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

Submission Title: [The Ultra-wideband Indoor Multipath Channel Model]
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Re: [IEEE P802.15-02/208r1-SG3a and IEEE P802.15-02/282r0-SG3a]

Abstract: [This contribution describes a simple model for simulation of the UWB indoor channel. It also consists of detailed characterization of multipath parameters such as Doppler spectrum, maximum excess delay, mean and RMS delay spread, average multipath intensity profile model, relative multipath powers and their amplitude and phase distribution. The work is based on over 300,000 frequency response measurements at 712 location in 23 homes.]

Purpose: [For IEEE 802.15.SG3a to adopt the multipath model and use it for performance evaluation of various UWB PHY proposals.]

The Indoor Ultra-Wideband Multipath Channel Model

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Outline

- Motivation
- Measurement technique and database
- Data reduction: background and key findings
- Insight on rms delay spread and Doppler
- Multipath component amplitude, phase distribution and correlation.
- Average multipath intensity profile
- Multipath intensity profile model
- Channel simulation results
- Conclusion

Motivation

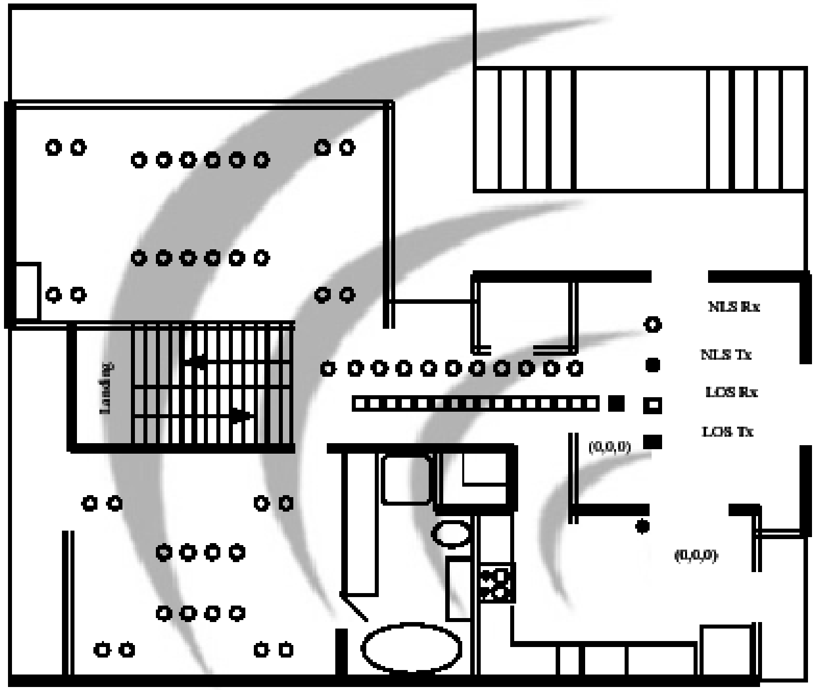
- To create a channel model for UWB channel that:
  - Represents a realistic UWB propagation channel without doing a costly sounding experiments.
  - Signifies a compact and simple method to simulate the multipath channel behavior.
  - Is useable for performance evaluation of various PHYs in-home environment.
- Most wireless channel models available, either:
  - Do not represent UWB channel,
  - Or are not in the environment and/or frequency spectrum of interest,
  - Or have database that is small for statistical characterization of the channel parameters.

Measurement Technique and Data Base

- Measurement technique:
  - Swept frequency measurement technique using VNA
    - Center frequency: 5 GHz
    - Bandwidth: 1.25 GHz $\Rightarrow$ $\Delta\tau = 0.8$ ns
    - Frequency bins: 401 $\Rightarrow$ $\tau_{max} = 1/\Delta f = 320.8$ ns
    - Sweep rate: 400 ms $\Rightarrow$ $f_{d,max} = 2.5$ Hz
- Data base includes:
  - 300,000 complex frequency responses of the ultra-wideband channel at 712 locations in 23 homes
  - 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

Measurement Set-up

- Transmit and receive antennas were separated such that T-R separations have uniform distribution.
- Measurements were performed in Line-of-Sight (LOS) and None Line-of- Sight (NLS).
- T-R separations in 1m to 15m in steps of ~ 0.9 m.



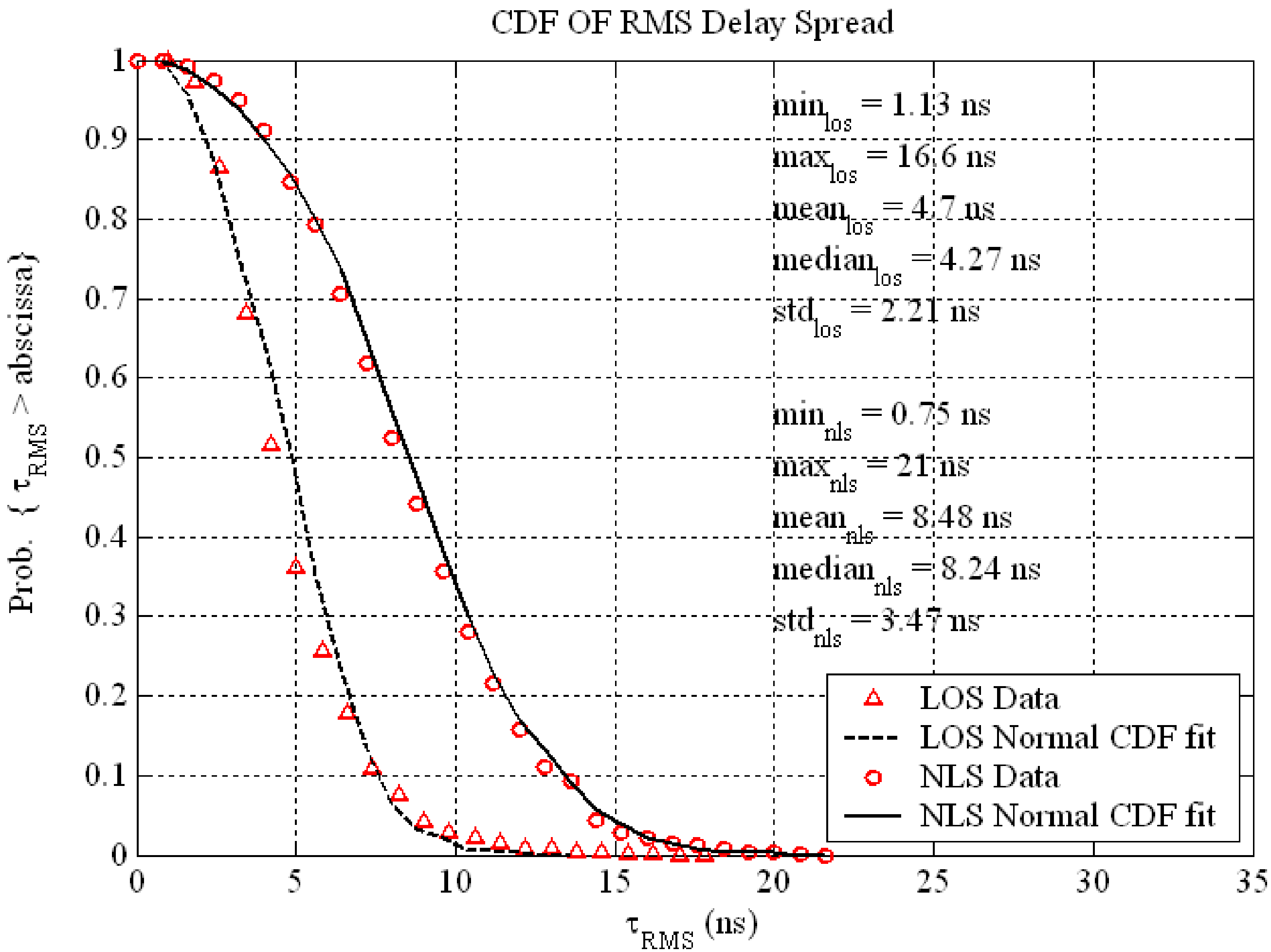
Data Reduction

- The following steps are taken to get the MIPs :
  - Calibration information is removed from the raw data.
  - The response is then locally averaged over time (since the receiver was kept stationary and maximum Doppler measured was no more than a few tenths of Hz.).
  - 401 point complex IFFT'd is taken to get the complex MIPs.
  - The MIPs are then normalized to the total average power.
  - Threshold (-30 dB) is set to +10 dB above the average noise floor (-40 dB).
  - The noise is removed from the data and MIP is re-normalized so that the area under MIP is one.
  - All MIPs are synchronized w.r.t. their delay at zero ns, representing the first return above the threshold.

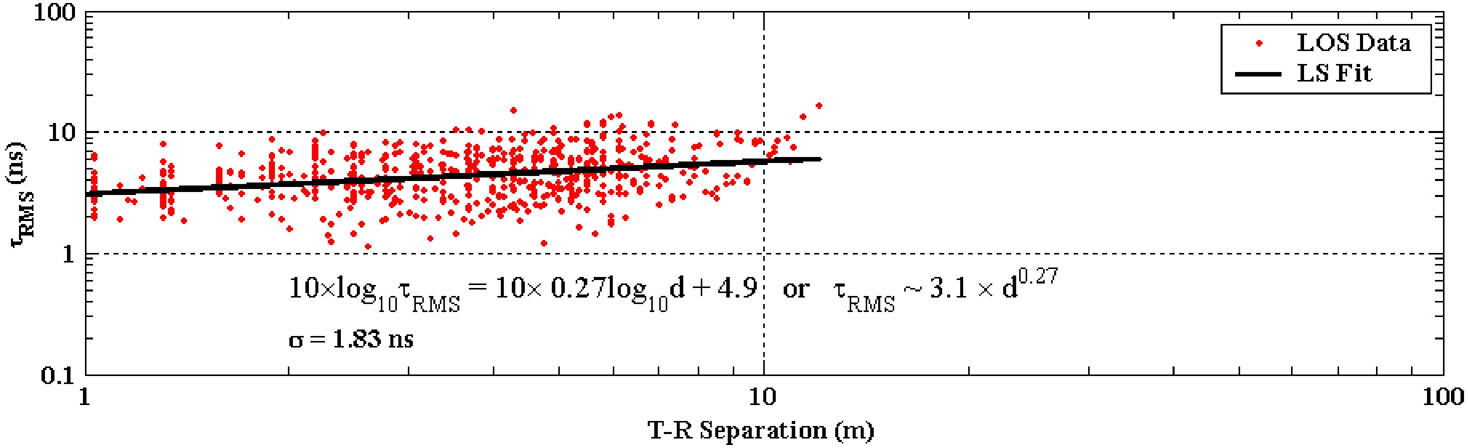
Insight on MIP Delay Parameters and Doppler

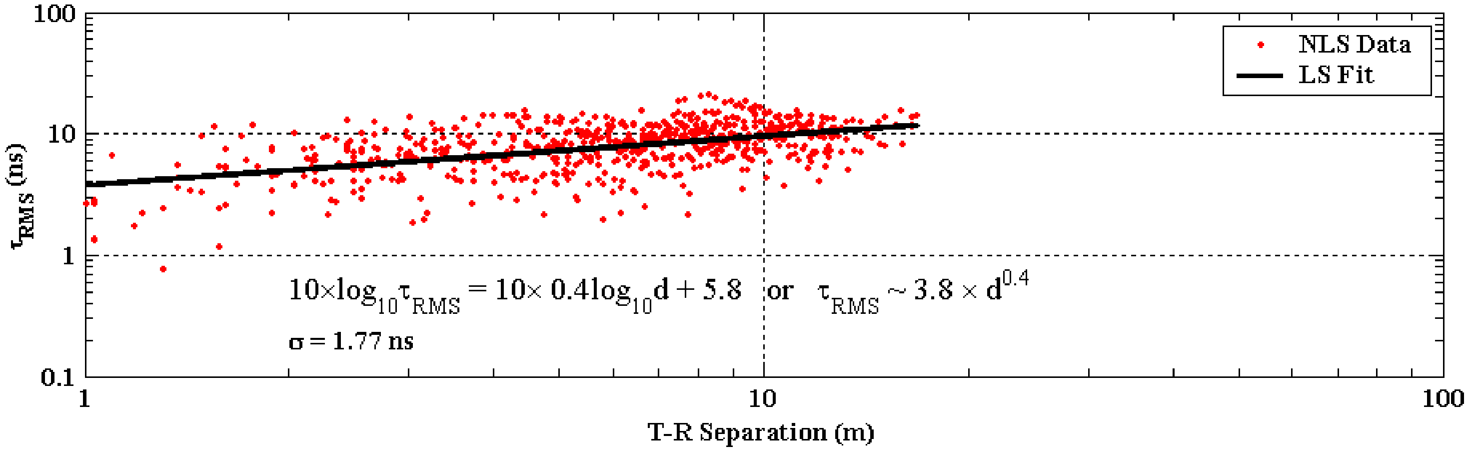
- Maximum excess delay observed was 70 ns.
- RMS delay spread has a normal distribution over all locations and homes
- RMS delay spread increases with T-R separation and therefore with path loss.
- Min. and Max. of RMS delay spread:
  - LOS: 1.1ns and 16.6 ns
  - NLS: 0.75 ns and 21 ns
- Mean and Standard deviation of RMS delay spread:
  - LOS: 4.7 and 2.2 ns
  - NLS: 8.4 ns and 3.8 ns
- Maximum Doppler frequency observed was 0.1Hz.

Distribution of RMS Delay Spread, τ_{RMS}

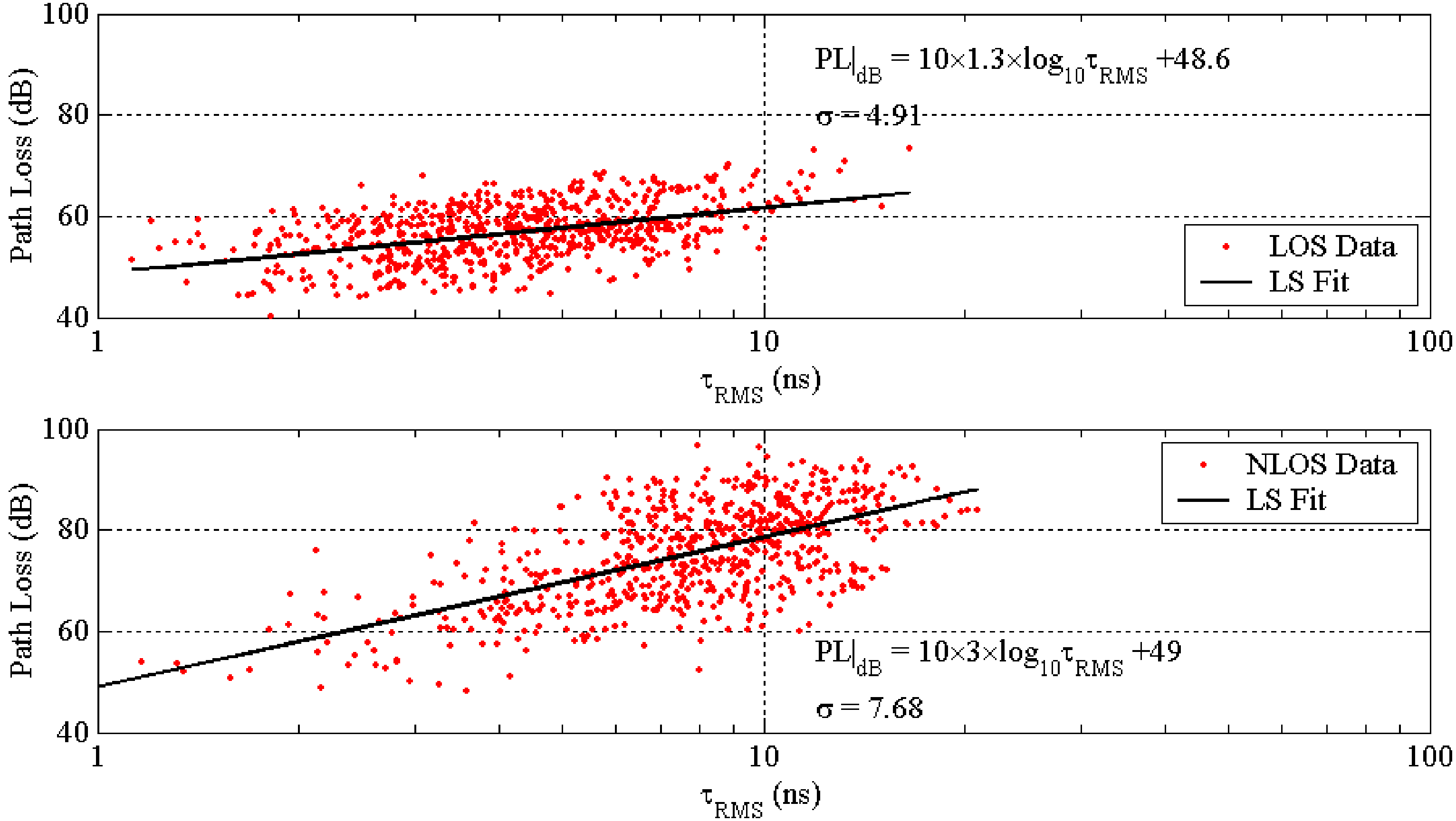


RMS Delay Spread vs. T-R Separation

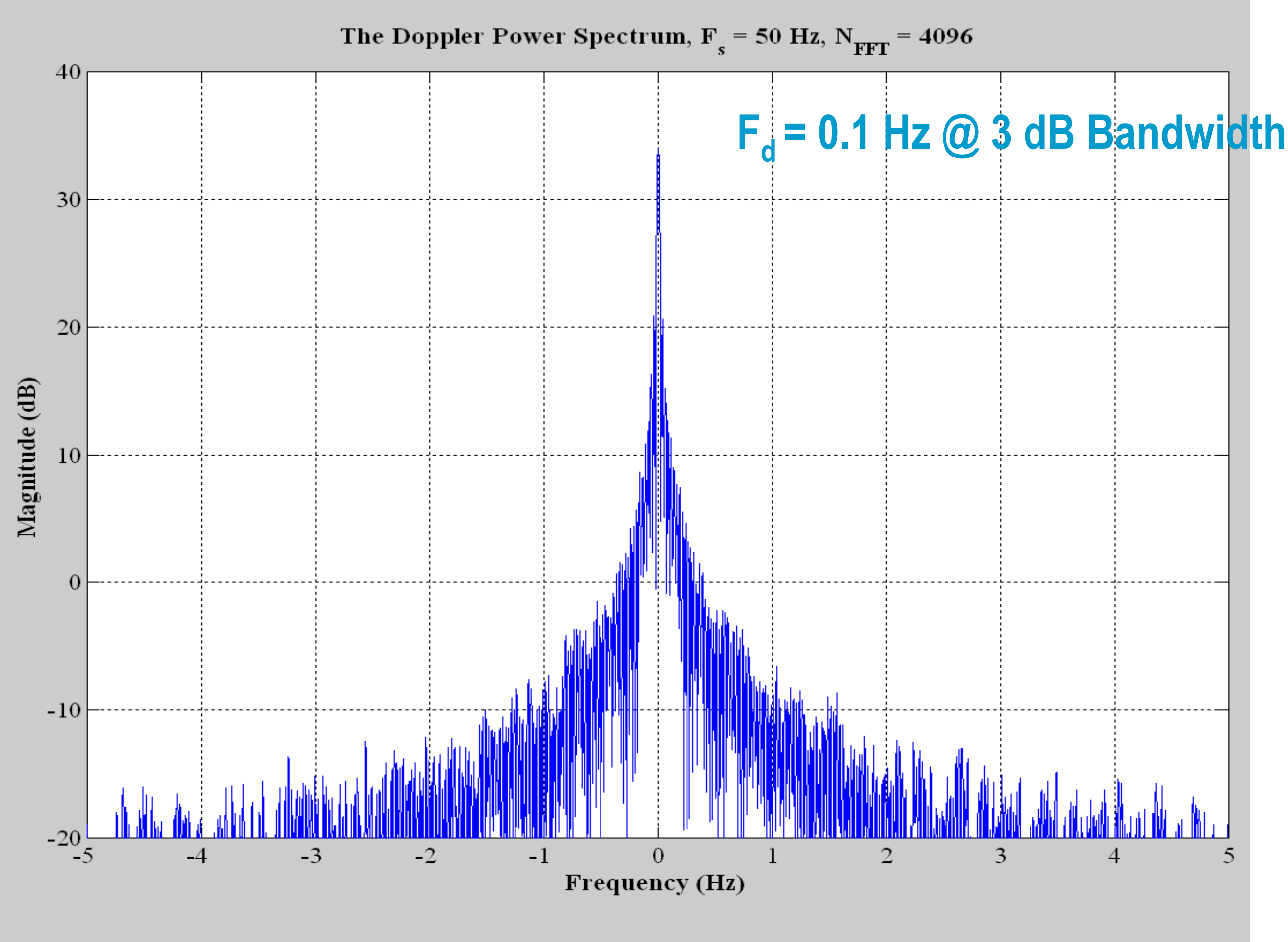




RMS Delay Spread vs. Path Loss



Doppler-Power Spectrum



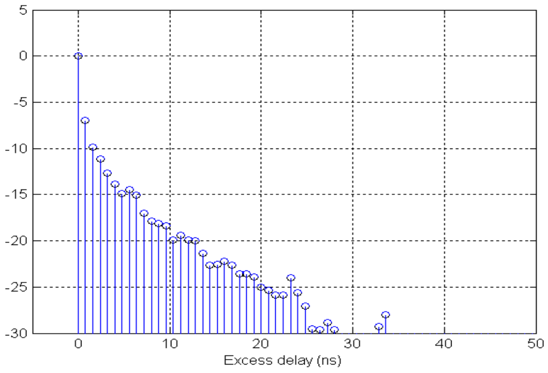
The Relative MIP Model

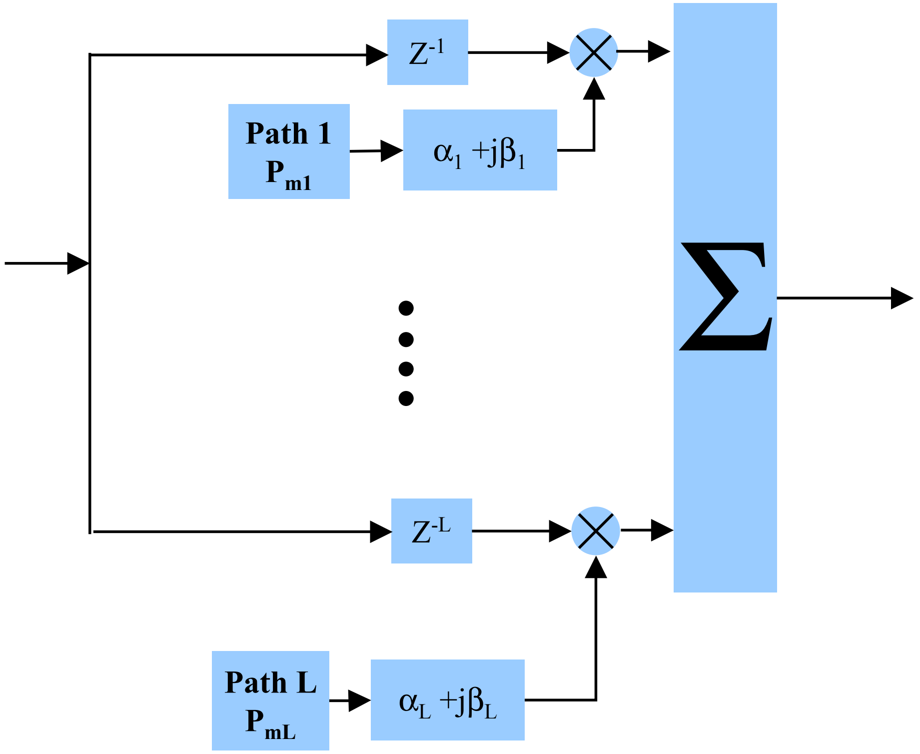
- Tapped-delay line model with randomly selected relative MIP power, random amplitude and phase variation.

$$P_{m,i} = \frac{P_{Path\_Loss} \times P_{relative\_i}}{P_T}$$

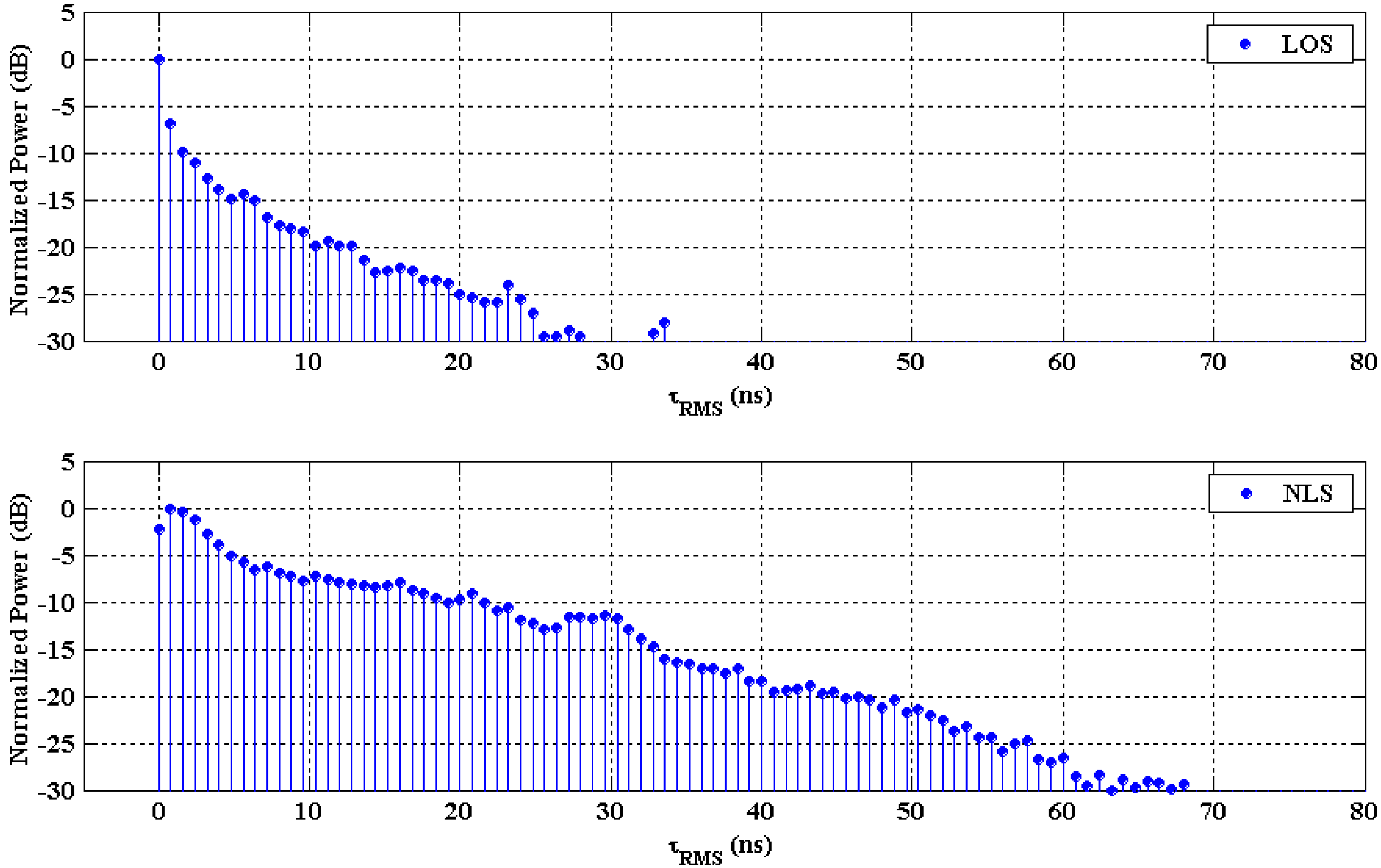
$$P_T = \sum_{i=1}^{L} P_{relative\_i}$$

Relative MIP Model





Average Relative MIP



- Relative MIPs are MIPs that are averaged over all locations and homes prior to normalization to their maximum power.

Average Relative MIP Limits, NLS

% Energy	L	dB from max	τ_{RMS} ns	τ_m ns	τ_{max} ns
20.8	2	1	0.4	1.17	1.6
41.6	5	3	1.0	1.5	3.2
52.4	8	6	2.17	1.6	5.6
71.1	17	8	4.1	3.82	16
84.3	26	10	6.1	5.8	20.8
96	42	15	8.5	8.5	32.8
98.6	57	20	9.2	9.7	44.8
100	85	30	10.7	9.8	68

Average Relative MIP Limits, LOS

% Energy	L	dB from max	τ_{RMS} ns	τ_m ns	τ_{max} ns
56.6	1	1	NA	NA	NA
56.6	1	3	NA	NA	NA
56.6	1	6	NA	NA	NA
68.8	2	8	4.1	3.82	0.8
73.8	3	10	6.1	5.8	1.6
87.8	8	15	8.5	8.5	5.6
95.4	17	20	9.2	9.7	12.8
100	38	30	4.5	2.2	33.6

Multipath Amplitude and Phase Distribution

- The multipath amplitudes undergo small variation which can be best characterized by Rician distribution with a K-factor greater than 40 dB.
- The phases of the multipath components are uniformly distributed between 0 and 2π.
- The multipath components are correlated with correlation coefficient ρ:

$$0 \leq \rho \leq 0.25$$

The Relative MIP Model Concept– NLS

- Typical representation of the multipath delay profile shape has been reported as a decaying exponential.
- Following this intuition, we formed the following function

$$P_{rel}(\tau)\Big|_{\mathrm{dB}} = \alpha\tau + S$$

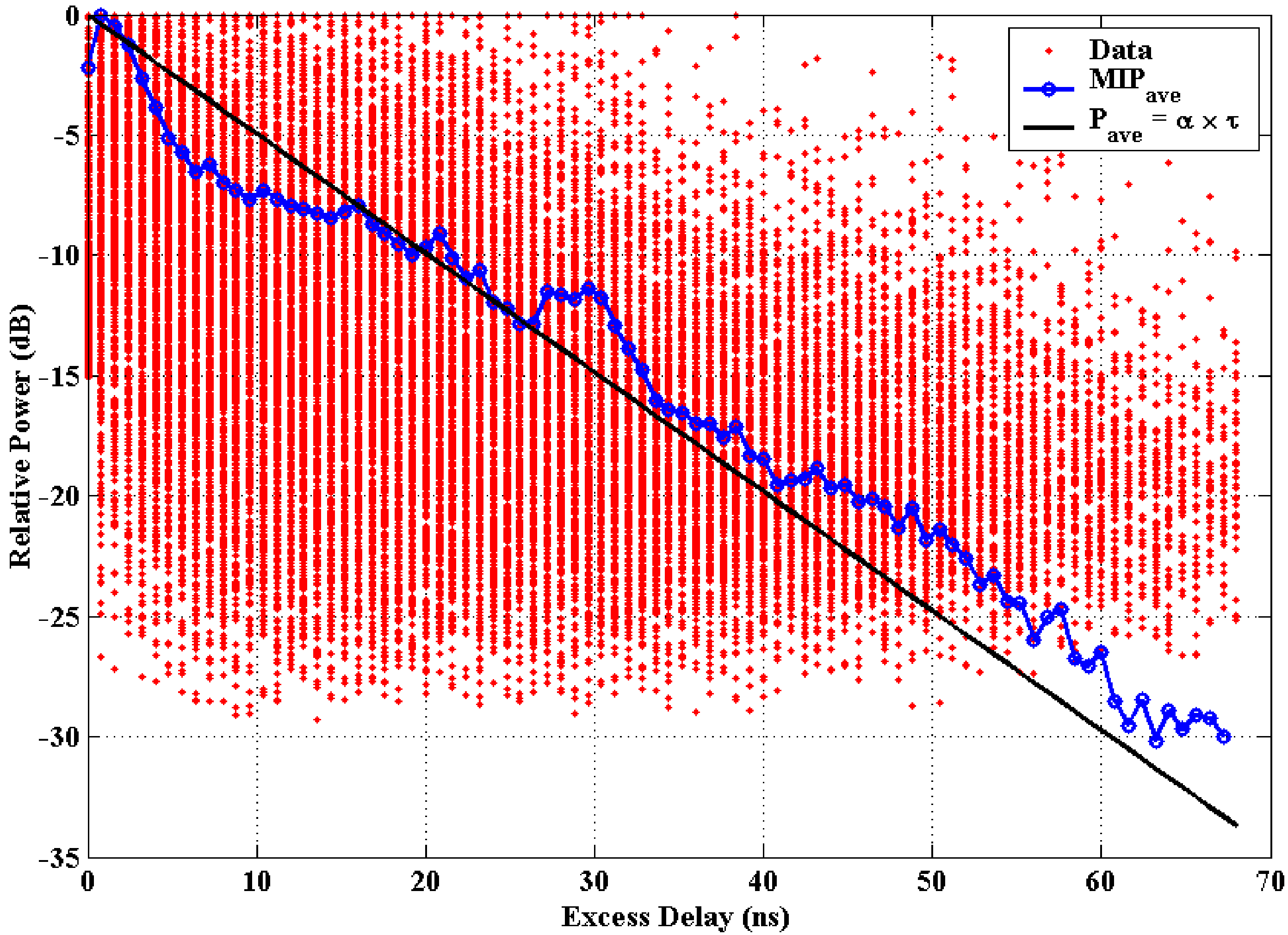
where α is decibel-decay constant and S is the variation (error) about the median relative MIP.

- The model assumes that the power of the first return for median relative MIP is the strongest one. This simplified the model considerably with insignificant increase in the slope.
- $\alpha\times\tau$ term is a least square fit to the decibel-power of each multipath component. α is then found such that the MSE of decibel-error, S, is minimized.
- We then characterize α and S over the population of homes.

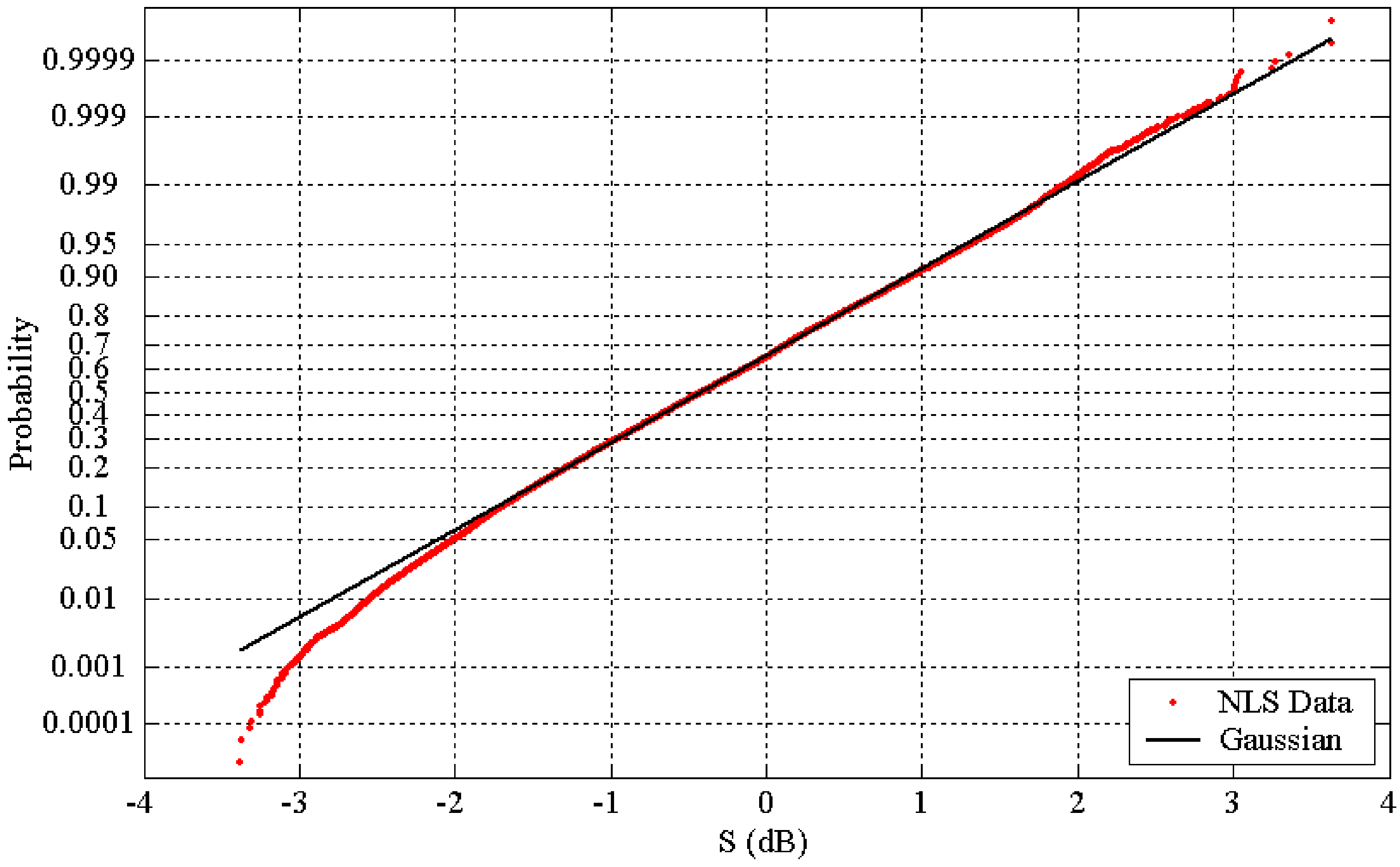
The Relative MIP Model Concept – NLS

- Due to randomness of the shape of profile observed over the population of data, we modeled the parameters over all homes.
- We observed the following:
  - Value of α [dB/ns] are normally distributed RVs, *N*[-0.50, 0.13].
  - values of S [dB] are normally distributed RVs *N*[-0.41, 7.80].
  - The mean of S was constant in each home; however, we observed that the standard deviation of S, σ_S, changes from one home to another. This variation was normally distributed over all homes with *N*[7.20, 0.88].

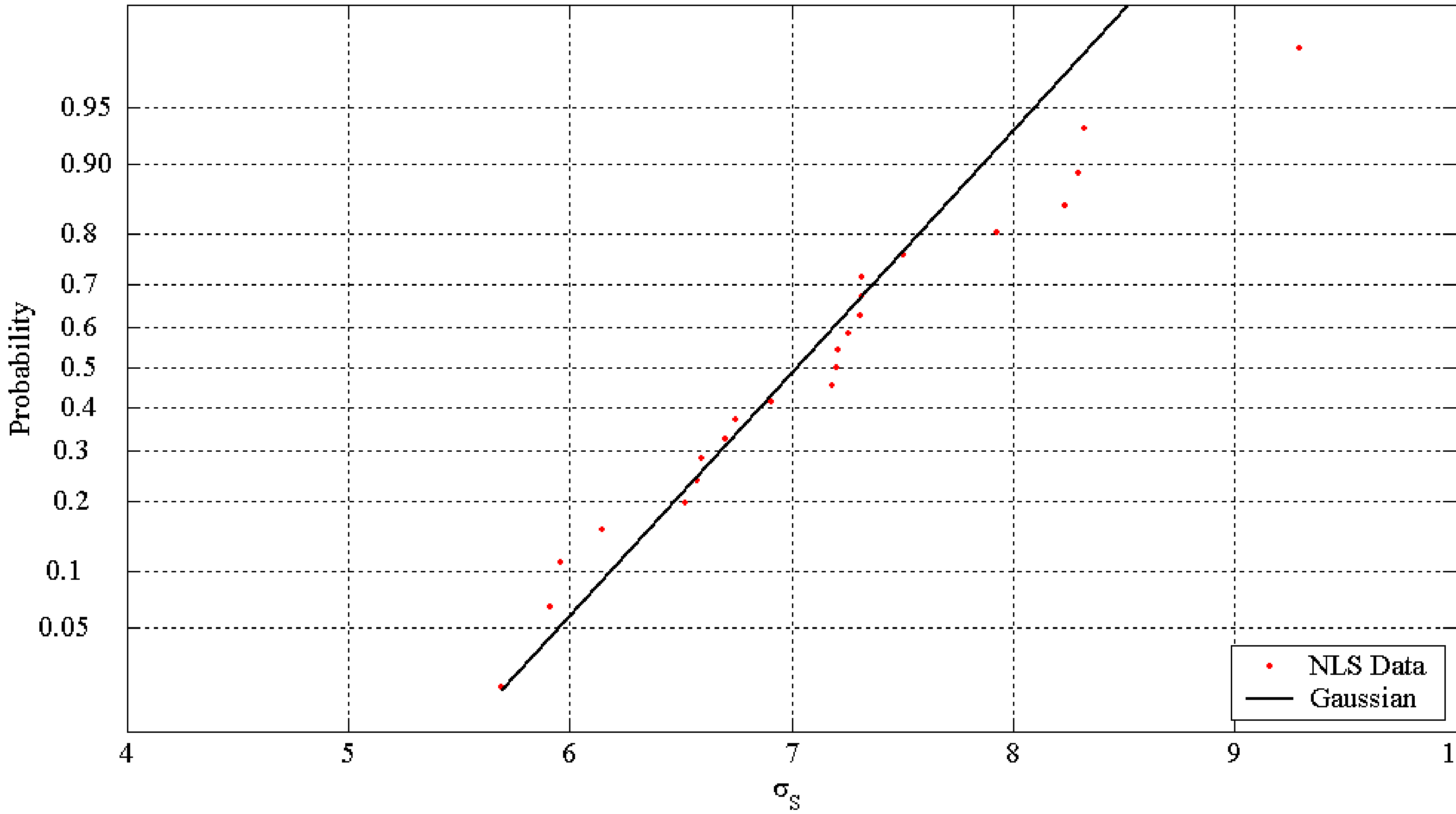
The Relative MIP Model – NLS



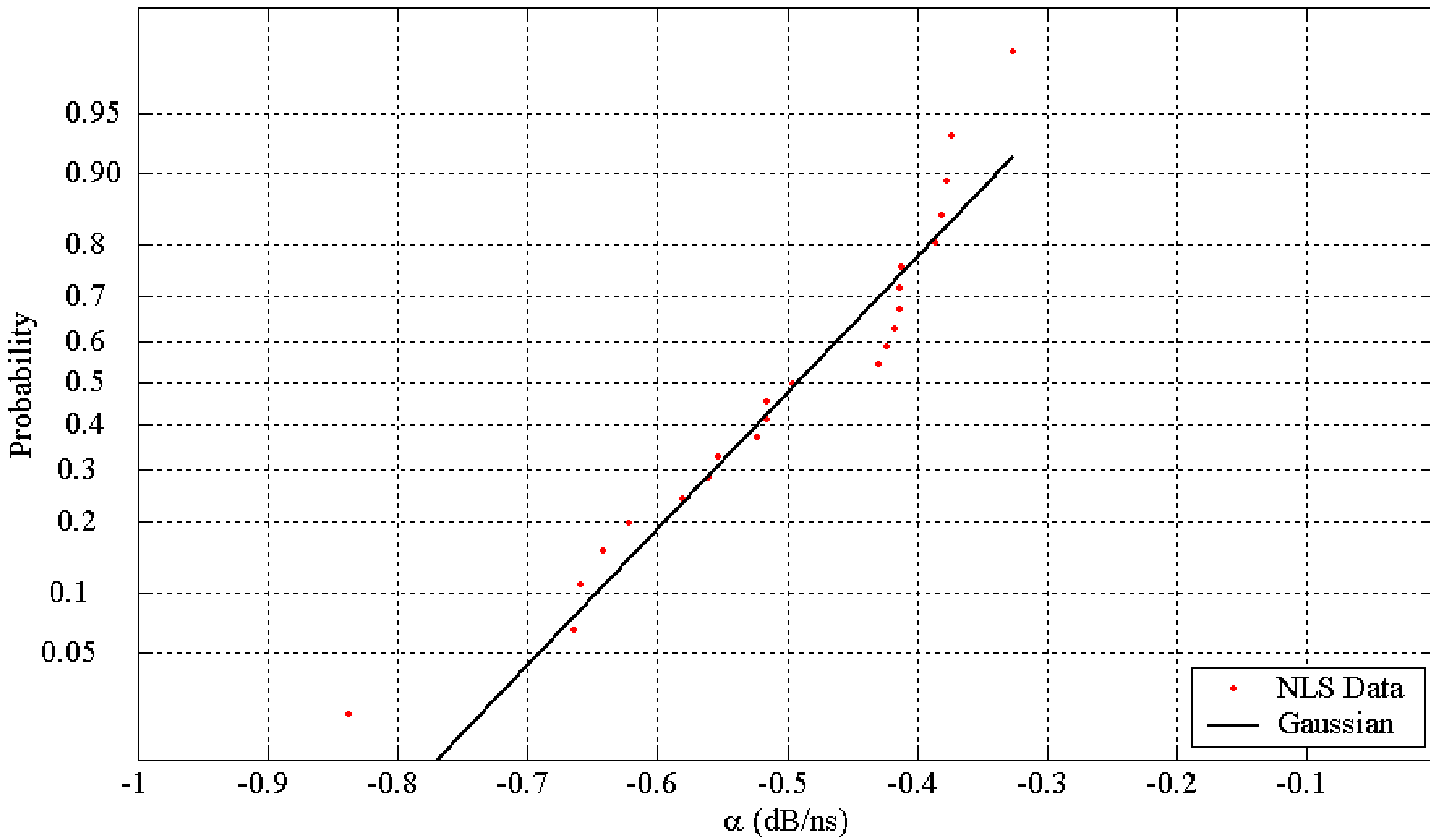
Distribution of *S* Over All Homes



Distribution of σ_S Over All Homes



Distribution of α



The Relative MIP Model - NLS

Introducing 3 RVs:

$$\alpha = \mu_\alpha + n_1\sigma_\alpha, \quad S = \mu_s + n_2\sigma_s \text{ and } \sigma_s = \mu_{\sigma_s} + n_3\sigma_{\sigma_s}$$

$$\left.\overline{P_{rel}(\tau)}\right|_{\text{dB}} = \alpha\tau + S$$

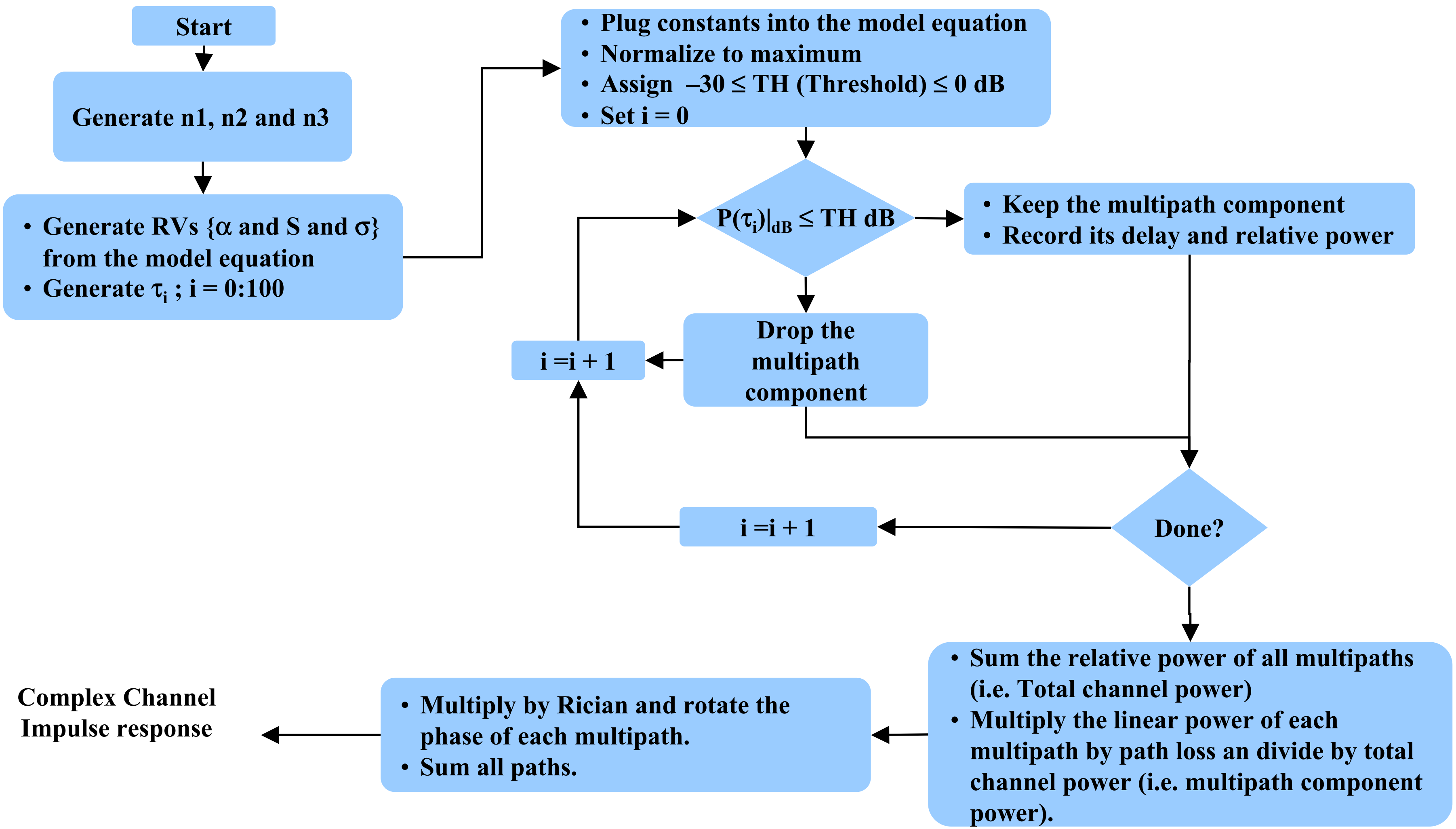
$$= (\mu_\alpha + n_1\sigma_\alpha)\tau + (\mu_s + n_2\sigma_s) = (\mu_\alpha + n_1\sigma_\alpha)\tau + \left[\mu_s + n_2\left(\mu_{\sigma_s} + n_3\sigma_{\sigma_s}\right)\right]$$

$$= \left[\mu_\alpha\tau + \mu_s\right] + \left[n_1\sigma_\alpha\tau + n_2\mu_{\sigma_s} + n_2 n_3\sigma_{\sigma_s}\right] \quad d_o \le d \le 15 \text{ m}$$

$$= [\textbf{Median delay profile}] + [\textbf{Random variation about median delay profile}]$$

- n_1, n_2 and n_3 are iid zero-mean, unit-variance Gaussian variates.
- n_2 is a fast-varying RV and varies from one delay to another. n_1 and n_3 are slow varying RVs and vary from one home to another.
- 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.

Flowchart for the Channel Simulator

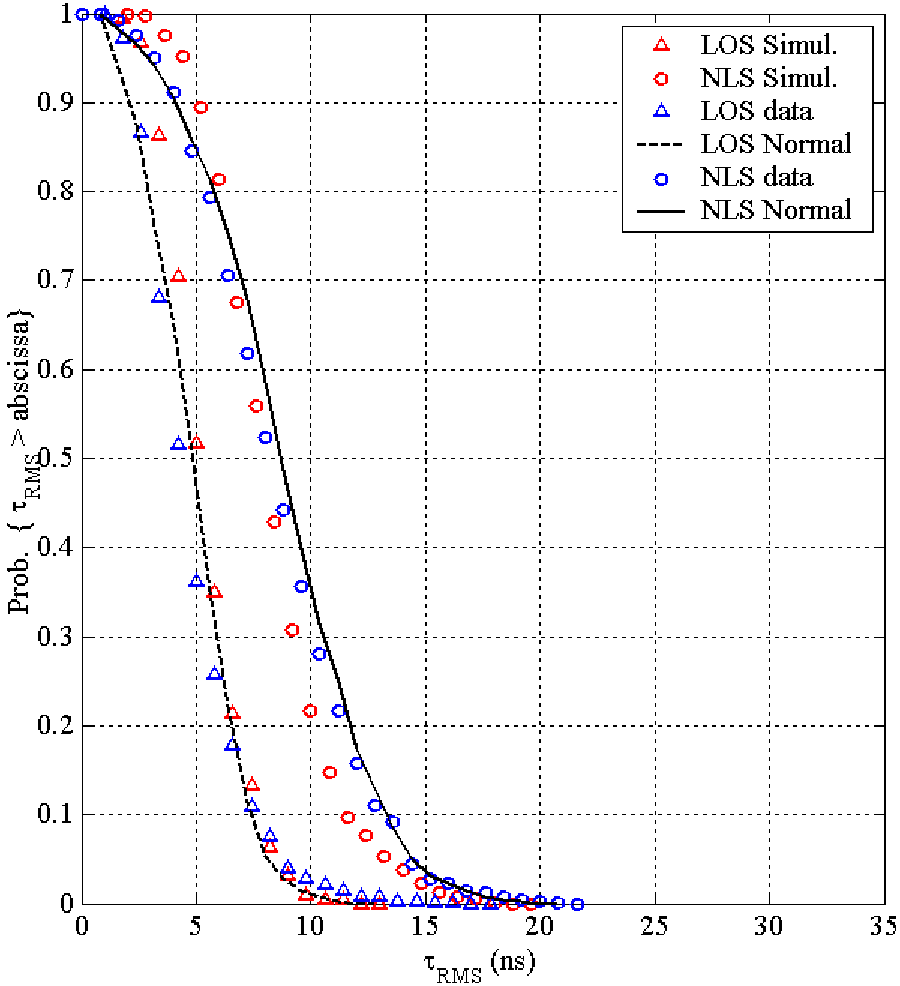


Live Channel Simulation Show

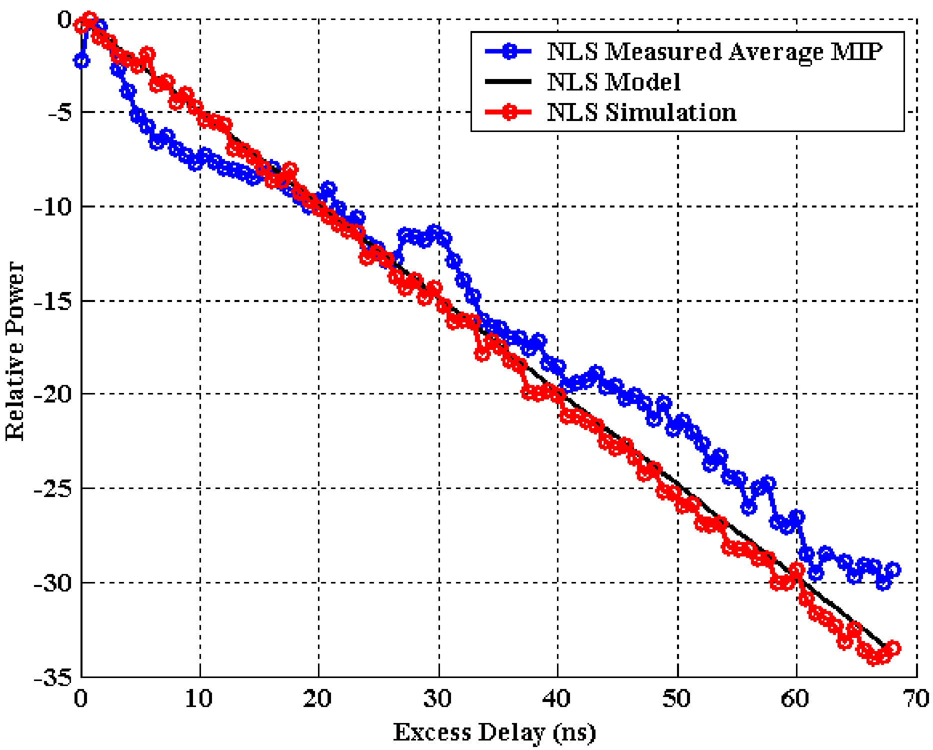
Channel Simulator Results

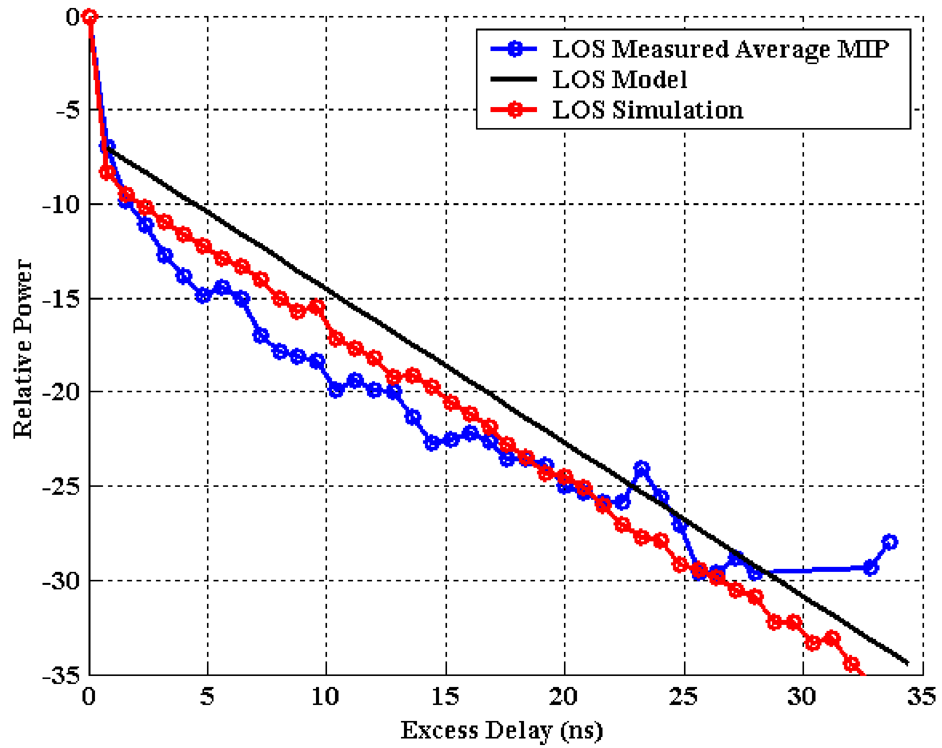
- We simulated the model to compare its statistical behavior with that of measured data. Specifically, we looked at:
  - CDF of RMS delay spread: Simulated vs. measured.
  - Average simulated profile vs. measured.
  - Standard deviation of the model error: Simulated vs. measured.

CDF of RMS Delay Spread: Simulated vs. Measured

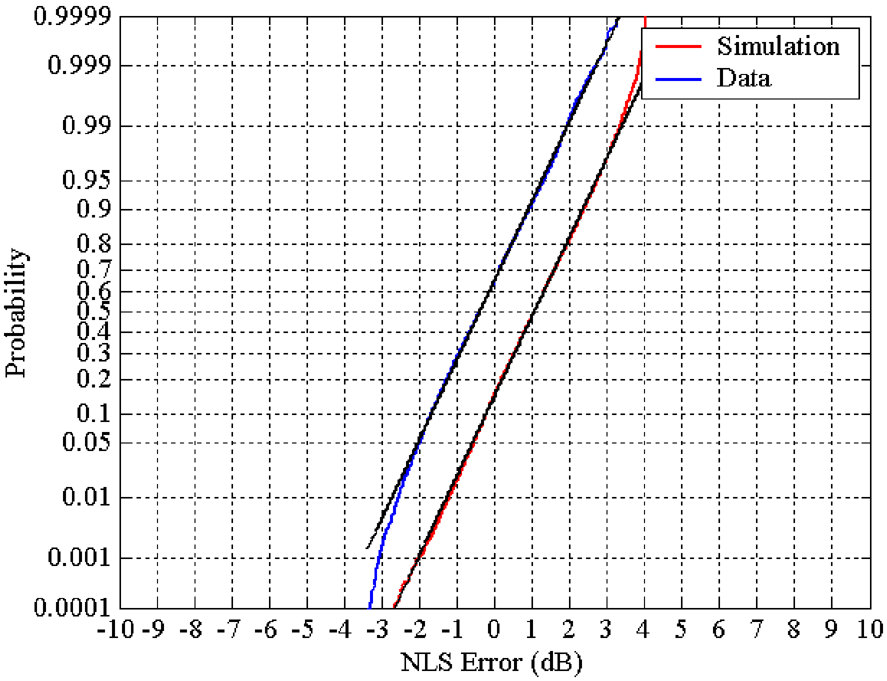


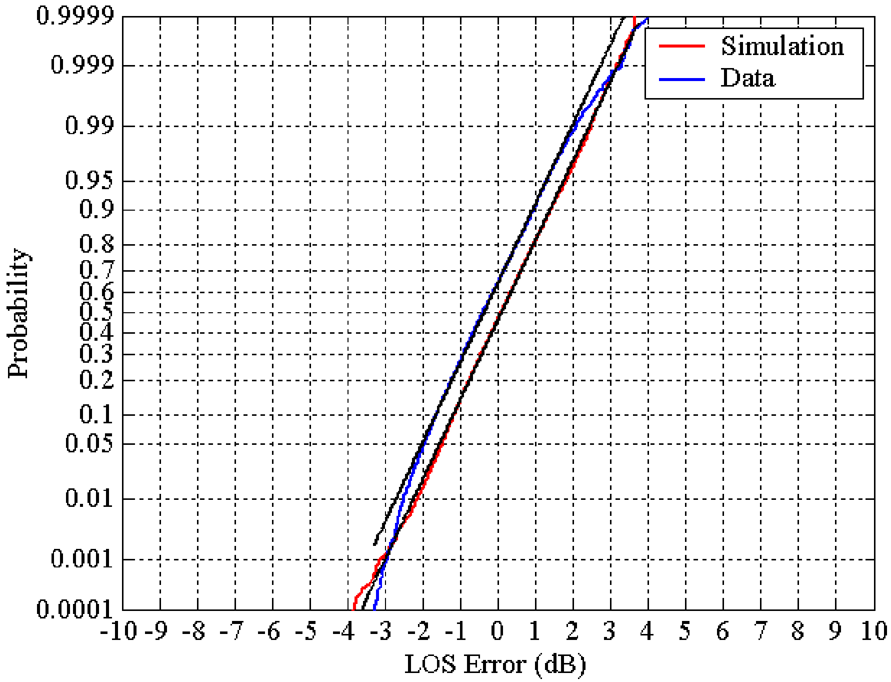
Average MIP: Simulated vs. Measured



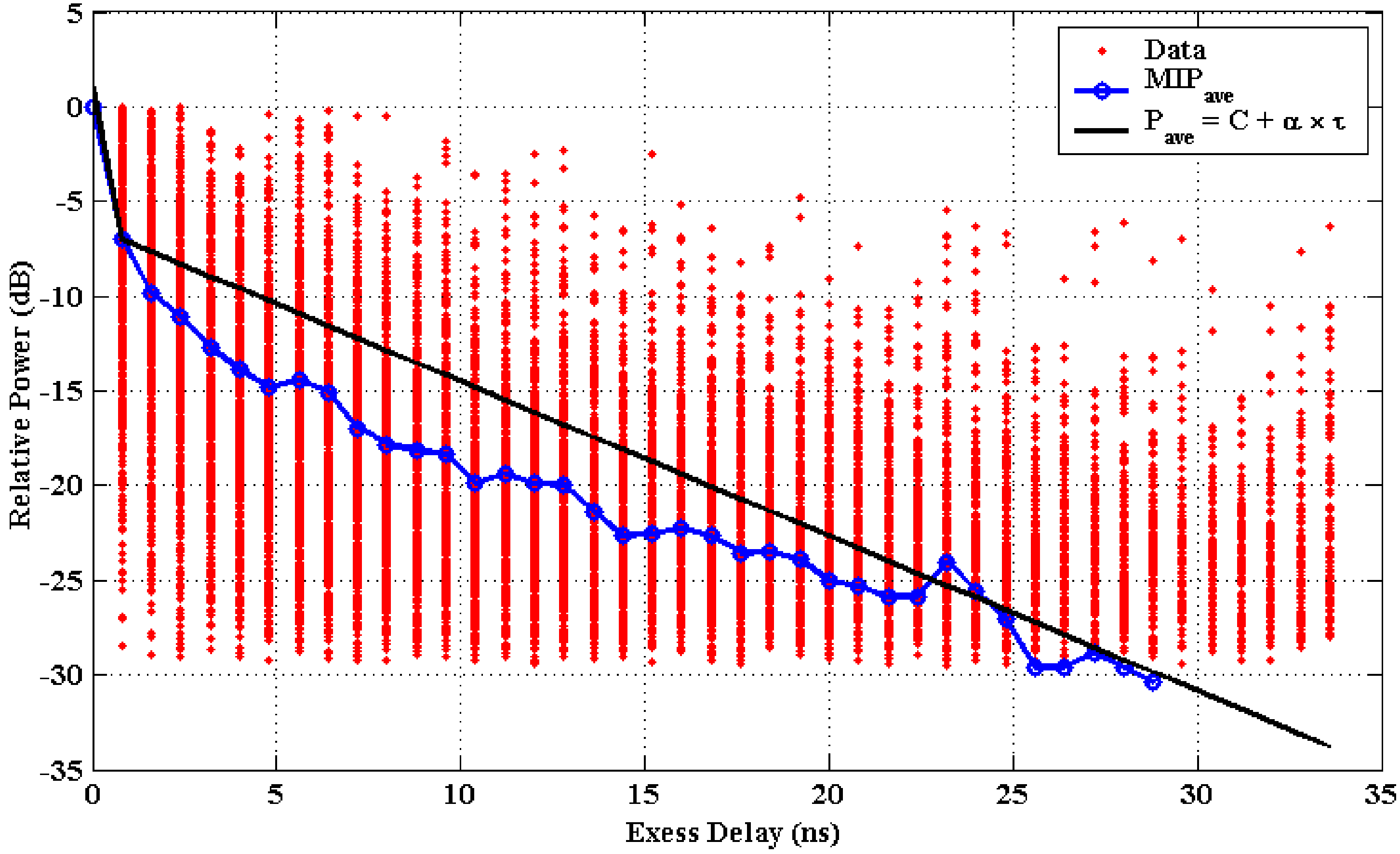


Model Error: Simulated vs. Measured

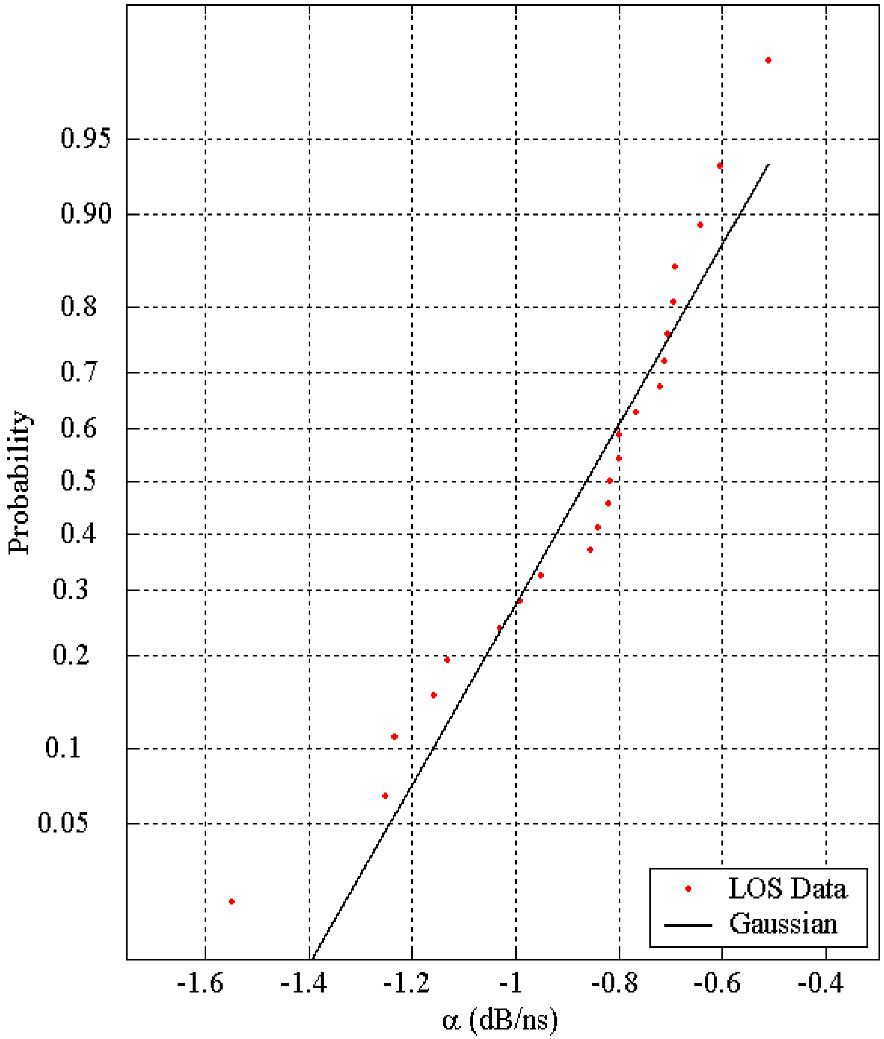


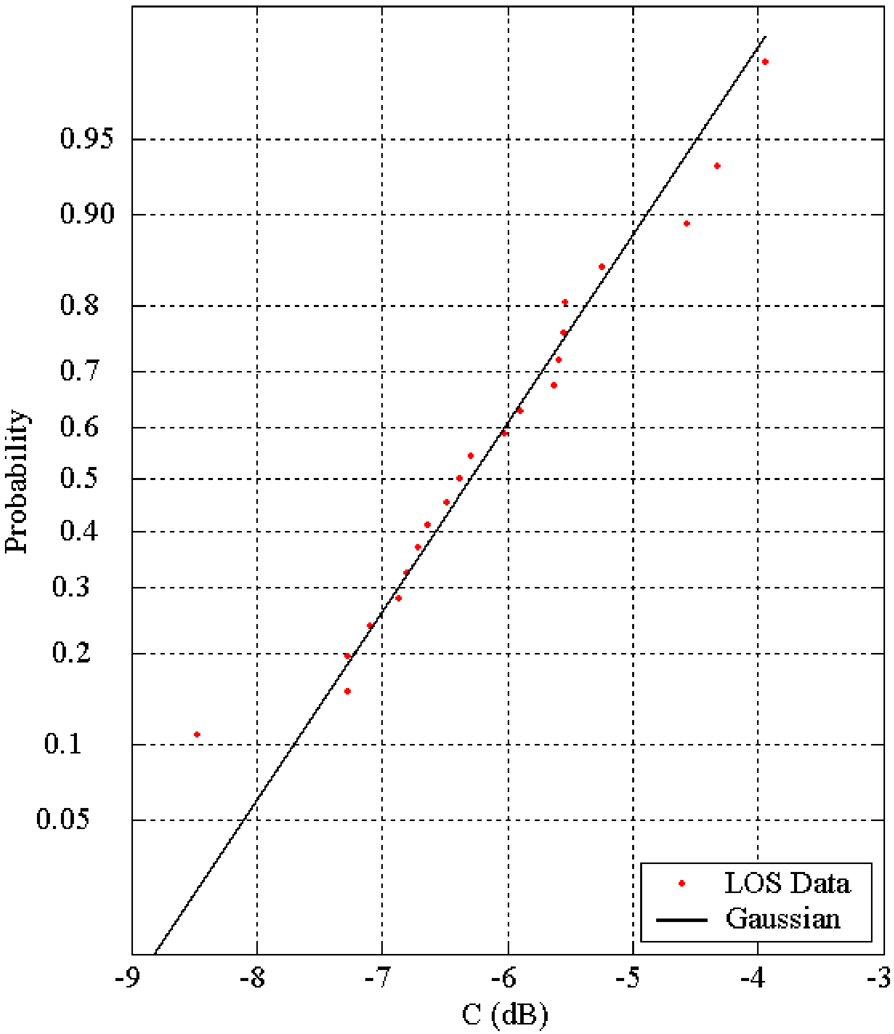


The Relative MIP Model – LOS

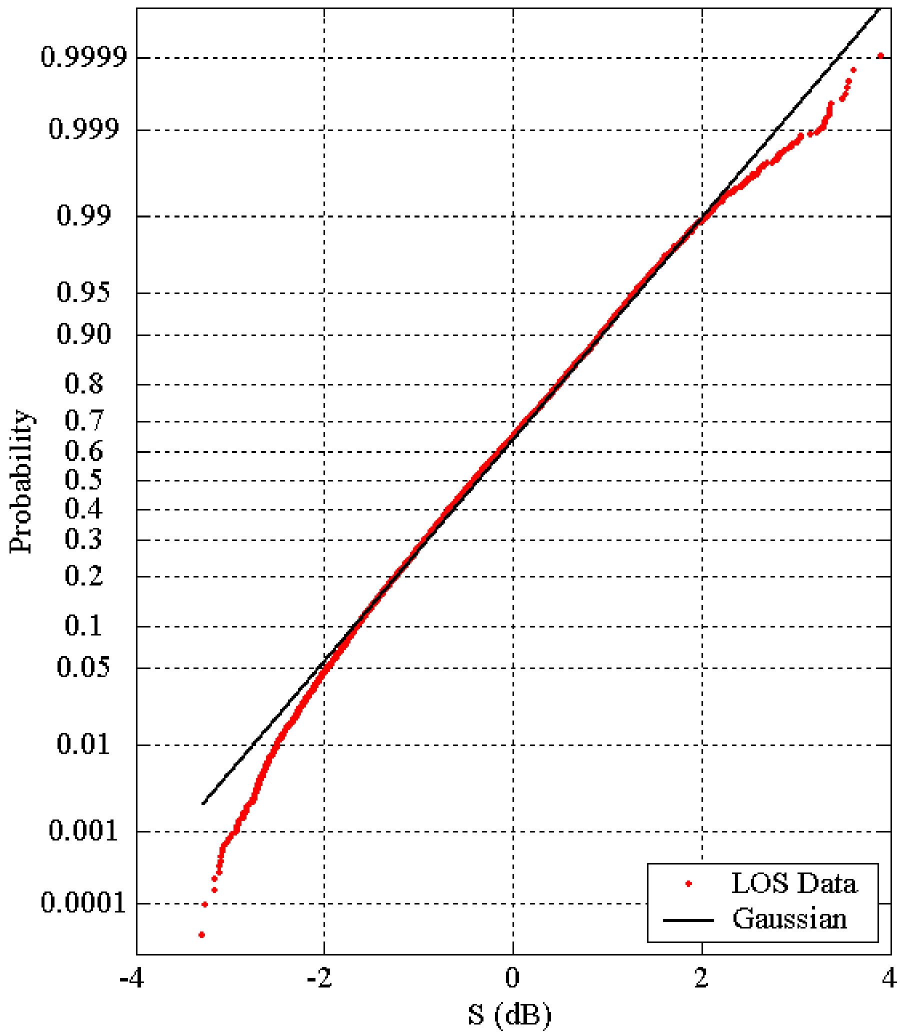


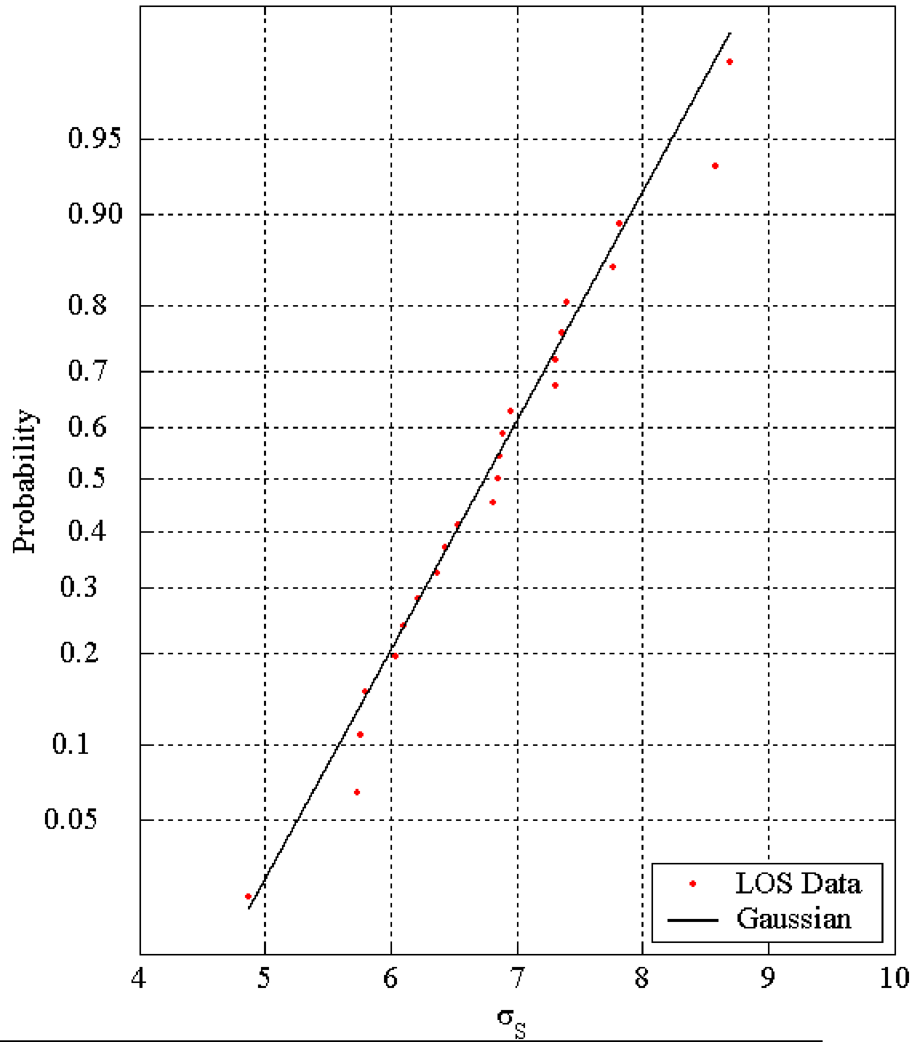
Distribution of *C* and α





Distribution of *S* and σ_S





The Relative MIP Model- LOS

Introducing four RVs:

$\alpha = \mu_\alpha + n_1\sigma_\alpha,\ C = \mu_c + n_2\sigma_c,\ S = \mu_s + n_3\sigma_s,$ and $\sigma_s = \mu_\sigma + n_4\sigma_\sigma$

$$\left.\overline{P_{rel}(\tau)}\right|_{\mathrm{dB}} = (C + \alpha\tau + S)u(\tau - 0.8ns)$$

$$= \left[(\mu_c + n_2\sigma_c) + (\mu_\alpha + n_1\sigma_\alpha)\tau + (\mu_s + n_3(\mu_\sigma + n_4\sigma_\sigma))\right]u(\tau - 0.8ns)$$

$$= \left[\mu_c + \tau\mu_\alpha + \mu_s\right]u(\tau - 0.8ns)$$

$$+ \left[n_2\sigma_c + n_1\sigma_\alpha\tau + n_3\mu_\sigma + n_3 n_4\sigma_\sigma)\right]u(\tau - 0.8ns) \quad d_o \le d \le 15\ \mathrm{m}\ \&\ \ \tau \ge 0$$

$= [$ **Median delay profile** $]$

$+ [$ **Random variation about median delay profile** $]$

Conclusion

- We reported on the statistics and dependencies of channel parameters such as delay spread, Doppler spectrum and average MIP for UWB indoor channels.
- We presented a simple statistical multipath that is easily integrated with the path loss model.
- The model is based on over 300,000 UWB frequency responses at 712 locations in 23 homes.
- The model statistically regenerates the properties of the indoor channel with small error.
- The model can be used for simulation and performance evaluation of the UWB systems and can be upgraded with further measurements.