Partition-Based Path Loss Analysis for In-Home and Residential Areas at 5.85 GHz

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Abstract – This paper presents a novel technique for organizing narrowband radio path loss measurements and finding optimal partition-based prediction models. The techniques may be applied to wireless system site planning for indoor, small-cell outdoor, and hybrid indoor-outdoor environments at any frequency. Specifically, this paper develops path loss models using 5.85 GHz continuous-wave (CW) measurements made in and around homes and trees; the resulting models demonstrate how site-specific information will improve path loss prediction. The results are particularly appropriate for site planning in the 5-6 GHz frequency regime for emerging wireless consumer devices that operate in the National Information Infrastructure (in the U.S.) and HIPERLAN (in Europe) bands.

I. Introduction

Conventional site planning for a wireless network is a tedious process that involves numerous, time-consuming measurements with the hope of gaining crude insight into typical signal strengths and interference levels. This paper presents a unique matrix formulation of path loss data and shows how to apply least-squares analysis to generate prediction models from measured data and site-specific information. Partition-based path loss models show remarkable gains in accuracy when compared to simple path loss exponent methods [1].

Throughout the paper, the techniques are discussed using examples from narrowband 5.85 GHz CW path loss measurements made inside homes and around residential areas [2], [3], [4]. Path loss was studied at 270 local areas, requiring 276,000 instantaneous CW power measurements. The 5.85 GHz measurements are applicable to the National Information Infrastructure (NII) band in the U.S. and HIPERLAN networks in Europe [5]. These high-bandwidth spectrum allocations may generate numerous residential and campus-wide wireless communication networks that have commercial applications such as home internet access, telecommunications, and wireless local loops [6]. Both NII and HIPERLAN frequency bands are in the 5-6 GHz range, which preliminary studies have shown to be lossier than PCS (1.9 GHz) or cellular (0.9 GHz) frequencies for both indoor propagation, outdoor propagation, and building penetration [7], [8], [9].

Outdoor and indoor 5.85 GHz path loss measurements were taken at three homes around Blacksburg, VA in middle to upper-middle class neighborhoods. Local area averages of received power, each measured over a 1m area, were used to calculate path loss values in order to eliminate small-scale fading effects. Repeated calibrations of hardware were made at each site to ensure the stability of the measurement system. At each home the transmitter antenna was placed 30-45m from the house at a typical utility pole height of 5.5m. Local area measurements were taken along the front and back of each house with receivers at heights of 1.5m (head level) and 5.5m as well as in every room of the house. Then the outdoor transmitter antenna was moved to a distance of 150-210m from the same house and kept at a height of 5.5m; the sequence of outdoor and indoor measurements was repeated. Figure 1 demonstrates the different receiver-transmitter configurations. Isolated stands of deciduous beech trees and coniferous pine trees were also measured to determine tree shadowing loss at 5.85 GHz.

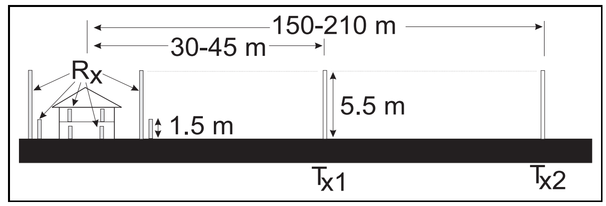

Fig. 1. Transmitters (TX) and receivers (RX) at different heights and separation distances.

All path loss values reported in this paper are with respect to 1m free space path loss, which is independent of receiver, transmitter, and antenna gains and losses. Path loss with respect to 1m free space, PL, fits into the link budget of Eqn (1):

$$\mathrm{PL} = P_T - P_R + G_T + G_R + 20\log_{10}\left(\frac{\lambda}{4\pi}\right) \quad (1)$$

where λ is wavelength (0.05m at 5.85 GHz), G_T and G_R are transmitter and receiver antenna gains in dB, and P_T and P_R are transmitter and receiver powers in dBm.

II. Path Loss Exponents

A popular technique for characterizing narrowband path loss is the use of path loss exponents. This method assumes that the average dB path loss with respect to 1m free space increases linearly as a function of logarithmic transmitter-receiver (TR) separation distance. The slope of this increase is characterized by the path loss exponent, n, in Eqn (2):

$$\overline{PL}(d) = 10n\log_{10}\left(\frac{d}{1\mathrm{m}}\right) \tag{2}$$

where d is TR separation in meters and $\overline{PL}$ is average path loss at a reference distance of 1m, which is typical for indoor and small-cell outdoor propagation.

If a large number of path loss measurements have been taken in an environment, *minimum mean-squared error* (MMSE) regression techniques may be applied to the data to calculate the path loss exponent [1], [10]. For N measured locations with PL_i denoting the ith path loss measurement at a TR separation of d_i, the value for n is given by

$$n = \frac{\sum_{i=1}^{N} \mathrm{PL}_i \log_{10}\left(\frac{d_i}{1\mathrm{m}}\right)}{10\sum_{i=1}^{N}\left[\log_{10}\left(\frac{d_i}{1\mathrm{m}}\right)\right]^2} \tag{3}$$

It also follows that an estimate of the standard deviation, σ, for the measured vs. predicted path loss is given by

$$\sigma^2 = \frac{1}{N}\sum_{i=1}^{N}\left[\mathrm{PL}_i - 10n\log_{10}\left(\frac{d_i}{1\mathrm{m}}\right)\right]^2 \tag{4}$$

Generally, path loss experienced by a wireless receiver in the field will be random. Eqns (3) and (4) estimate the $log-normal$ statistics of large scale path loss. The log-normal distribution provides a convenient, "best-fit" description for large-scale path loss [11], [10]. For given propagation conditions, such as fixed TR separation, a histogram of dB path loss measurements will roughly assume a gaussian shape characterized by a mean or average dB value, μ, and a standard deviation σ. The value σ represents an approximate two-thirds confidence interval about the dB mean that is predicted by the path loss exponent.

Table I shows path loss exponents and standard deviations for the 5.85 GHz indoor/outdoor residential measurement campaign. The number of measured points, N, for each calculation is included since this indicates the reliability of each path loss exponent; a large N allows a system designer to use the corresponding n and σ to estimate log-normal statistics in the propagation environment. As an example, for residential wireless network design involving outdoor transmitters and indoor receivers at a TR separation of 100m, the predicted path loss with respect to 1m free space according to Table I would be 68 dB with $\sigma = 8$ dB. In other words, the path loss with respect to 1m free space at this TR separation will fall in the interval [60 dB, 76 dB] about 67% of the time. Path loss exponents based on data from individual houses were also included in Table I to show the similarity between different homes, indicating that the overall path loss exponents may be applied to 5.85 GHz propagation in and around *any* residence.

TABLE I
Path loss exponents in and around homes for various receiver sites using an outdoor 5.85 GHz CW transmitter at a height of 5.5m.

TR Configuration	n	σ (dB)	N	# of Homes
Indoor				
Overall	3.4	8.0	96	3
First Floor	3.5	8.3	58	3
Second Floor	3.3	7.3	38	3
Outdoor				
Overall	2.9	7.9	147	3
1.5m	2.9	9.0	73	3
5.5m	3.0	6.4	74	3
Rappaport				
First Floor	3.5	9.7	23	1
Second Floor	3.5	7.4	10	1
1.5m Outdoor	3.1	10.2	26	1
5.5m Outdoor	3.0	6.5	27	1
Woerner				
First Floor	3.2	6.2	8	1
Second Floor	3.3	7.7	22	1
1.5m Outdoor	2.9	8.2	22	1
5.5m Outdoor	3.1	6.2	20	1
Tranter				
First Floor	3.6	6.9	8	1
Second Floor	3.4	3.1	27	1
1.5m Outdoor	2.7	6.4	26	1
5.5m Outdoor	2.8	5.3	26	1

III. Partition-Dependent Propagation Analysis

In propagation analysis, the path loss exponent n that minimizes the standard deviation is useful for gaining quick insight into the general propagation. These methods often lead to large, unacceptable standard deviations for prediction at specific locations. To decrease the standard deviation for a prediction and extract useful propagation information about the site, a more comprehensive propagation model is needed [1], [12]. Specifically, this section explores partition-based models, which lend themselves to efficient computer implementation with relatively little site information [13]. Originially, these models were applied strictly to indoor path loss prediction, partly due to the availability of computer-generated floorplans [12], [14].

This section shows a new, generalized matrix formulation of partition-based path loss analysis and presents a method for calculating the optimal attenuation values. Examples from the 5.85 GHz residential path loss measurements show how partition-based models can be applied to outdoor-to-indoor propagation.

A. Least-Squares Formulation

Finer propagation models use *partition-dependent attenuation factors*, which assume $n = 2$ free space path loss with additional path loss based on the objects that lie between the transmitter and the receiver [1], [13]. For the outdoor-to-indoor propagation environment, these objects may be trees, wooded patches, house exteriors, or series of plasterboard walls. The path loss with respect to 1m free space at any given point is described by

$$PL(d) = 20\log_{10}(d) + a \times X_a + b \times X_b \cdots \tag{5}$$

where a, b, etc. are the quantities of each partition type between the receiver and transmitter and X_a, X_b, etc. are their respective attenuation values in dB [13].

For measured data at a known site, the unknowns in Eqn (5) are the individual attenuation factors X_a, X_b, etc. One method to calculate the attenuation factors is to minimize the mean squared error of measured vs. predicted data in dB. If P_i represents the path loss w.r.t. 1m FS measured at the ith location, then N measurements will result in this system of equations:

$$\begin{aligned} P_1 &= 20\log_{10}(d_1) & +a_1 \times X_a & & +b_1 \times X_b & \cdots \\ P_2 &= 20\log_{10}(d_2) & +a_2 \times X_a & & +b_2 \times X_b & \cdots \\ & \vdots & \vdots & & \vdots & \\ P_N &= 20\log_{10}(d_N) & +a_N \times X_a & & +b_N \times X_b & \cdots \end{aligned} \tag{6}$$

This system can be written more elegantly in matrix notation:

$$\mathrm{A}\vec{x} = \vec{p} - 20\log_{10}(\vec{d}) \tag{7}$$

where

$$\vec{p} = \begin{bmatrix} P_1 \\ P_2 \\ \vdots \\ P_N \end{bmatrix}, \quad \vec{d} = \begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_N \end{bmatrix}, \quad \vec{x} = \begin{bmatrix} X_a \\ X_b \\ \vdots \\ X_z \end{bmatrix},$$

$$\text{and} \quad \mathrm{A} = \begin{bmatrix} a_1 & b_1 & \cdots & z_1 \\ a_2 & b_2 & \cdots & z_2 \\ \vdots & \vdots & \ddots & \vdots \\ a_N & b_N & \cdots & z_N \end{bmatrix} \tag{8}$$

The vector $\vec{x}$ is the unknown quantity in (7) but cannot be solved immediately because there are more measured points in $\vec{p}$ than unknowns in $\vec{x}$. Multiplying both sides by the transpose of A yields a tractable linear matrix equation:

$$\mathrm{A}^T\mathrm{A}\vec{x} = \mathrm{A}^T\left[\vec{p} - 20\log_{10}(\vec{d})\right] \tag{9}$$

Eqn (9) represents a system called the *normal equations.* Solving the normal equations – taking the proper precautions against ill-conditioned matrices – simultaneously minimizes the mean-squared error with respect to all values in $\vec{x}$ [15]. Once the optimal $\vec{x}$ is calculated, the mean squared error (or variance) of the measured vs. predicted system is given by

$$\sigma^2 = \frac{1}{N}\left|\mathrm{A}\vec{x} + 20\log_{10}(\vec{d}) - \vec{p}\right|^2 \tag{10}$$

Assuming that the path loss values are log-normally distributed, the calculated σ estimates a two-thirds confidence interval similar to the path loss exponent analysis. The only difference is that the partition-based σ tends to be much smaller than the path loss exponent σ, signifying a model that is more reliable for predicting path loss at specific locations.

B. Example of Attenuation Factor Calculation at Rappaport Home

This section presents a sample attenuation factor calculation using data for the 30m transmitter at the Rappaport home. Refer to the site information and path loss records in Figure 2 for the analysis. Attenuation in addition to ideal free space path loss for this environment is attributed to three types of objects: the small tree in the front yard, the exterior brick wall, and the interior plaster walls. By studying the house site and floor plan, the TR separation and quantity of each partition between the transmitter and receiver were recorded in Table II.

As an example, consider the receiver location in Rear Bedroom 1. The front yard tree, the exterior brick wall, and one plaster wall lie between the indoor receiver and the outdoor transmitter. At the row corresponding to this measurement, a 1 is placed in each column in Table II, since one of each obstruction type lies between the transmitter and receiver. This procedure repeats for all of the measured locations. The outdoor measured points that lie directly *behind* the house were not included in the calculation, since multipath propagation appears to dominate at these locations and not transmission through the house. The inclusion of these locations would distort the correlation between partitions and path loss and are best studied separately [2].

The calculation of $\vec{x}$ results in attenuation values of 3.5 dB for the small deciduous tree outside, 4.7 dB for the interior plaster walls, and 10.2 dB for the brick exterior. A comparison of the optimized predictions to measurements results in a standard deviation of 2.6 dB – a remarkable decrease when compared to the typical path loss exponent σ of 8.0 dB. The low standard deviation is intuitive since the procedure minimizes mean squared error between measured and predicted data in dB.

C. Summary of Partition Values

A summary of all partition-based model results are shown in Table III. Attenuation values represent loss in excess of free space, which is the loss induced by the obstruction in addition to the ideal free space path loss ($n = 2$). Each overall attenuation in Table III value is a dB average of several similar calculated partition-based attenuations. For example, the attenuation of 4.7 dB listed under *Plaster walls* is an average of the attenuations calculated for the two different TR separations used at the Rappaport home. Note, however, the consistency of results for all plasterboard or plaster walls calculated from measurements. All attenuation values lie between 3.6 and 5.6 dB, implying

TABLE II

Partition frequency, distance, and 5.85 GHz path loss w.r.t. 1m free space for the 30m transmitter at the Rappaport home using an outdoor 5.5m transmitter height.

Location	Small Tree	Brick Ext.	Int. Wall	TR Sep. (m)	PL (dB)
1	1	0	0	22	31.3
Outdoors 2	1	0	0	22	33.4
Front Side 3	0	0	0	23	32.4
5.5m height 4	0	0	0	25	33.7
5	0	0	0	27	31.8
6	0	0	0	29	32.0
1	1	0	0	22	31.3
Outdoors 2	0	0	0	23	25.9
Front Side 3	0	0	0	25	27.3
1.5m height 4	0	0	0	27	32.1
5	0	0	0	29	32.0
1st Floor					
Living Room	1	1	0	32	40.1
Front Hall	0	1	0	30	39.6
Office	0	1	0	32	41.6
Stairs	0	1	0	31	45.8
Bathroom	0	1	1	35	46.7
Laundry	0	1	1	35	43.7
Kitchen	0	1	2	38	51.2
Dining Room	1	1	0	38	42.5
Family Room	0	1	2	41	51.9
2nd Floor					
Front Bed	1	1	0	32	44.4
Rear Bed 1	1	1	1	38	51.2
Bathroom	0	1	2	38	51.7
Rear Bed 2	0	1	1	42	46.6
Master Bed	0	1	0	34	40.6
	$\underbrace{\qquad\qquad}_{A}$			$\underbrace{\quad}_{\vec{d}}$	$\underbrace{\quad}_{\vec{p}}$

TABLE III

Summary of all attenuation values (loss in excess of free space) at 5.85 GHz with outdoor transmitters at 5.5m height above ground.

Partition	Loss (dB)	σ (dB)	$\Delta\sigma$ (dB)
Home exteriors			
Brick†	12.5		
Rappaport Home, 30m TX	10.2	2.6	3.1
Rappaport Home, 150m TX	14.8	2.1	4.5
Brick*	16.4		
Tranter Home, 48m TX	16.1	3.4	3.9
Tranter Home, 160m TX	16.6	3.2	4.5
Wood Siding†	8.8	3.5	0.9
Cinderblock wall	22	3.5	6.4
Subterranean basement	31		
Tranter Home, 48m TX	34	3.4	3.7
Tranter Home, 160m TX	29	3.2	2.7
Home Interior			
Plaster walls	4.7		
Rappaport Home, 30m TX	4.7	2.6	1.1
Rappaport Home, 150m TX	4.6	2.1	0.8
Plasterboard walls	4.6		
Tranter Home, 48m TX	3.6	3.4	1.9
Woerner Home, 30m TX	5.6	3.5	1.2
Foliage Shadow			
Small deciduous tree	3.5	2.6	0.5
Large deciduous tree	10.7		
Woerner Home, 30m TX	9.0	3.5	1.7
Woerner Home, 210m TX	12.3	3.3	2.4
tree line, 5.5m RX	12.4	–	–
Large coniferous tree	13.7		
tree line, 5.5m RX	16.4	–	–
tree line, 1.5m RX	11.0	–	–

† paper-backed insulation
* foil-backed insulation

that the typical value of 4.7 dB may be a near-optimal value for interior walls in *any* home.

The right-hand column of Table III, labeled $\Delta\sigma$, represents the change in optimal standard deviation between measured vs. predicted values for a model *with* and *without* the specified partition. For example, the model in the previous section included a partition for the brick wall of the Rappaport home and resulted in a measured vs. predicted standard deviation error of 2.6 dB. If the partition for the brick wall was removed from the model and new optimal partition values were calculated, then the standard deviation error would increase by 3.1 dB to 5.7 dB, according to Table III. The value $\Delta\sigma$ roughly gauges the importance of the specific partition to the model.

D. Extending Least-Squares to Other Models

Mathematically, the least-squares technique for finding partition-based path loss models is very similar to the MMSE technique for finding a path loss exponent. Both models correlate site information with linear parameters to minimize standard deviation between measured and predicted path loss. In the case of partition-based models, the site information is the type and quantity of partitions; in the case of path loss exponent models, the site information is the logarithmic TR separation. In the case of partition-based models, the linear parameters are partition attenuations; in the case of path loss exponent models, the linear parameter is the path loss exponent. The primary difference between the models is that a partition-based model usually has more than one linear parameter.

Since least-square methods can be formulated to optimize any linear path loss parameter, it is trivial to extend the technique to other propagation models. For example, instead of a single path loss exponent, a signal that propagates across multiple regions (indoor and outdoor, for example) may use least-square matrix form to calculate MMSE path loss exponents for each region traversed. In fact, it is possible to extend the least-squares model to site-specific information that seems more abstract than partitions, such as the number of windows or the number of doors in a room where the path loss is being predicted.

It is *extremely* important not to infer too much physical meaning from a least-squares propagation model since the least-squares method is simply a way of producing a "best fit" between path loss measurements and site information. For example, if the least-squares analysis of a partition-based model results in an attenuation of 5 dB for a plaster wall, then an engineer should *not* interpret that result to mean that an electromagnetic wave impinging on a plaster wall will experience 5 dB of transmission loss. Rather, a low standard deviation prediction for the plaster wall model only implies two things: 1) a *strong correlation* exists between path loss and the number of plaster walls between a transmitter and a receiver and 2) a good rule-of-thumb for accurate prediction is to add 5 dB of path loss per plaster wall. Real-life propagation is extremely complicated and a partition attenuation value depends on factors such as building geometry, structure, furnishing, etc. as well as the material properties of a partition.

IV. Conclusions

This paper presented techniques for incorporating site-specific information into path loss predictions in the context of 5.85 GHz outdoor-to-indoor residential path loss measurements. The results have specific applications for designing and deploying home-based commercial wireless NII-band and HIPERLAN networks in residential neighborhoods, although the approach is applicable to any type of indoor, microcell, or hybrid indoor-outdoor wireless system design at any frequency.

This paper also demonstrates the relationship between path-loss exponent models and more sophisticated prediction techniques that incorporate site-specific information. The results clearly quantify the trade-off between accuracy (low standard deviation between measured vs. predicted path loss) and the amount of available site-specific information. Furthermore, the partition-based analysis on the three homes indicates two important results. First, the small standard deviation error in measured vs. predicted path loss implies that optimal partition values accurately describe propagation within a measured building. Second, the consistency of optimal partition attenuations at the different homes implies that the typical values in Table III are applicable to similar, *unmeasured* residential areas and homes.

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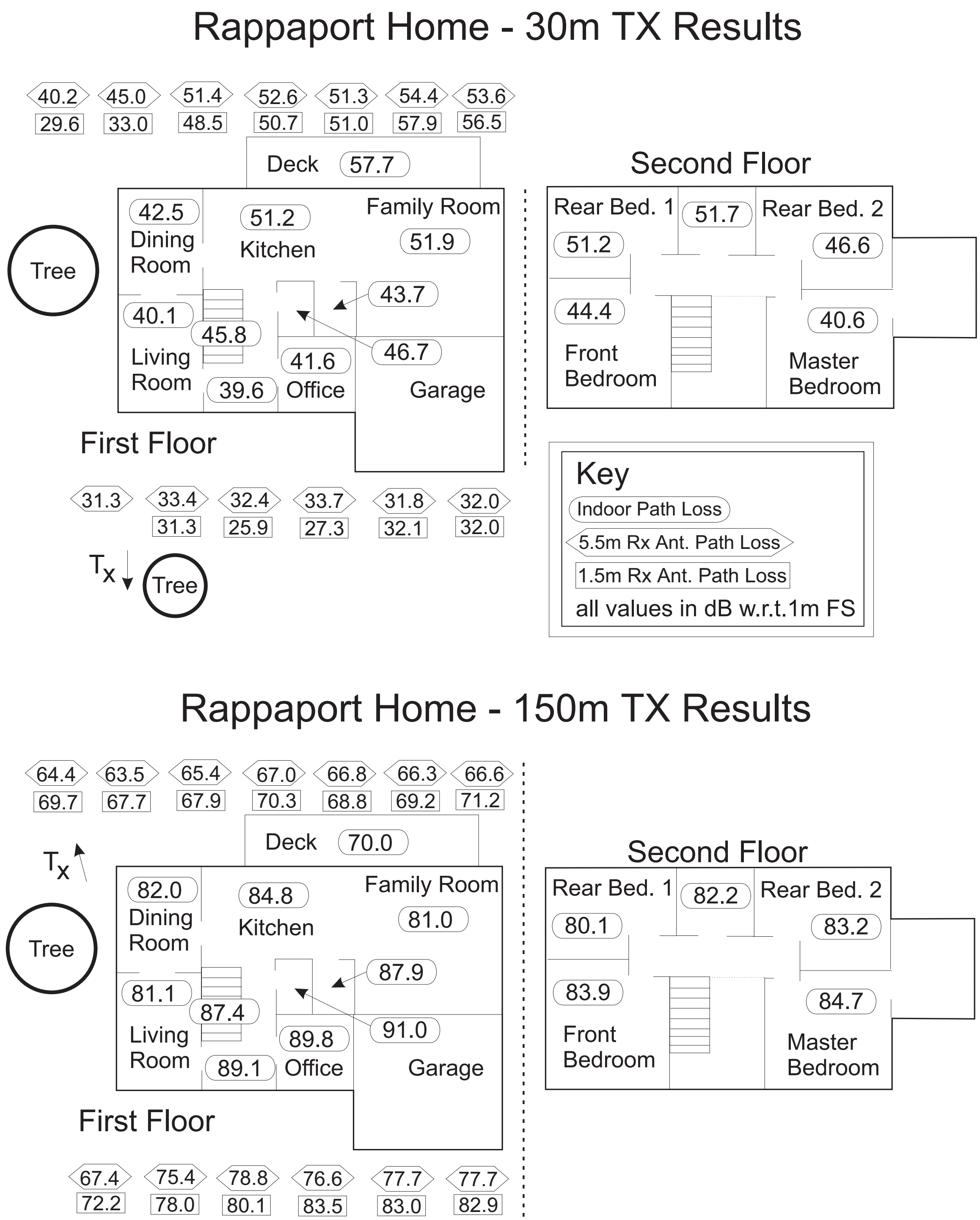

Fig. 2. Summary of 5.85 GHz path loss measurements at the Rappaport home.