Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: [The Ultra-wideband Indoor Path Loss Model]
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Source: [Dr. Saeed S. Ghassemzadeh] Company [AT&T Labs-Research]
Address [Rm. B237, 180 Park Ave., Florham Park, NJ 07932 US]
Voice:[973-236-6793], FAX: [973-360-5877], E-Mail:[saeedg@research.att.com]

Re: [IEEE P802.15-02/208r1-SG3a and IEEE P802.15-02/277r0-SG3a]

Abstract: [This contribution describes a simple statistical model for evaluating the path loss in indoor environments. It consists of detailed characterization of path loss model parameters of Ultra-Wideband Band (UWB) signals having a nominal center frequency of 5 GHz. The proposed statistical path loss model is for in-home UWB channel and it is based on over 300,000 frequency response measurements.]

Purpose: [For IEEE 802.15.SG3a to adopt the path loss model and use it in link budget calculations for validation of throughput and range requirements of UWB PHY proposals.]

The Ultra-wideband Indoor Path Loss Model

Saeed S. Ghassemzadeh
AT&T Labs-Research

Outline

- Motivation
- Background: Measurement Technique and Database
- Data Reduction: Background and Key Findings
- The Path Loss Model
- Model Simulation
- Conclusion
- Q/A

Motivation

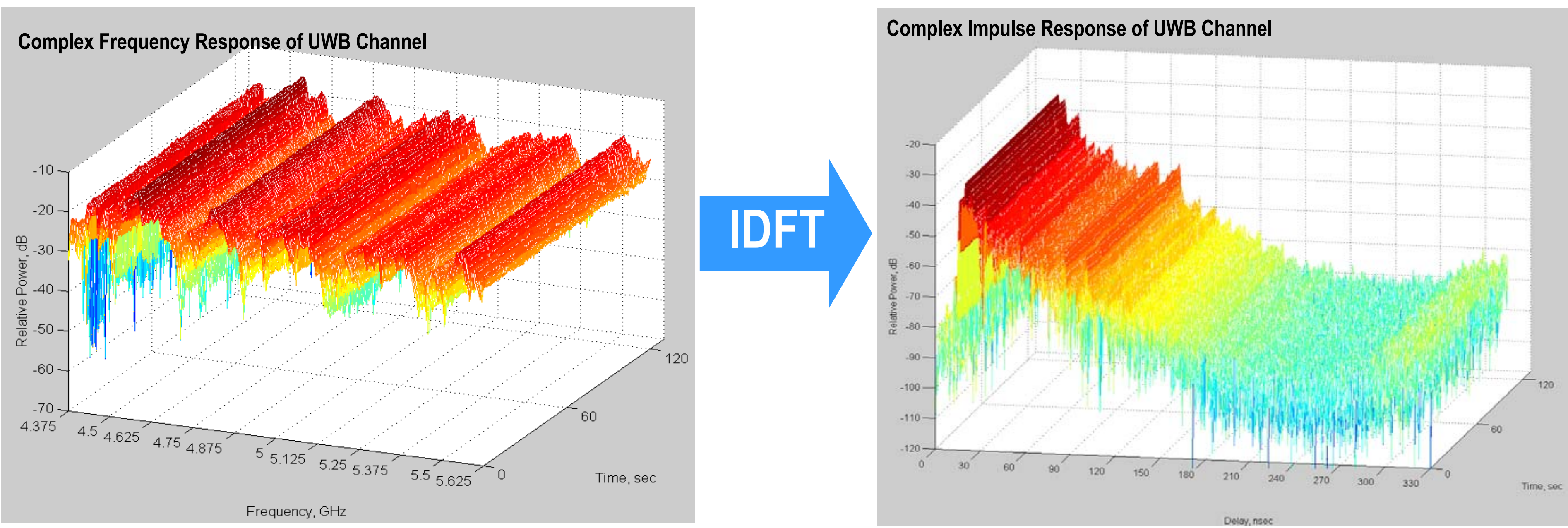
- To create a channel model for UWB channel that:
  - Represents a realistic UWB propagation channel without doing a costly sounding experiments.
  - Signifies a compact and simple method to simulate the channel's propagation behavior.
  - Be able to use the model for various PHY performance evaluation for in-home environment.
- Most Wireless channel models available, either:
  - do not represent UWB channel,
  - or are not in the environment and frequency spectrum of interest,
  - or have database that is small for statistical characterization of the channel parameters.

Swept Frequency Measurement Technique

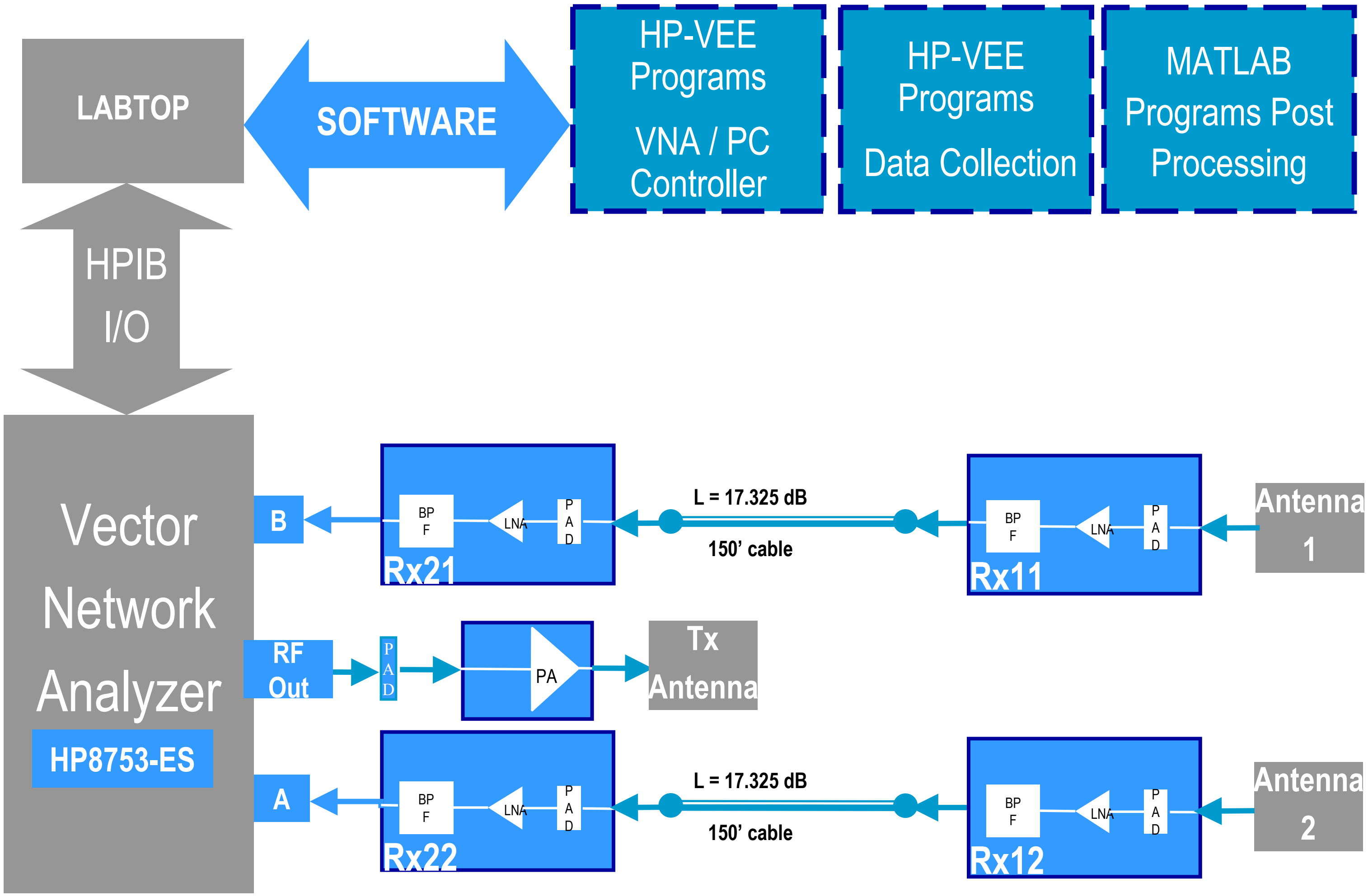
- Center frequency: 5 GHz
- Frequency bins: 401

$\Rightarrow$ $\Delta f = 3.125$ MHz, $\tau_{max} = 320.8$ ns

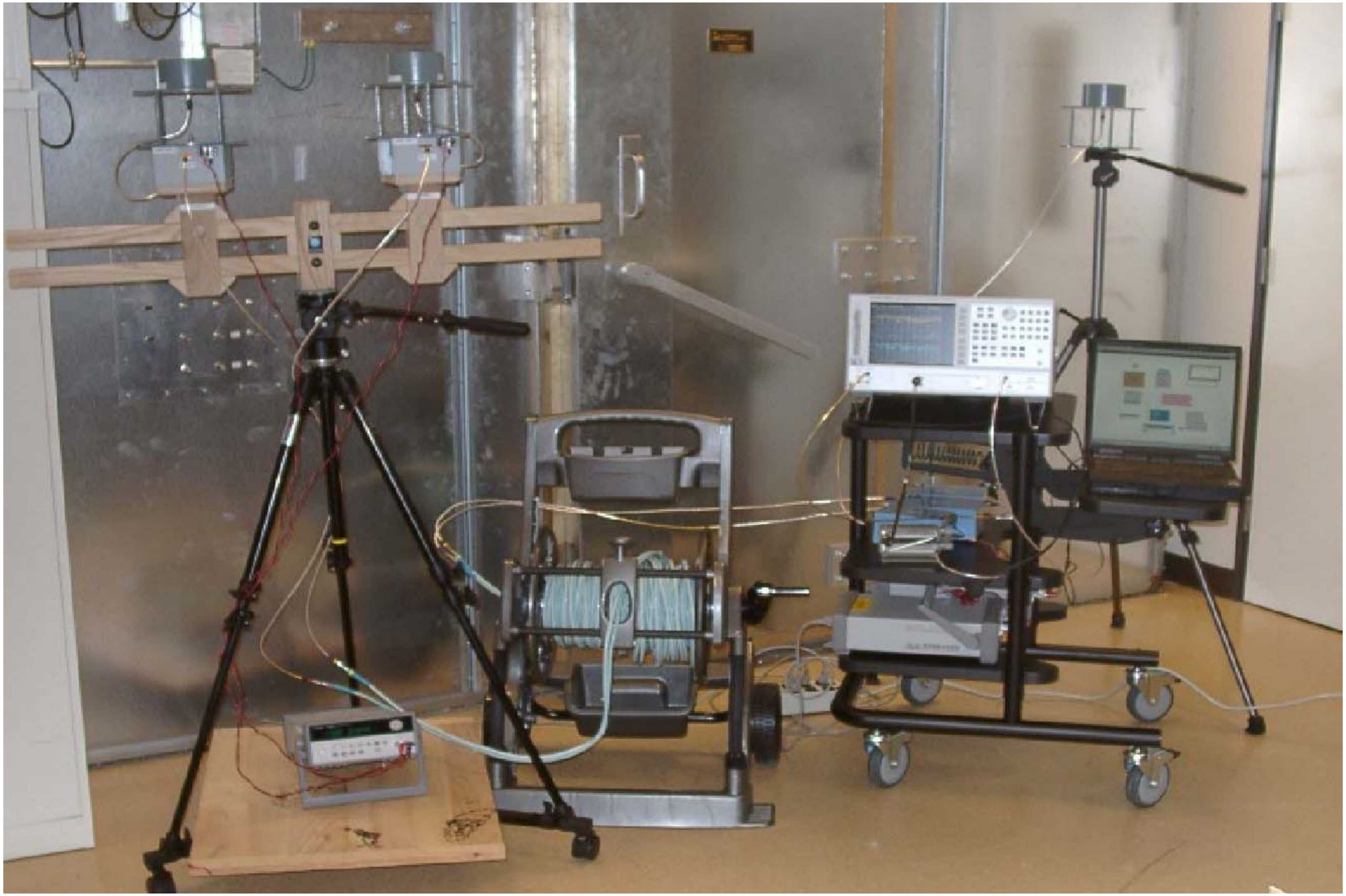
- Bandwidth: 1.25 GHz $\Rightarrow$ $\Delta\tau = 0.8$ ns
- Sweep rate: 400 ms



Channel Sounder System Block Diagram



Indoor UWB Channel Sounder



Data Base

- Data base Includes:
  - Measurements at 23 different homes at 5 GHz
  - 712 locations with T-R separations ranging from 1m to ~15 m
  - Simultaneous measurements of 2 antennas separated by 38 inches at each location over 2 minute intervals
  - From one wall to maximum of 4 walls penetration
  - 300,000 complex frequency responses of a 1.25 GHz ultra-wideband channel.

Data Reduction: Background

- We define Path Loss, $Pl(d) = \frac{G_r G_t P_t}{\overline{P_r}}$; where $\begin{cases} \overline{P_r} = \text{Average received power} \\ P_t = \text{Transmit power} \end{cases}$

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

- Typical Representation of Path Loss (PL) vs. Distance (d):

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

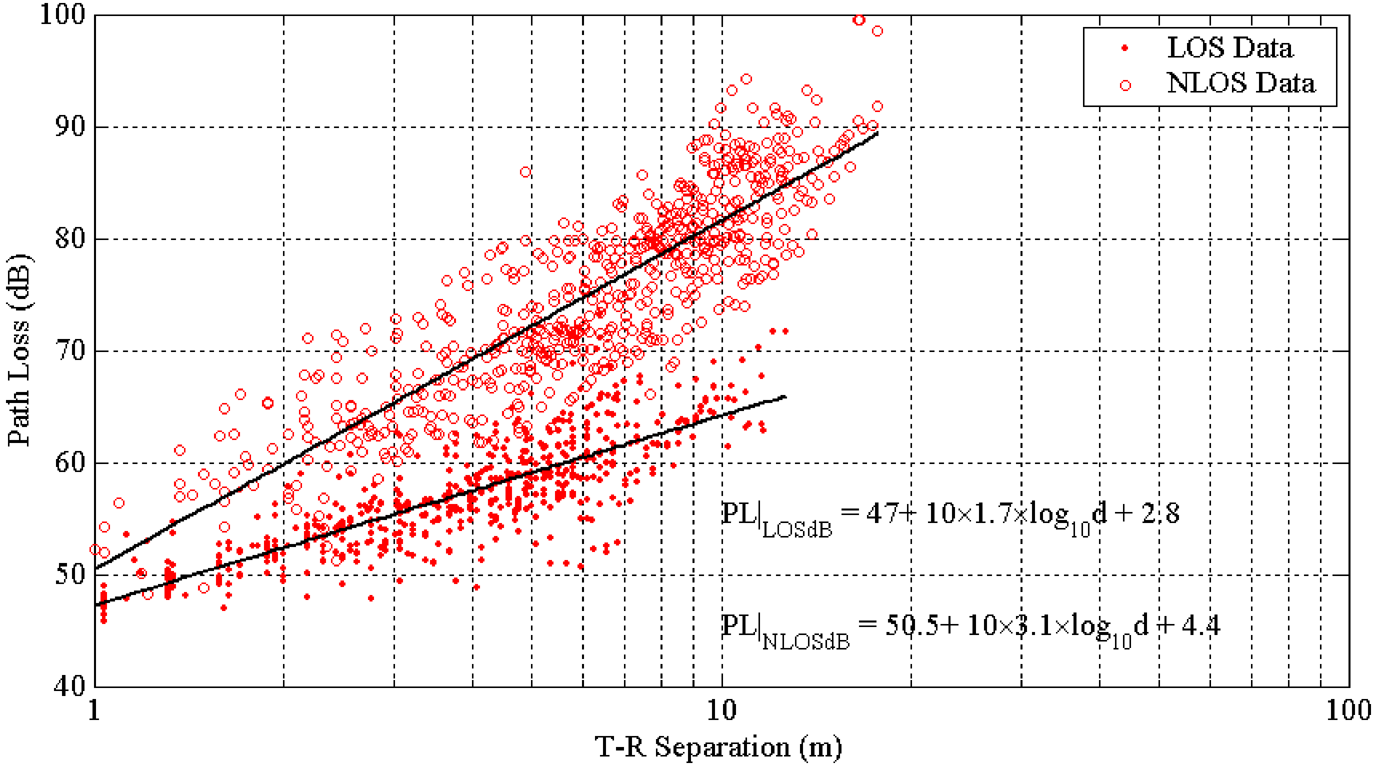
  - d_o is a reference distance, e.g., d_o = 1 m.
  - Bracketed term is a least-squares fit to pathloss, *PL*(*d*).
  - PL_0 (intercept) and γ (path loss exponent) are chosen to minimize $\overline{S^2}$.
  - *S* is the random scatter about the regression line, assumed to be a zero-mean Gaussian variate with standard deviation σ dB.

Data Reduction: Key Findings

- 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_o 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. We chose the intercept value to be the mean path loss at 1m measured in 23 homes.
- Path loss exponent, γ, changes from one home to another. It is a Normal RV with $N_{LOS}[1.7, 0.3]$ and $N_{NLOS}[3.5, 0.97]$.
- Shadow-fading, *S*, is zero mean Gaussian RV with variance that also changes from one home to another. This variance is also a Normal RV with$N_{LOS}[1.6, 0.5]$ and $N_{NLOS}[2.7, 0.98]$.

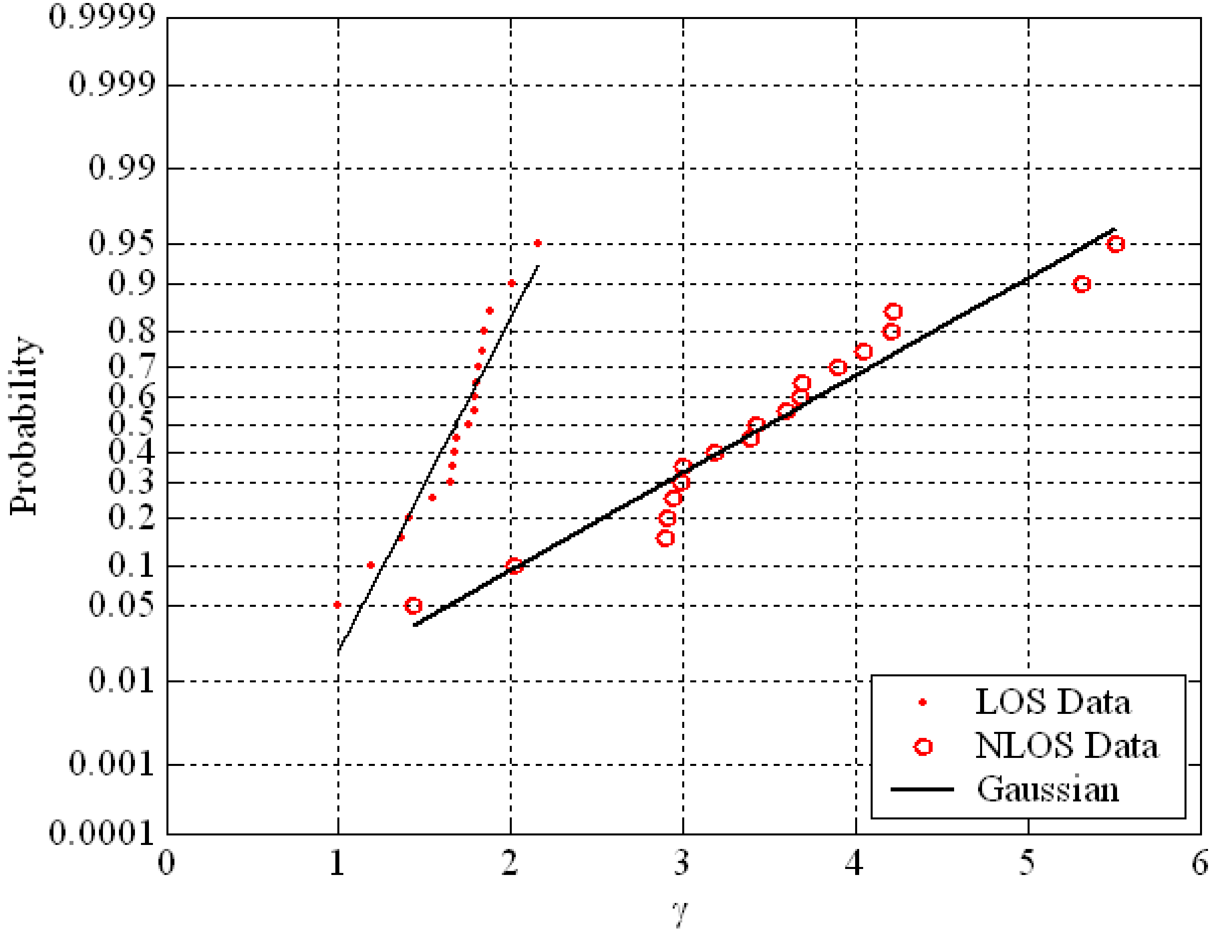
	LOS		NLOS	
	Mean	Std. Dev.	Mean	Std. Dev.
PL_o (dB)	47	NA	51	NA
γ	1.7	0.3	3.5	0.97
σ (dB)	1.6	0.5	2.7	0.98

Path Loss vs. Distance Scatter Plot

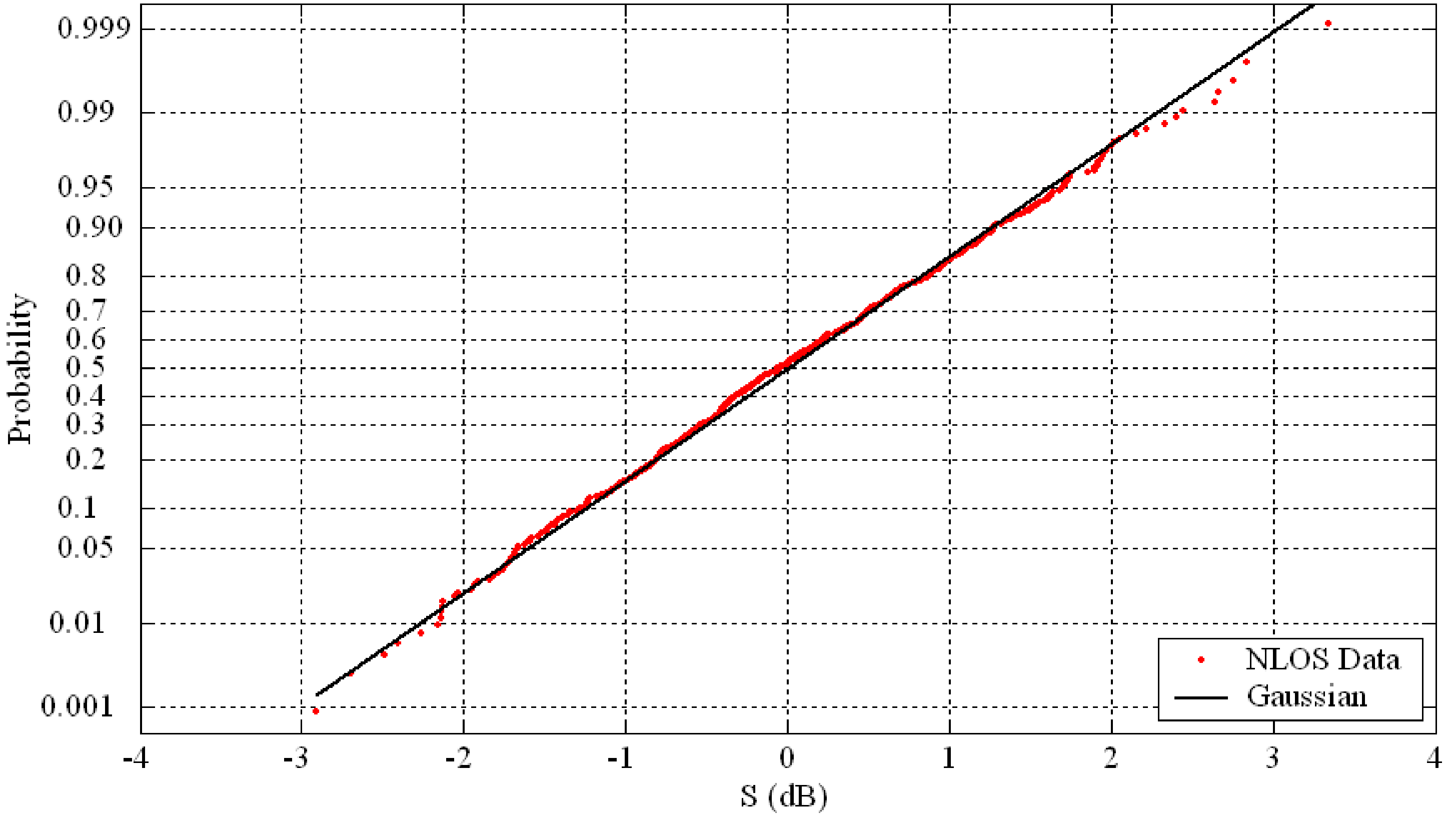


- Model the path loss over the population of data.
- Intercept point, PL_o, is 47 dB and 50.5 dB in LOS and NLOS.
- Path loss exponent, γ, is 1.7 and 3.1 for LOS and NLOS.

CDF of Path Loss Exponents

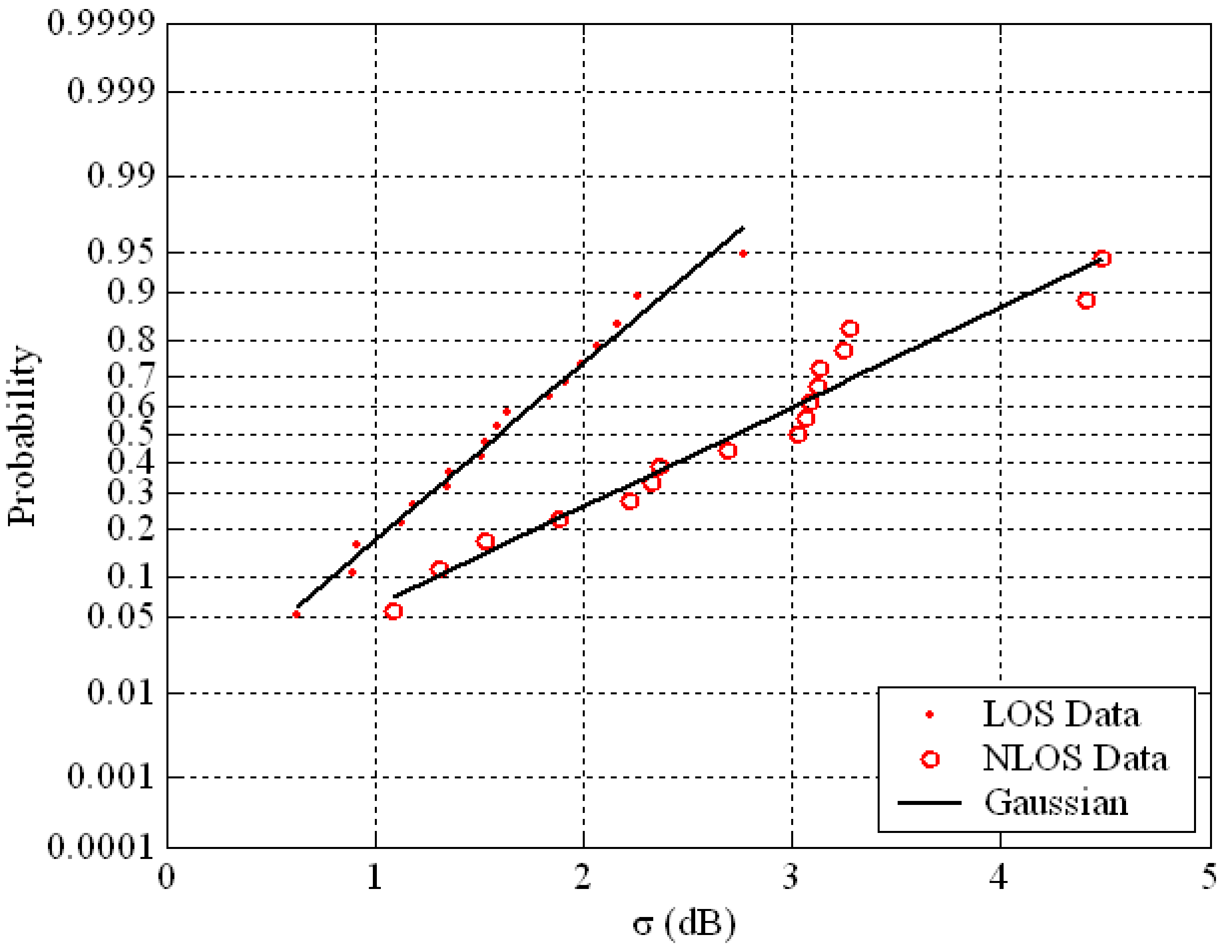


CDF of Shadow fading



- Shadow-fading is log-normal as expected with zero mean and variance (over the population of data) of about 2.8 and 4.4 dB, in LOS and NLOS, respectively.

CDF of Variance of Shadow Fading



The Path Loss Model

Introducing three new RVs: $\gamma = \mu_\gamma + n_1\sigma_\gamma,\ S = n_2\sigma$, and $\sigma = \mu_\sigma + n_3\sigma_\sigma$

$$\overline{PL(d)}\Big|_{\text{dB}} = \left[PL_0 + 10\gamma\log_{10}d\right] + S$$

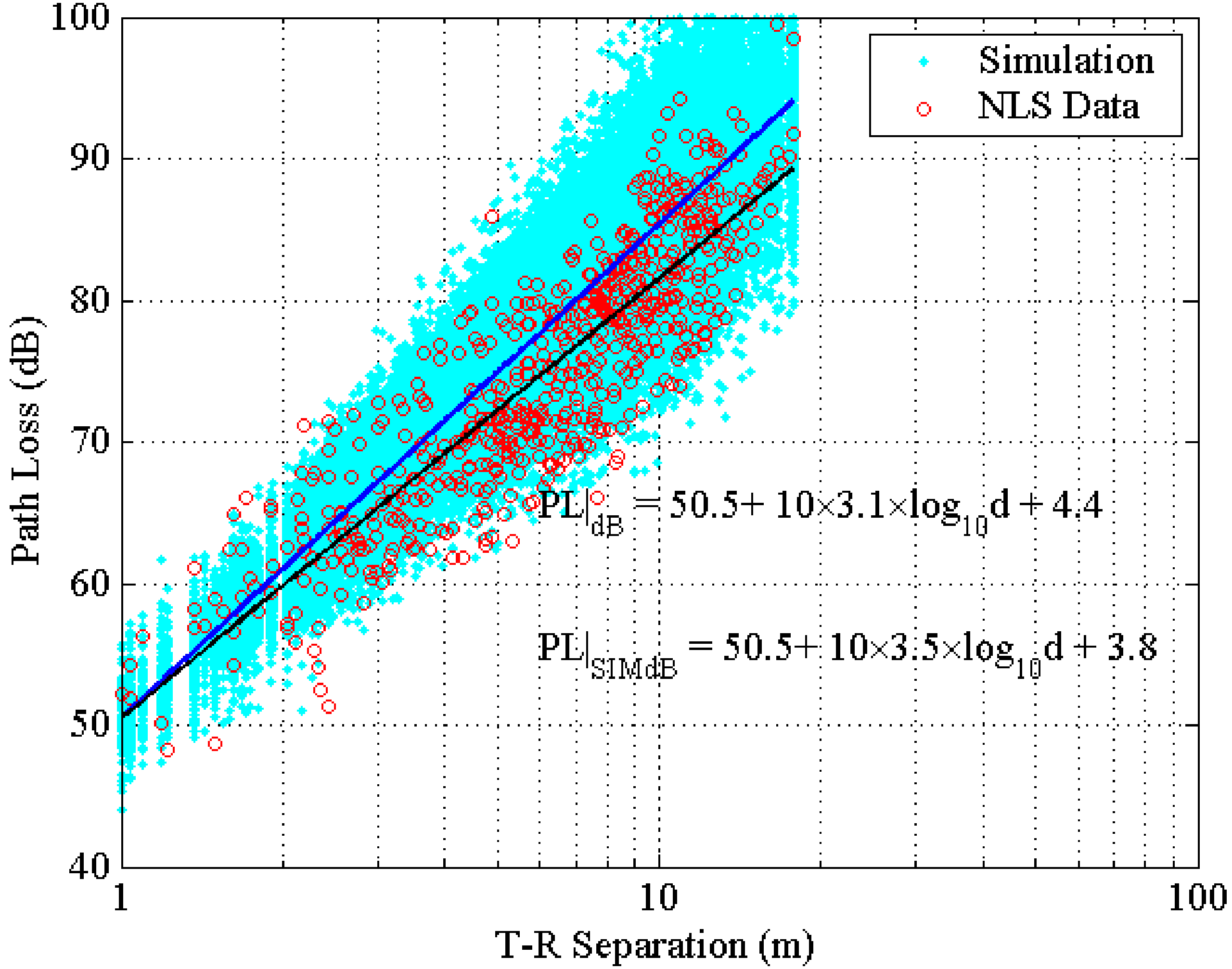
$$= \left[PL_o + 10\left(\mu_\gamma + n_1\sigma_\gamma\right)\log_{10}d\right] + \left[n_2\left(\mu_\sigma + n_3\sigma_\sigma\right)\right]$$

$$= \left[PL_o + 10\mu_\gamma\log_{10}d\right] + \left[10n_1\sigma_\gamma\log_{10}d + n_2\mu_\sigma + n_2n_3\sigma_\sigma\right];\quad d_o \le d \le 15\text{ m}$$

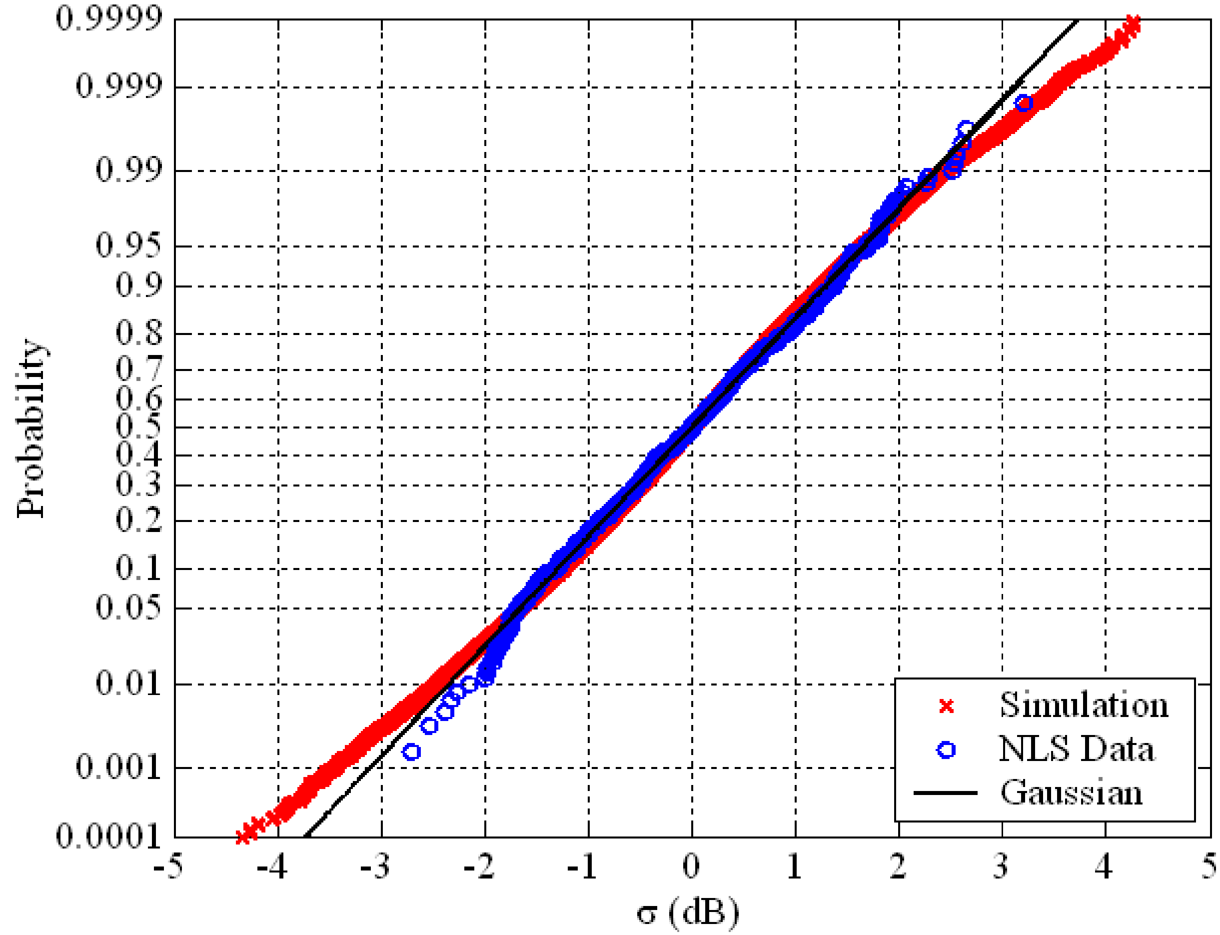
= [**Median path loss**] + [**Random variation about median path loss**]

- n_1, n_2 and n_3 are iid zero-mean, unit-variance Gaussian variates.
- n_1 varies from one home to another while n_2 and n_3 vary from one location to another within each home.
- The variable part of above equation is not exactly Gaussian since $n_2 \times n_3$ is not Gaussian. However, this product is small w.r.t. the other two Gaussian terms. Therefore, it can be approximated as a zero mean random variate with standard deviation of $\sigma_{\text{var}} = \sqrt{100\sigma_\gamma^2\left(\log_{10}d\right)^2 + \mu_\sigma^2 + \sigma_\sigma^2}$.

Model Simulation



Gaussian AssumtionValidity of σ_{var}



A Final note on Simulation

- For simulation purposes, it is practical to use truncated Gaussian distributions for n_1, n_2 and n_3 keeping γ, σ and S from taking on unrealistic values.
- One possible range for these values are:

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

Conclusion

- We performed propagation experiments to characterize the UWB path loss in homes.
- We presented a statistical path loss model for UWB signals at 5 GHz.
- The model is based on over 300,000 UWB frequency responses in 23 homes.
- The model accounts for key path loss parameters from one home to another.
- The result is a general statistical path loss model which can be upgraded with further measurements.