UWB Path Loss Characterization In Residential Environments

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(Invited Paper)

***Abstract*—In this paper, we describe a simple method for measurement of the Ultra-Wideband Band (UWB) frequency response for evaluation of the path loss and impulse response of the UWB indoor channel. We propose a simple statistical path loss model for the residential channel that is based on over 300,000 frequency response measurements. The Probability distributions of the model parameters for different locations are presented.**

***Index Terms*—Channel modeling, path loss exponent, Shadowing, propagation, and UWB.**

I. Introduction

The techniques for generating UWB signals for radar applications have been around for several decades. Many researchers have studied the application of this technology to military and commercial communications while some have demonstrated prototypes of UWB radio links. Applications of UWB signaling include: high-speed mobile local area networks (LANs), imaging and surveillance systems, military communications, ground penetration radars, automotive sensors, medical monitors and most recently wireless personal area networks (WPANs).

The FCC currently defines a UWB signal as any signal where its bandwidth is greater than 500 MHz [1]. UWB radio signals inherently possess very fine time resolution. As a result, it is possible to resolve multipath components down to differential delays on the order of tenths of a nanosecond (corresponding to less than 1-foot path differentials). This significantly reduces fading effects in indoor environments and results in fade margin reduction. The reduction of required fade margins and power spectral density of the UWB spectrum makes UWB technology a favorable technology for low power and short-range communications, as required for operation in indoor environments. As a result, UWB technology may be used as an extension of WLANs or WPANs at transmissions rates in excess of a 54 Mbps for short ranges.

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To design an air interface accommodating such a high data rate [2], the indoor UWB channel must be understood. Signal propagation in homes has been studied extensively in the past by many researchers [3]-[11] which mainly could be applied to signal bandwidths much narrower than those of UWB. The indoor UWB propagation measurements have been performed in [12]-[14], but they either did not account for the frequency of interest; or did not represent the proper bandwidth or the database was small for statistical comparison of the channel parameters. Since the indoor structure changes from one home to another, therefore, in our research, we are mainly concern with statistical variations of the UWB propagation path loss parameters as environment changes.

II. Measurement Equipment And Experiment Procedure

A. Measurement Equipment

Fig. 1 illustrates the transceiver configurations. A Vector Network Analyzer (VNA) is used for measuring the frequency response of the channel. The VNA generates a signal as the input to a variable attenuator and a 34 dB gain broadband transmitter RF amplifier chain. The output of the RF power amplifier is propagated by a vertically polarized, conical monopole, omni-directional (in the H-plane) over the 4.375 – 5.625 GHz frequency range. The signal from the identical conical monopole receive antenna is first passed through a Low Noise Amplifier (LNA) with a gain of 34 dB. It is then returned to the VNA via 150 feet of coaxial cable with a 17-dB loss followed by another LNA with a gain of 36 dB. High quality doubly shielded cable was used to insure no leakage from the air into the receiver by the cable. The VNA records the variation of 401 complex tones across the frequency range; by measuring the S-parameter, S_{21}, of the UWB channel which is essentially the transfer function of the channel. The VNA performs this task by sweeping the spectrum in about 400ms over 401 assigned tones and compares their values to the pre-calibrated coefficients without the channel present. The inverse of Doppler spread indicates the coherence time (i.e., the time over which the frequency response is essentially invariant), in our experiments, it takes about 400ms to sweep and record the complex frequency response. This implies that the maximum

0-7803-7694-3/03/$17.00 © 2003 IEEE

measurable Doppler spread would be 1/400ms or 2.5 Hz. The complex data from the VNA was stored on a laptop computer via a GPIB interface. The transmitter's power level was adjusted so that the VNA always operated within the linear range of its detectors and well above noise floor. The antenna effects were removed from the channel measurements.

B. Experiment Procedure

The experiments were performed inside 23 homes in the northern and central New Jersey area. The homes had differing structure, age, size and clutter. The transmit antenna from the VNA was always located in a fixed position, and the receiving antenna mast was moved throughout the houses on a pre-measured grid. Knowledge of the physical distance between the transmitter and the receiver allowed the measured data to be correlated with the distance. For all measurements, the height of the transmit/receive antennas was fixed at 1.8 m.

Measurements were made while the transmit/receive antennas were within Line-of-Sight (LOS) of each other or while they were within non-LOS (NLOS) of each other. Two different experiments were performed in each home. In 15 homes, we selected over 20 LOS locations and over 20 NLOS locations and in the other 8 homes, 10 LOS, and 10 NLOS locations. Hence, our database contains about 1240×273 (over 300,000) independent measurements of the channel frequency response ranging from 1 to 15 meters. The transmit antenna location was placed for best signal coverage inside each home and optimized for minimum possible T-R separation for NLOS experiments.

III. Large Scale Fading

A. Background

In our study, we measure the local mean path loss by time and frequency averaging of a swept CW transmission over 1.25 GHz of bandwidth by a fixed receiver. Upon removal of the hardware calibration information and the effect of the antenna pattern, we use the measured complex frequency response data, $H(f_i, t_j; d)$, to estimate the local mean path loss at any T-R separation, d, by performing the following on:

$$pl(d) = \frac{1}{MN}\sum_{i=1}^{N}\sum_{j=1}^{M}\left|H(f_i,t_j;d)\right|^2 \quad (1)$$

where N is the number of observed frequencies and M is the number of frequency response snap shots over time at d meters.

It is well known that the median of this path loss is directly proportional to d raised to some exponent γ (See [6], [8], [9] and [12]). The path loss in dB at some distance d is then:

$$PL(d) = \left[PL_0 + 10\gamma\log_{10}\left(\frac{d}{d_0}\right)\right] + S(d);\ d \geq d_0 \quad (2)$$

where PL_0 , the intercept point, is the path loss at d=1 m; $10\gamma\cdot\log_{10}(d/d_0)$ is the mean path loss referenced to 1 m; γ is referred to as the path loss exponent which depends on the structure of the home; and S is the lognormal shadow fading in dB. Equation (2) states that, on a logarithmic scale the path loss corresponds to a straight line with a slope γ. This straight line provides the mean value of the random path loss. This amounts to 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 about the regression line is minimized. Figure 2 shows the scatter plot of the path loss as a function of T-R separation for all homes. Random shadowing effects of the channel, S, occur at locations where the T-R separation is the same but have different levels of clutter in their propagation paths. This random variable is usually a zero mean normal random variate with standard deviation of σ in dB. The normal distribution regression line fit to the dB values confirmed the log-normality of shadow fading in all 23 homes (See Figure 3.). This has been accepted by many researchers [6]-[14].

All models in the literature, find values for PL_0, γ, and σ that fit the global data in equation (2) Knowledge of PL_0, γ, and σ for path loss model is useful only in a limited way as it averages the effect of indoor structure out of the data. By doing so, one can easily under predict the path loss in homes where the indoor structure is worse than average. A good model will predict propagation in homes, not only, where measurements have not been performed but it also accounts for the effect of the structure where measurements have been performed. In our experiments, we observed that the path loss parameters did indeed change from one home to another and that taking measurements in one home alone or pooling the data from all homes together would not on the average represent the parameters in all homes. This motivated us to assume that the propagation parameters PL_0, γ, and σ could be treated as random variables in each home and then one can characterize their distribution and inter dependencies (if any) by taking measurements in more than one home. We found some interesting results which are discussed in the next section.

B. Key Findings

Following our intuition in previous section in characterizing the model parameters over all homes, we found the following key findings:

The Intercept Point, PL_0: For LOS environment, the average path loss measured, over 1.25 GHz of bandwidth centered at 5 GHz, followed closely those given by theory at 1-m T-R separation in free space. This value is:

$$20\log_{10}\left(4\pi d/\lambda\right) \sim 47\text{dB}$$

For NLOS environment, the intercept point depends on the materials blocking the signal within 1m of T-R separation and the home structure. The measured values of PL_0 for NLOS were very close to that of LOS path loss plus a few dB more loss due to the obstacle(s) blocking the LOS path. For ease of modeling, we excluded the frequency dependency of this parameter. Therefore, for LOS and NLOS, we chose the intercept value to be the mean path loss at 1 m measured in 23 homes.

The σ Parameter: Over the population of our data, we note that the values of σ vary from one home to another. The values of σ have normal distribution $N[\mu_S,\sigma_S]$, whose mean μ_S and standard deviation σ_S are determined statistically from the measured data. Figure 4 illustrates the distribution of standard deviation of shadow fading σ in all homes.

The γ Parameter: The values of γ also change from one home to another and have a normal distribution $N[\mu_\gamma,\sigma_\gamma]$. Figure 5 depicts the distribution of the path loss exponent, γ. The statistical values for PL_0, γ and σ are presented in Table I. These values were comparable with results found for wideband indoor channels in the literature, with the exception of shadowing. In the following section we explain the model and how these parameters may be used for simulation of the in-home UWB path loss.

C. The Path Loss Model

Base on the above observations, we have constructed a statistical path loss model for UWB propagation in residential environments. The model is based on 300,000, 1.25 GHz wide UWB frequency responses taken at 5 GHz in 23 homes. In this section, we give detail description of the model.

Starting with equation (2), we treat PL_0, γ, and σ as random variables. The intercept point, PL_0 is a fixed quantity and is given in Table I, for LOS and NLOS environments. The values of γ changed from one home to another and have a normal distribution $N[\mu_\gamma,\sigma_\gamma]$. That is

$$\gamma = \mu_\gamma + n_1\sigma_\gamma \tag{3}$$

where n_1 is zero-mean Gaussian variate of unit standard deviation $N[0,1]$. Also, recall that the shadow fading S varies randomly from one location to another location within any home. It is a zero-mean Gaussian variate with standard deviation σ which itself is a Gaussian variate over all homes. This can be represented mathematically as:

$$\begin{aligned} S &= n_2\sigma \\ \sigma &= \mu_\sigma + n_3\sigma_\sigma \end{aligned} \tag{4}$$

where n_2 and n_3 are zero-mean Gaussian variate of unit standard deviation $N[0,1]$. By inserting (4) and (3) into (2) and rearranging the results, we get:

$$\begin{aligned} \overline{PL(d)}\Big|_{\text{dB}} &= \left[PL_o + 10\mu_\gamma \log_{10} d\right] \\ &+ \left[10 n_1\sigma_\gamma \log_{10} d + n_2\mu_\sigma + n_2 n_3\sigma_\sigma\right] \end{aligned} \tag{5}$$

The first bracketed term of equation (5) is the median path loss and the second bracketed term represents the random variation about the median path loss. The variable part of equation (5) is not exactly Gaussian due to the fact that $n_2 \times n_3$ is not Gaussian. However, this product is small with respect to the other two Gaussian terms. Therefore, it can easily be shown that it is a zero mean random variate with standard deviation of:

$$\sigma_{\text{var}} = \sqrt{100\sigma_\gamma^2\left(\log_{10} d\right)^2 + \mu_\sigma^2 + \sigma_\sigma^2} \tag{6}$$

The simulation results for the NLOS environments are depicted in Figure 6. Note that γ is now increased by about 4 dB per decade of T-R separation with respect to when we pool all data together. This simply means that by allowing the path loss exponent to increase an extra 4 dB, one can account for path loss in homes with higher propagation path loss. This is the extra margin that was averaged out of data and is not accounted for in most models in literature and therefore system evaluations.

In our experiments, 50% of homes accounted for mean path loss higher than average. As a result, averaging the effect of indoor structure out of the model causes UWB devices to have a lower range in those homes. Finally, in using this model for simulation purposes, it would be practical to use truncated Gaussian distributions for n_1, n_2 and n_3 so as to keep γ, and σ from taking on impractical values. One such possibility is to confine them to the following ranges:

$$n_1 \in [-0.75, 0.75] \;\&\; n_2, n_3 \in [-2, 2]$$

IV. Conclusion

We have reported on a program of extensive measurement, data reduction and modeling of the propagation for in-home UWB channel. The results are based on over 300,000 frequency response profiles measured in 23 homes. We have derived a statistical model for indoor path loss. A complete characterization of the model parameters was described, along with probability distributions and dependencies between parameters.

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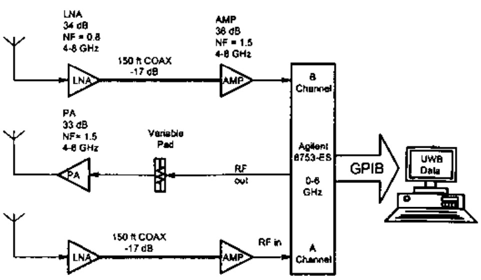

Figure 1: Channel sounder configuration.

	LOS		NLOS	
	Mean	Std. Dev.	Mean	Std. Dev.
PL_o (dB)	47	NA	51	NA
γ	1.7	0.3	3.5	0.97
σ(dB)	1.6	0.5	2.7	0.98

Table I: Statistical values of the path loss parameters.

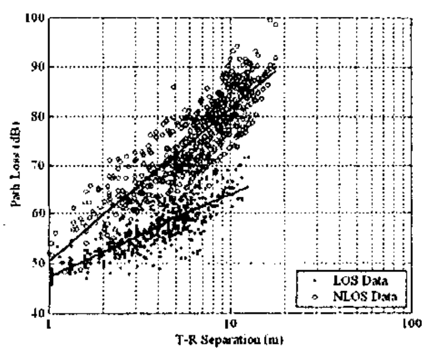

Figure 2: Path loss vs. T-R separation.

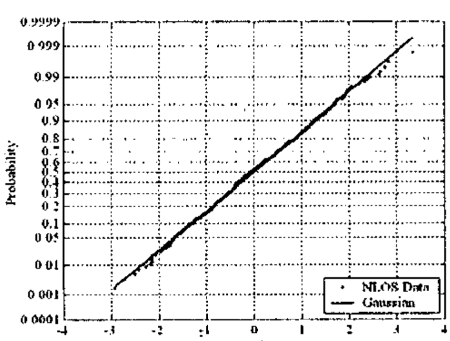

Figure 3: Confirming the log-normality of shadow fading in a typical home.

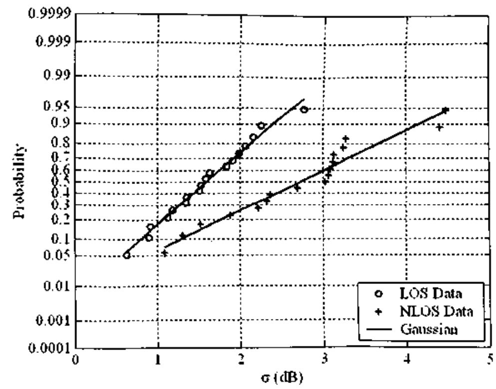

Figure 4: CDF of standard deviation of shadow fading.

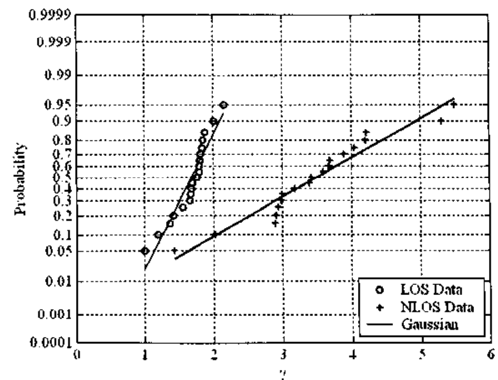

Figure 5: CDF of path loss exponent.

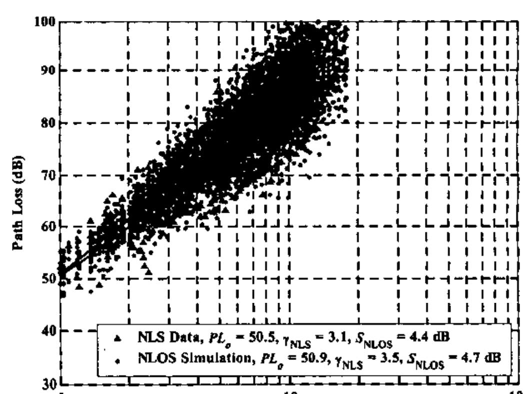

Figure 6: Simulation vs. measured NLOS path loss.