Abstract—We describe a channel sounding system designed for small outdoor cell (~400 meter radius) wireless channel characterization. We report on a program of path loss measurements using a 2×2 MIMO configuration and data reduction in the frequency range of 5.7–5.75 GHz. The results are based on over 10,000 independent complex frequency responses collected in residential neighborhoods in northern New Jersey. We characterize and report on key path loss parameters such as path loss exponent and shadowing for low base station antenna heights. Based on our data analysis, we propose a statistical model for path loss in neighborhood area networks in suburban environments.

Index Terms—Channel modeling, path loss, shadowing, propagation, neighborhood area networks.

I. INTRODUCTION

The proliferation of “smart” portable devices has challenged wireless networks to deliver more throughput, capacity, and quality to more “always on” users. Technology advances at the physical layer such as MIMO and space-time coding have provided some relief, but smaller cells, more intense frequency reuse, and richer backhaul are most likely to offer longer-term answers to the challenge, enabled by the relentless spread of broadband fiber to the very edges of the "wired" network. The trend toward Neighborhood Area Network (NAN) topologies, forecast by enlargement of Local Area Networks (LANs) and shrinkage of Wide Area Network (WAN) cells is likely to result in hybrid architectures sharing characteristics of both. The common thread of smaller, neighborhood-size cells offers challenges of its own however, including smaller, lower height, more landscape-harmonized radio network distribution nodes that may have to capitalize on a variety of spectrum availability opportunities [1]–[2].

For effective deployment of high performance broadband wireless systems in neighborhood environments, it is imperative that propagation characteristics of wide-bandwidth channels and low base station antenna heights are thoroughly understood. Propagation characterization and modeling of Radio Frequency (RF) has been well-studied in the cellular and PCS bands and at 4–6 GHz in and around neighborhoods based on large cell network topology. We shall not recount all of these studies, but encourage the reader to examine the included references and the many citations within them. The majority of these studies are based on a database using WAN or microcellular PCS assumptions with cellular base station antenna heights 20 meters and above. See [3]–[5]. In contrast, antenna heights which are considered for WLANs are typically around 6–7 meters. Low height antennas used in neighborhoods with RF obstructions such as foliage and tiered home placements create larger areas of non-line-of-sight propagation and multipath. While in [6]–[8], the authors report on penetration losses due to foliage and residential homes, little propagation information is presently available for WLAN-like systems operating in the 5.70–5.75 GHz spectrum for low antenna height base stations with cell sizes in order of 400 meters characteristic of NANs. The experiments and data collection procedures outlined in this paper were aimed at characterization of channel behavior for such neighborhood wireless networks to improve layout planning and provide higher confidence in meeting capacity, throughput, and quality of service goals. It should also be noted that while the collected database within our experiments includes valuable 2×2 MIMO channel information, it is our intention to report solely on path loss characteristics part of the channel due to IEEE limitations on paper length.

In particular, in Section II, we describe the measurement equipment and the experiment procedure. In Section III, we provide a background on large scale fading, its parameters and discuss our key findings, followed by our conclusion in Section IV.

II. MEASUREMENT EQUIPMENT AND EXPERIMENT PROCEDURE

A. Measurement Equipment

We deployed an Agilent Programmable Network Analyzer (PNA) to measure the discrete complex frequency response of a 2×2 MIMO channel (See Fig. 1). Like other sounding systems

The PNA applies the test signals to a 44 dB gain power amplifier chain. The output of the power amplifier is passed through RF relays configured as 45 dB switchable attenuators and then to 6.5 dBi vertically-polarized directional transmit antennas (60° H-Plane and 56° E-Plane) capable of operation in 5.7–5.75 GHz frequency. The transmitter’s power level was adjusted so that the PNA always operated within the linear
range of its detectors and well above the noise floor.

The received signal from the two vertically-polarized, omni-directional antennas were returned to the PNA through two LNAs, two RF-to-optical converters, 457.2 meters of single mode optical fiber with 0.1dB/km insertion loss and two optical-to-RF converters. Not only does this system require no synchronization between transmitter and receiver, it also replaces the need for high loss coaxial cables used for returning the received signal to VNA. This is an ideal setup for short-distance indoor/outdoor experiments.

The PNA records the variation of 401 complex tones across the 50 MHz frequency spectrum by measuring S-parameter sets, most importantly S11, and S21 (e.g., A/R1, A/R2, B/R1, B/R2. See Fig. 1.) of the channel. The complex data is returned via an optical Ethernet connection to a laptop computer at the remote end of the system to allow data monitoring prior to storage. The antenna pattern effects were removed from the channel measurement using anechoic chamber calibration data prior to data reduction.

The RF receiver along with its associated RF-to-optical converter hardware was mounted on a backpack frame which also contained a survey-quality GPS receiver with a spatial resolution of 50 cm. This was a crucial part of the setup as most consumer GPS receivers have spatial resolutions no better than 10-15 meters.

**B. Experimental Procedure**

The experiments were performed in two similar suburban neighborhoods of northern New Jersey. The homes in these neighborhoods had similar structure, age, size and surrounding clutter such as trees and vegetation. Neighborhood 1 is characterized by flat terrain with trees while Neighborhood 2 is moderately flat with small hills and trees. Homes were separated from each other by about 25-50 feet on average. We performed four independent experiments in each neighborhood with different transmitter locations. Measurements were made while the transmit/receive antennas were within Line-of-Sight (LOS) of each other and when No Line-of-Sight (NLS) was present. In seven out of eight experiments, around each local point, d, we collected five more pairs of complex frequency responses of a 2×2 MIMO channel located on the perimeter of a one foot radius centered at d, as illustrated in Fig. 2. Two of these pair of points overlapped each other. We refer to these points as spatial points. Intervals between spatial points were not uniform and exact positions were determined by distance from the transmitter.

The transmit antennas, separated by 0.2m, were mounted on a horizontal beam aligned approximately perpendicular to the bisector of the measured area. The receiving antennas, with the same separation, were mounted atop the remote receiver backpack. For LOS paths, the measurements were taken at intervals of typically one to three meters while for NLS paths we chose completely random locations within the antenna pattern. Knowledge of the computed physical distance between the transmitter and the receiver via GPS coordinates allowed the measurement locations to be determined within 0.5m. For all measurements, the heights above ground were set to 6.1m for the transmit antennas and ~1.9m for the receive antennas.

Overall, we collected independent complex frequency response snapshots of a 2×2 MIMO channel at 563 and 2,700 local points in Neighborhood 1 and Neighborhood 2, respectively. The T-R separations range from 5 meters to about 350 meters in both LOS and NLS areas.

**III. LARGE SCALE FADING**

**A. Background**

Path loss, $p_L$, can be thought of as reduction in signal power from a transmitter to a received location. In practice, this is defined as the transmit power multiplied by transceiver antenna gains divided by average received power:
In our study, we measure the local mean path loss by frequency averaging of a swept CW transmission of 401 tones over 50 MHz of bandwidth as received by a fixed MIMO receiver setup centered at 5.725 GHz. After removal of the pre-stored hardware calibration information and the effect of the antenna pattern, we then use the measured complex frequency response data, $h(f_i; d)$, to estimate the local mean path loss, $p_l(d)$, for each of the transmit-receive (T-R) separations, $d$. Note that since the spatial path loss is relatively insensitive to frequency, we can represent it as an average over collected frequency tones by performing the following:

$$p_l = \frac{P_l \cdot g_i \cdot g_j}{p_i}.$$  

(1)

Therefore, to get the local mean path loss at a point $d$ meters from the transmitter, we first average $|h(f_i; d)|^2$ over $N$ observed frequencies, then again over $M$ frequency response snapshots collected as spatial points. We know that average path loss for each of the individual MIMO channels should not vary significantly from one another and so we may want to also average the mean path loss across the 4 MIMO links as well.

The mean path loss value itself depends on many variables such as transmitter and receiver antenna heights, distance, frequency, season, environment and location. The effect of these variables has been researched extensively in the past and path loss models that describe reflection, refraction and scattering for both LOS and NLS paths are readily found in the literature. It is well known that the mean path loss is directly proportional to T-R separation; $d$ raised to some exponent $\gamma$ and its value in dB can be best described by a well-known linear equation

$$PL(d) = PL_0 + 10 \gamma \log_{10} \left( \frac{d}{d_0} \right) + S(d); \quad d \geq d_0$$  

(3)

where $PL_0$, the intercept point, is the path loss at some predefined reference point, $d_0$, for LOS paths and NLS paths. In practice, setting this value mainly depends on the experiment location and its availability at the experiment time. We shall further discuss this in our “Key Findings” section. The $10\gamma \log_{10} \left( \frac{d}{d_0} \right)$ term represents the mean path loss and it is referenced to $d_0$; $\gamma$ is the path loss exponent which strongly depends on environment, season and antenna height. The spatial variation of $S$ (a distance dependent variable) in dB is usually referred to as shadowing, and it captures the path loss deviation from its median value. It is a zero mean Normal random variable with standard deviation $\sigma$.

Equation (3) also states that on a logarithmic scale the path loss corresponds to a straight line with a slope $\gamma$. This straight line provides the mean value of the random path loss. It can be viewed as fitting a least squares linear regression line through the scatter of measured path loss points in dB such that the root mean square deviation of path loss points, $S$, about the regression line is minimized. Recall that these random shadowing effects of the channel occur at locations where the T-R separation is the same but where different levels of clutter occur in the propagation paths.

### B. Scatter Plot

We maintain that equation (3) relates to a straight line which will provide the mean value for the random path loss. As we stated earlier, this is done by fitting a least squares linear regression line through the scatter of measured path loss points in dB, such that the root mean square deviation of path loss points, $S$, about the regression line is minimized. This is shown in Fig. 3. Here the random nature of shadowing of the channel in dB due to different types and behaviors of clutter in paths with the same T-R separation is clearly observed. Fig. 4 confirms the log-normality of shadow fading in Neighborhood 1. Similar behavior was observed for LOS paths as well as in Neighborhood 2.

All models in the literature find values for $PL_0$, $\gamma$, and $\sigma$ that...
fit the global data in (3). Past experience (See [5] and [9].) dictates that knowledge of $P_{L0}$, $\gamma$, and $\sigma$ for a path loss model is useful only in a limited way as it averages the effect of environmental scatterers out of the data. By doing so, one can easily under-predict the path loss in some neighborhoods where the density of scatterers is worse than average. A good model will predict coverage for a given transmitter location not only where measurements have been performed, but also where measurements have not been performed by taking into account the effect of the channel. In our experiments, we observed that the path loss parameters did indeed change not only within the same neighborhood but also from Neighborhood 1 to Neighborhood 2 and that taking one set measurements from one neighborhood alone or pooling the data from all neighborhoods together would not, on the average, represent the parameters in all neighborhoods. Our experience with this problem motivated us to again assume that the propagation parameters $P_{L0}$, $\gamma$, and $\sigma$ could be treated as random variables in each neighborhood. Therefore, one can characterize their distribution and interdependencies (if any) by taking measurements in more than one neighborhood. We found some interesting results which are discussed in the following sections.

C. Key Findings

Following our intuition in characterizing the model parameters over different neighborhoods, we have arrived at several key findings. We present them here, where we have separated them in terms of LOS and NLS paths for each of the two neighborhoods:

The Intercept Point, $P_{L0}$: The selection of this point depends highly on experiment location and base station height. During our experiments, we could not find a fixed distance for both LOS and NLS paths. We therefore chose two different reference distances to represent the intercept point for these paths. For the LOS environment, the mean path loss measured over the 50 MHz of bandwidth centered at 5.725 GHz followed closely those given by theory at 5.3m T-R separation in free space:

$$20\log_{10}\left(\frac{4\pi d}{\lambda}\right) \sim 62 \text{ dB}$$

The average values of $P_{L0}$ for LOS paths varied between 59 and 61.5 dB with mean of 60.6 dB and standard variation of \sim 1.3 dB. See Table I.

For NLS paths, the closest distance to transmitter that we could find was 10.3m. The path loss at this point depended on the type of home (small or large), the home structure, extend of foliage surrounding the home and blocking of NLS paths. The values of $P_{L0}$ for NLS paths were measured to be between 76 and 82 dB. However, for ease of modeling we decided to treat it as a fixed number with a value equal to the mean value over all the measured data at 10.3 meters. See Table I.

The $\gamma$ Parameter: We computed the values of $\gamma$ for all experiments and they are summarized in Table I. Note that the values of $\gamma$ do change within each neighborhood. We also noted that these values were comparable to results found for outdoor PCS or fixed wireless channels (See [4] and [5]). Fig. 5 shows the distribution of $\gamma$ where the values are seen to exhibit a normal RV behavior with mean and standard deviation listed in Table I and its statistical values of listed in Table II.

The $\sigma$ Parameter: Over the population of our data, we recognize that the values of $\sigma$ vary from one transmitter location to another within both sampled neighborhoods. This is mainly because while the two neighborhoods were very similar in foliage and home density, certain NLS paths were more obstructed than others. It therefore seems reasonable to assume that their measured shadowing values will be somewhat different. Fig. 6 shows the CDF of $\sigma_{LOS}$ and $\sigma_{NLS}$ as computed over all data. They both have a Normal distribution with mean and standard deviation as summarized in Table I.

In the following section we explain the model and how these parameters may be used for simulation of NAN path loss. In
our modeling, we are essentially following the modeling methods in [5] and [9] and our findings justify this approach. See Figs. 5 and 6.

IV. THE MODEL AND THE SIMULATIONS

A. The Path Loss Model

We define a statistical model based on (3), with a fixed intercept point $PL_o$ and treating $\gamma$ and $\sigma$ themselves as Gaussian random variates over transmit sites within the same neighborhood. Thus, we can write

$$\gamma = \bar{\gamma} + x_1\sigma \gamma$$ \hspace{1cm} (4)

where $x_1$ is a zero-mean Gaussian variate of unit standard deviation $N[0,1]$. Also, shadow fading varies randomly from one local point to another within both neighborhood and is a zero-mean Gaussian variate with standard deviation $\sigma$. Following the approach for $\gamma$, we treat $\sigma$ as varying from one transmit site to another with a Gaussian distribution. Thus, we can write

$$S = y\sigma$$

$$\sigma = \bar{\sigma} + x_2\sigma_o$$ \hspace{1cm} (5)

where $y$ and $x_2$ are zero-mean Gaussian variates of unit standard deviation $N[0,1]$. Inserting (4) and (5) into (3) and rearranging the results, we get

$$\frac{PL(d)}{PL(d)_{\text{int}}} = \left[PL_o + 10\gamma \log_{10} \frac{d}{d_o} \right] + \left[10x_1\sigma \gamma \log_{10} \frac{d}{d_o} + y\bar{\sigma} + yx_2\sigma_o \right]$$ \hspace{1cm} (6)

where the first bracketed term of (6) is the mean path loss and the second term is the random variation about the mean.

B. Simulations

We simulated the path loss model (6) and compared its model parameters to our finding from measured values. Recall that we have 8 experiments with LOS paths and 7 experiments with NLS paths. Therefore, for simulation of each path we generated $m$ (where $m$ is either 8 or 7, depending on path type and the number of transmitter locations) pairs of $(x_1, x_2)$ and $n$ pairs of $(d, y)$ where $n$ represents the number of receiver locations at which measurements were taken for each pair $(x_1, x_2)$. We should emphasize that random variables $x_1$ and $x_2$ and $y$ should be truncated such that the path loss values do not take on values outside the range computed from data.

In Figs. 7 and 8, we compare the LOS and NLS simulated path loss results to the measured scatter plots, respectively. Parameters from the simulation are summarized in Table II. Note that there are only minor disagreements between the parameters. A notable point is that shadow fading, $S$, is a distance-dependent variable which we clearly do not observe in the scatter plots of Figs. 7 and 8. This could be due to lack of data and it may be worthy of more data collection for further research.

V. CONCLUSION

We have described a 2x2 MIMO channel sounding system and experimental measurements to characterize small outdoor cell (~400 meter radius) wireless channels. We have reported on path loss parameters by using over 10,000 independent complex frequency responses collected in two residential neighborhoods of northern New Jersey. We characterize and report on key path loss parameters such as the path loss exponent and shadowing for low base station antenna heights. Based on our observations, we proposed a model for regeneration of the path loss parameters found for this set of data. We acknowledge that more data is needed for verification of the path loss parameters’ dependencies on types of neighbor-hoods other than those selected for these experiments.

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REFERENCES

Table I: Model Parameters for different Neighborhoods.

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Path loss parameters for four experiments in Neighborhood 2

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Table II: The path loss parameters from measurement and model simulations.

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