as a function of σ.

Figure 4: Modeling propagation outside the building.

[2] Cisco Aironet 1200 Series Access Points. Product Data Sheet. Cisco Systems, Inc., 2003.

[3] M. Balazinska and P. Castro. Characterizing Mobility and Network Usage in a Corporate Wireless Local Area Network. In *Proc. of the First International Conference on Mobile Systems, Applications, and Services (Mobisys'03)*, San Francisco, CA, May 2003.

[4] G. Durgin, T. S. Rappaport, and H. Xu. Measurements and Models for Radio Path Loss and Penetration Loss in and Around Homes and Trees at 5.85 GHz. *IEEE Transactions on Communications*, 46(11):1484-1496, Nov. 1998.

[5] H. Hashemi. The Indoor Radio Propagation Channel. *Proceedings of IEE*, 81(7):943-968, July 1993.

[6] D. Kotz and K. Essien. Analysis of a Campus-wide Wireless Network. In *Proc. of the Eigth Annual ACM/IEEE International Conference on Mobile Computing and Networking (Mobicom'02)*, pages 107-118, Atlanta, GA, Sept. 2002.

[7] J. Medbo and J.-E. Berg. Simple and Accurate Path Loss Modeling at 5 GHz in Indoor Environments with Corridors. In *Proc. of IEEE Vehicular Technology Conference (VTC)*, volume 1, pages 30-36, Sept. 2000.

[8] D. Molkdar. Review on Radio Propagation into and within Buildings. *IEE Proceedings-H*, 138(1):61-73, Feb. 1991.

[9] T. S. Rappaport. *Wireless Communications - Principles and Practice*. Prentice Hall PTR, 1996.

[10] S. Y. Seidel and T. S. Rappaport. 914 MHz Path Loss Prediction Models for Indoor Wireless Communications in Multifloored Buildings. *IEEE Transactions on Antennas and Propagation*, 40(2):207-217, Feb. 1992.