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

Submission Title: [Indoor UWB Channel Measurements from 2 GHz to 8 GHz]
Date Submitted: [24 August, 2004]

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Re: [IEEE 802.15.4a Channel Modeling Subcommittee Call for Contributions]

Abstract: [This presentation describes UWB channel measurements from 2 to 8 GHz, conducted in two office buildings at ETH Zurich, Switzerland. Measurements were taken for LOS, OLOS and NLOS settings in a corridor and a large entrance lobby, with transmitter-receiver separations ranging from 8 m to 28 m]

Purpose: [To provide additional data for the proposed generic 802.15.4a channel model and discuss some of the modeling aspects used in the generic model]

Indoor UWB Channel Measurements from 2 GHz to 8 GHz

Ulrich Schuster and Helmut Bölcskei,

Swiss Federal Institute of Technology (ETH), Zurich

August 24, 2004

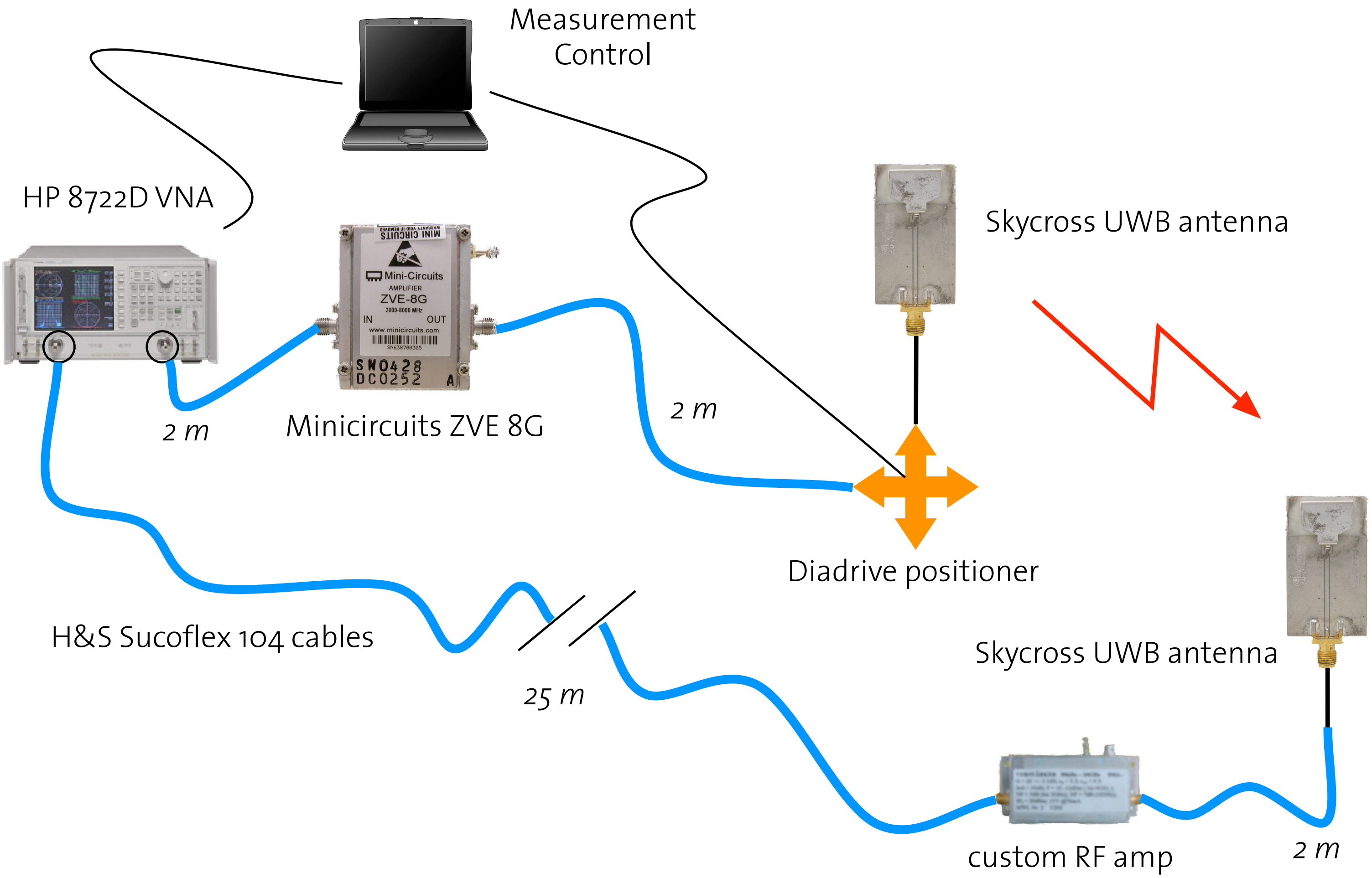
Objectives

Main goal: establish and verify UWB channel models suitable for **theoretical analysis**, concerning

- Tap statistics
- Stochastic degrees of freedom
- Uncorrelated scattering assumption

Genuine focus was **not** IEEE 802.15.4a channel modeling work, hence not all 802.15.4a channel model parameters could be extracted.

Measurement Setup — Schematic



ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Measurement Setup — Details

Measurements were taken in the frequency domain

- HP 8722D vector network analyzer (VNA), 50 MHz – 40 GHz
- Minicircuits ZVE 8G power amplifier, 2GHz – 8 GHz, 30 dB gain
- Skycross SMT-3TO10M UWB antannas (prototype), Omni
- Custom RF amplifier, 20 dB gain up to 10 GHz, NF $<$ 6
- H&S Sucoflex 104 cables
- Custom modified Diadrive 2000 positioning table
- Control via Matlab (Instrument Control & Data Acquisition Toolboxes)

VNA Settings

The VNA was equipped with option 12, “direct sampler access”, for improved dynamic range

- Frequency range 2–8 GHz, divided into two bands
- 1601 points per band, for a total of 3201 points
- 1.875 MHz point spacing
- Max. resolvable delay of 533 ns, equivalent to 160 m path length
- IF bandwidth 300 Hz
- Total sweep time 19 s
- Calibration included all equipment except antennas

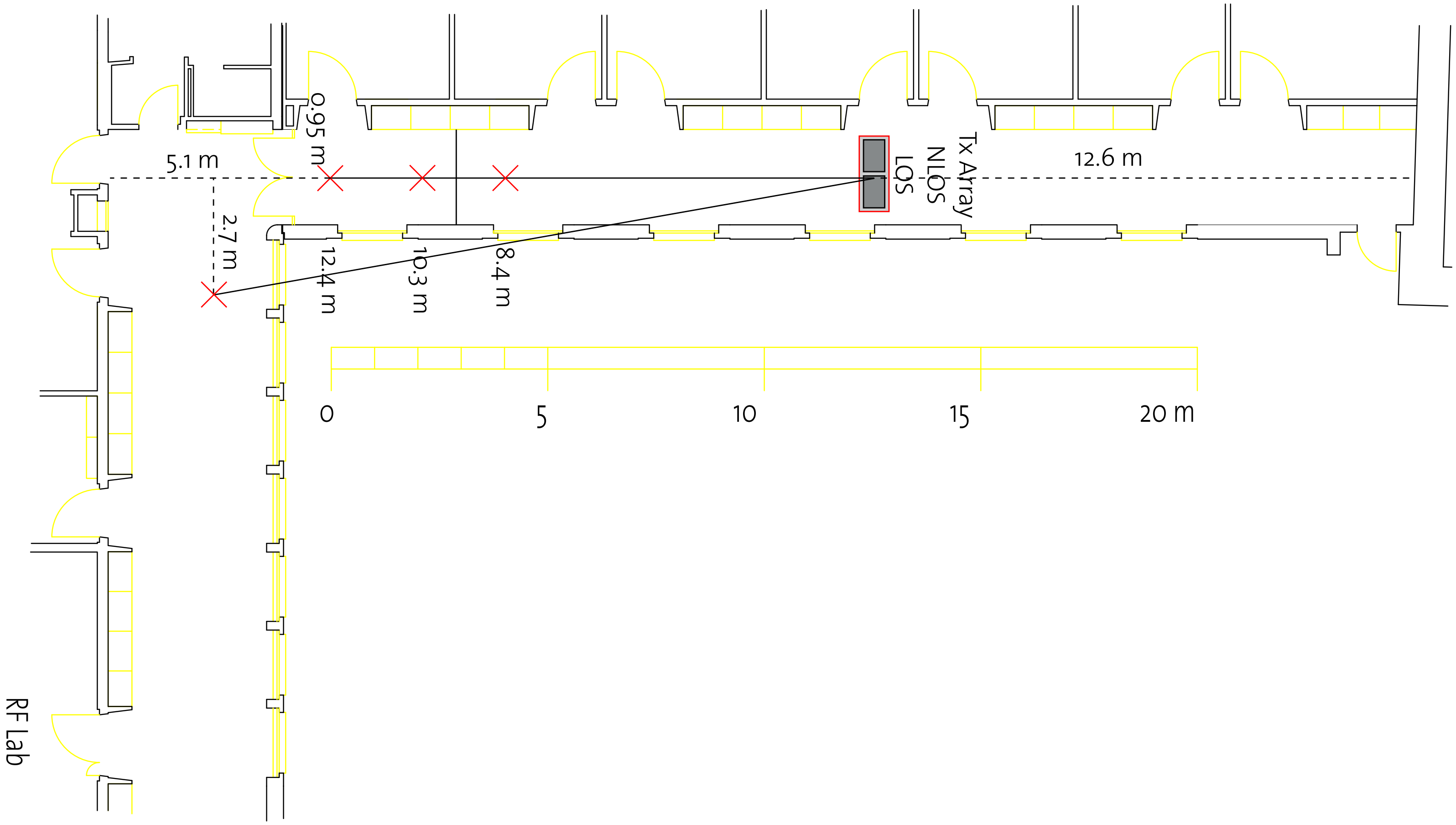
Environments

We measured two different environments at the premises of ETH Zurich, Switzerland, in typical European style office buildings.

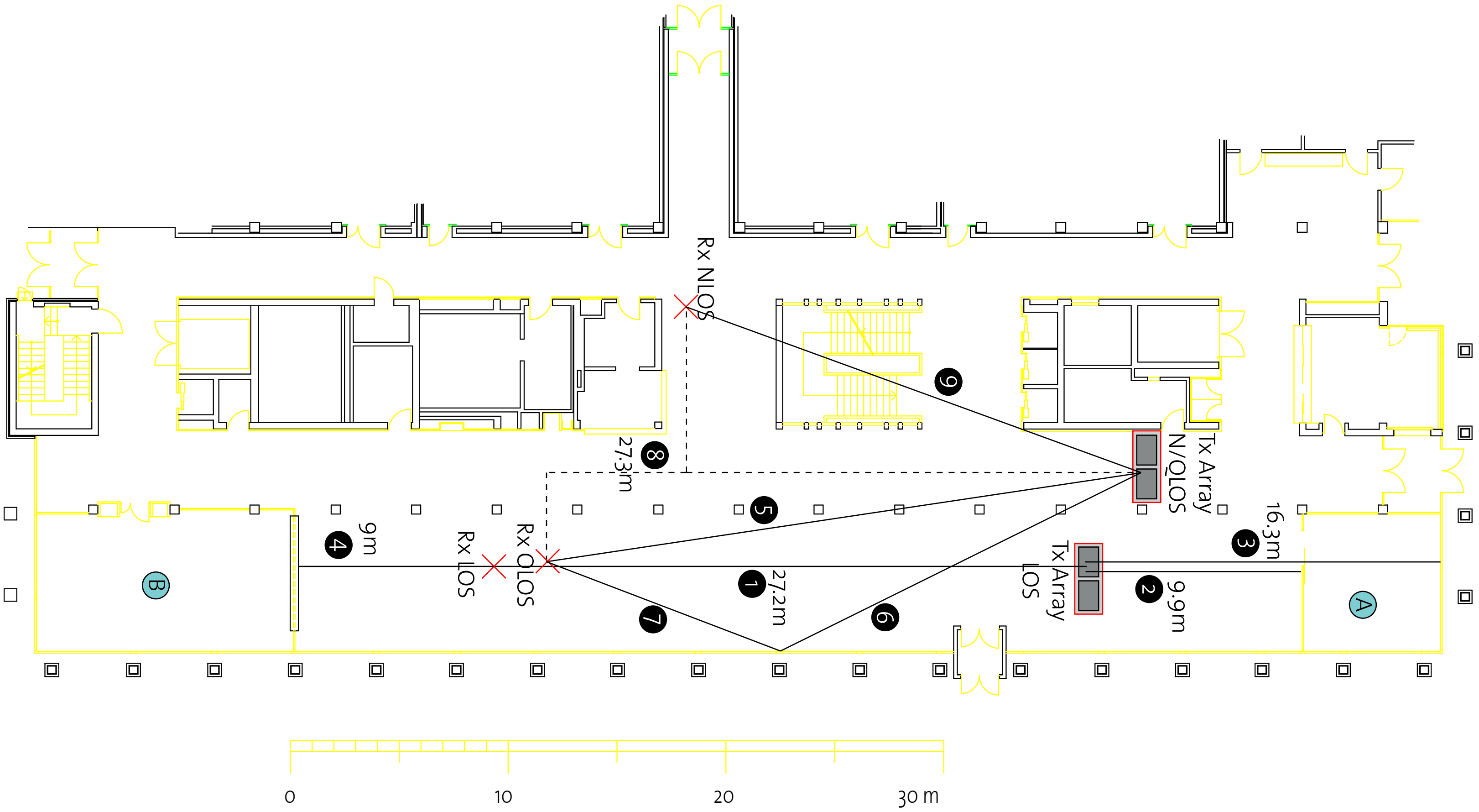
- Corridor, e.g. for sensing applications; brick walls, windows, concrete floor and ceiling
- Entrance lobby, typical public space; tiled floor, large glass windows, concrete walls

All measurements were taken **at night on weekends** to ensure a **static channel**.

Corridor Environment



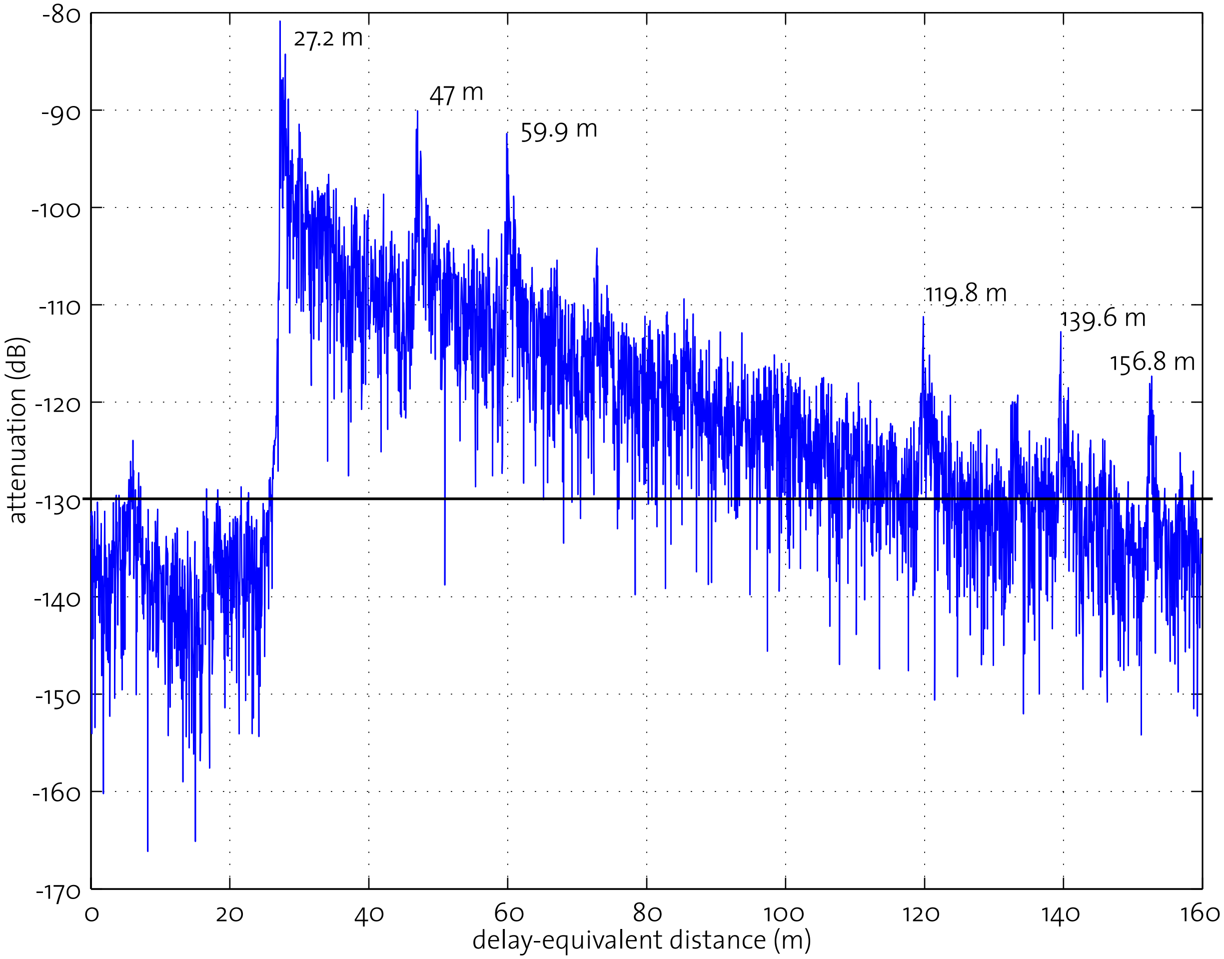
Lobby Environment



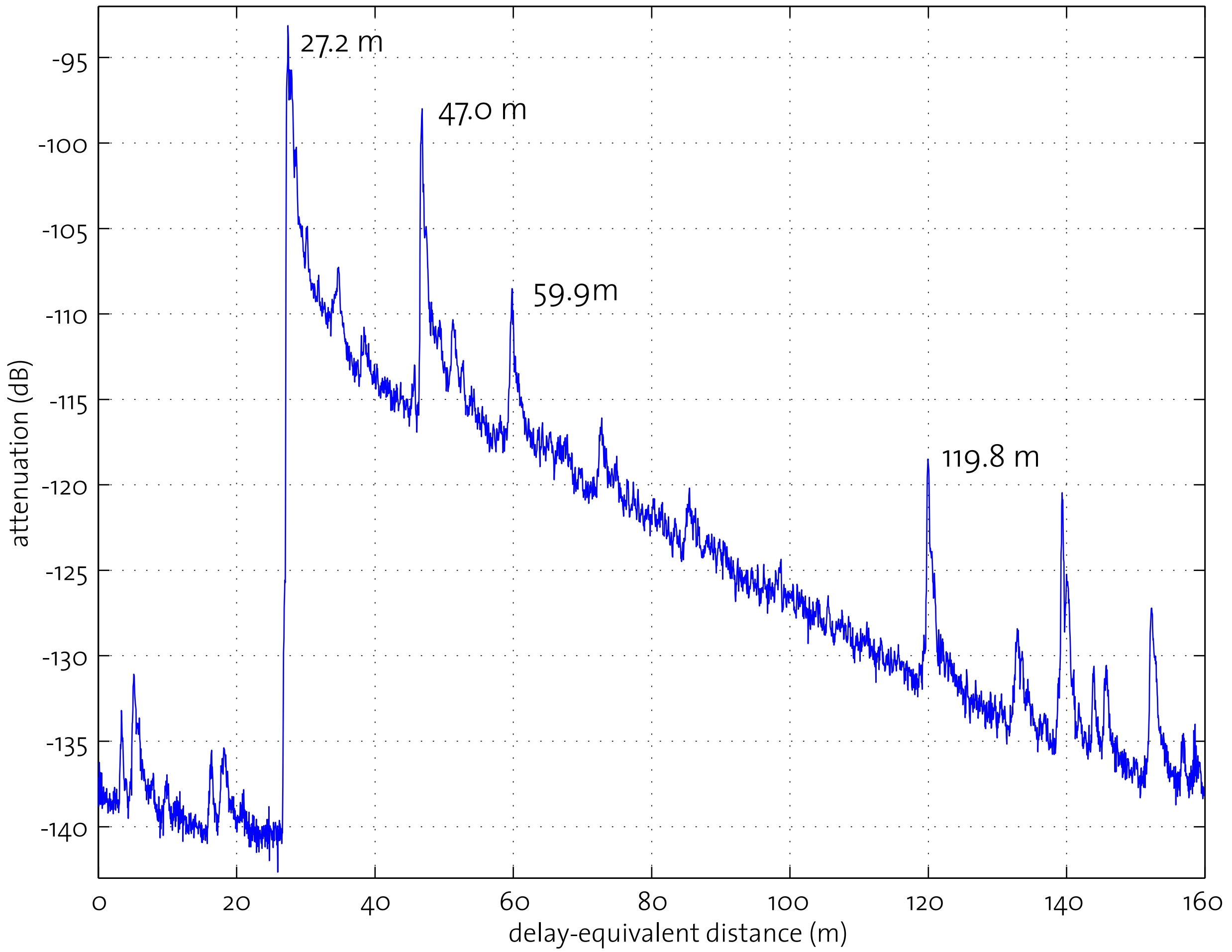
Measurement Methodology

- **Virtual array** approach to obtain enough small scale data
- Array spacing is 7 cm, 5×9 grid
- measured two arrays per Tx–Rx separation for **90 points total**
- recorded one frequency response per array point
- measured several **scenarios** (LOS, OLOS, NLOS), with various Tx–Rx separations in each scenario

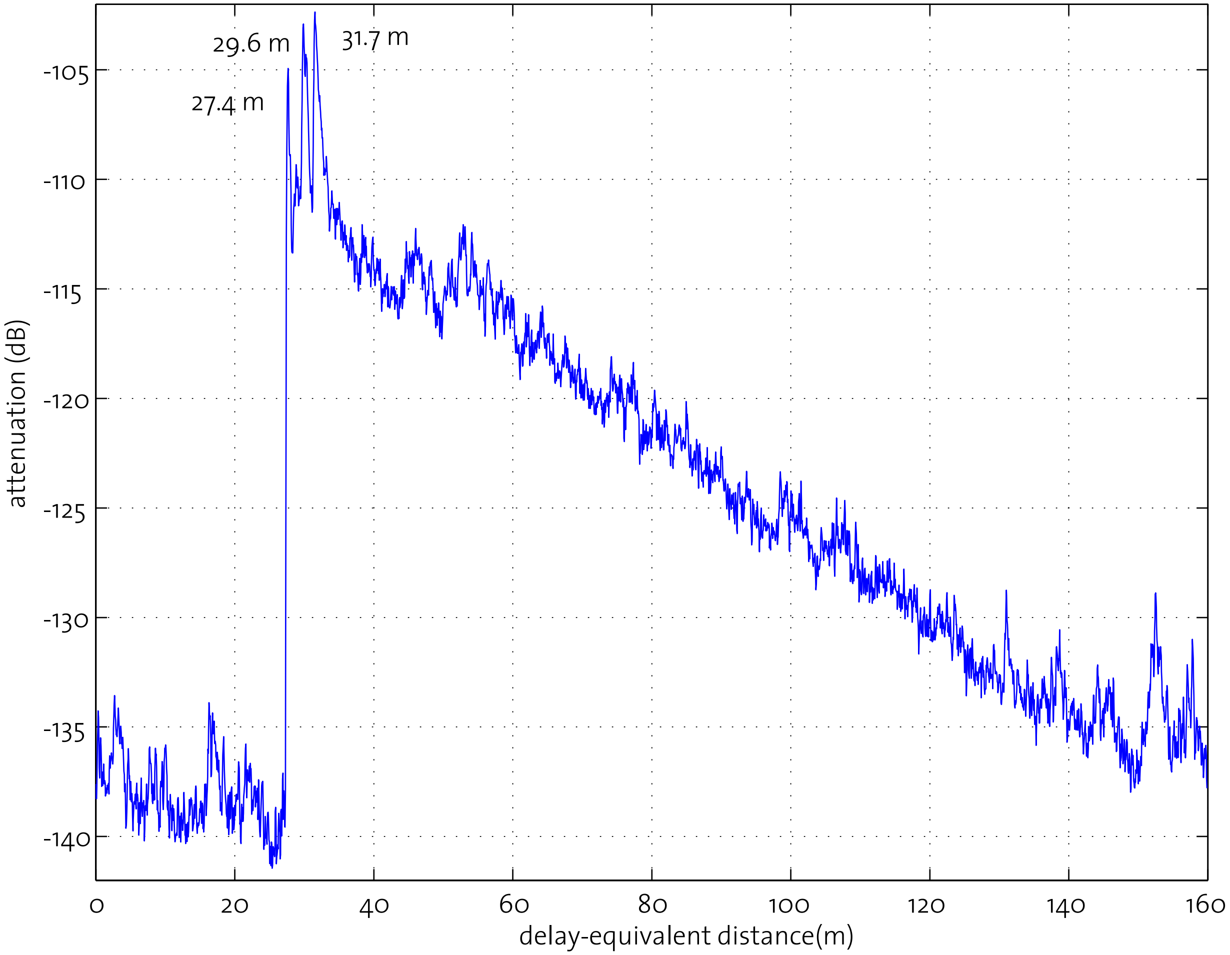
Sample Impulse Response Magnitude — Lobby LOS



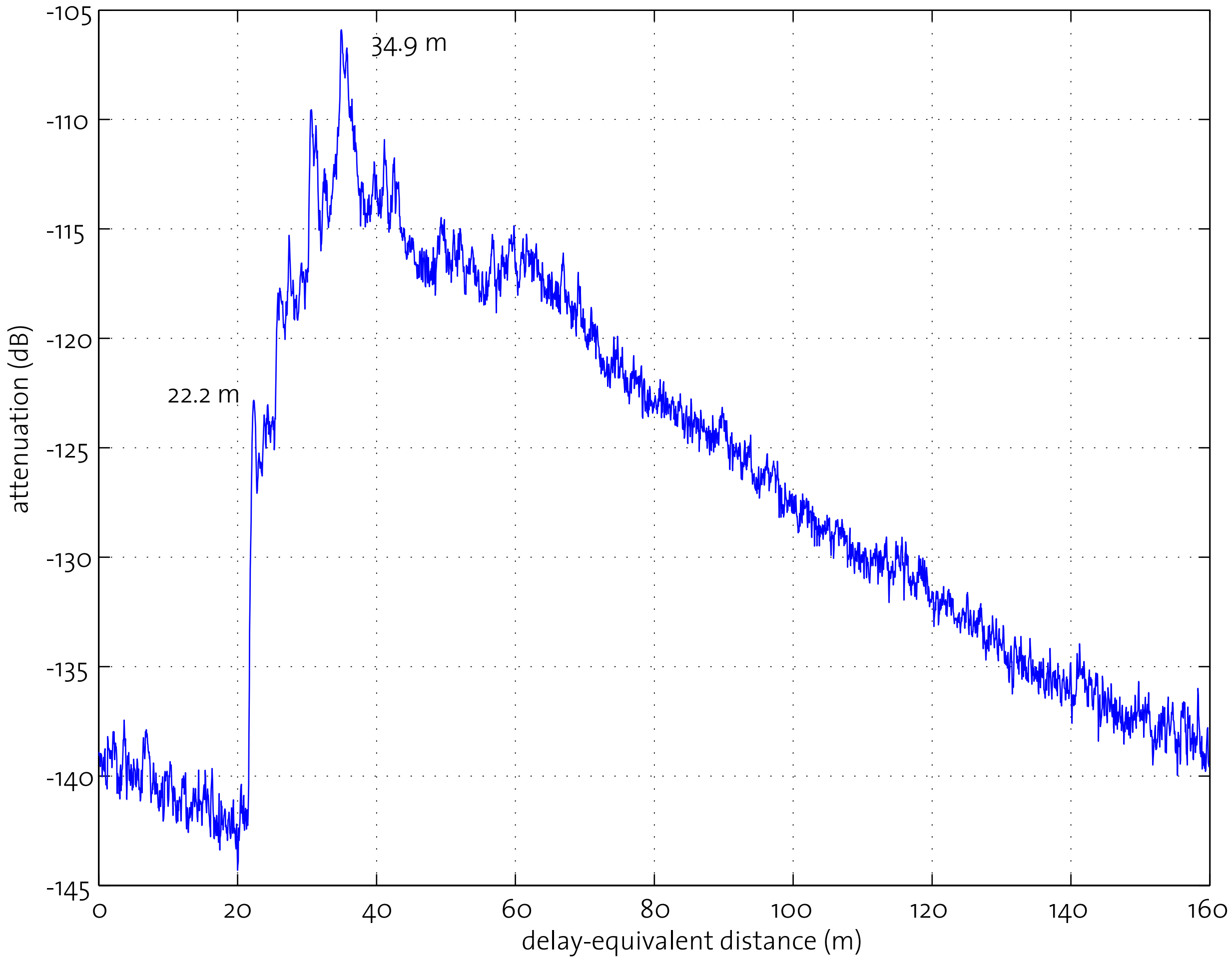
Average Impulse Response Magnitude — Lobby LOS



Average Impulse Response Magnitude — Lobby OLOS



Average Impulse Response Magnitude — Lobby NLOS



Modeling Considerations

The standard wideband fading model

$$h(t,\tau) = \sum_{k=0}^{N(\tau)-1} a_k(t)\delta(\tau - \tau_k(t))e^{j\theta_k(t)}$$

assumes **specular** reflections — there are distinct, frequency independent propagation paths.

Assumption might not hold for UWB Channels!

Instead, we simply consider the discrete time LTI system $h[n]$. There is no notion of resolvable paths; the model is still sufficient for system analysis and design.

Fading Tap Statistics

We use the small scale **spatial** variations of the received amplitude across the virtual array for statistical analysis.

Goal: find the best fitting distribution within a set of candidate models:

- Rayleigh
- Rice
- Nakagami
- Lognormal
- Weibull

This is a **model selection** problem. Hypothesis testing is **not a meaningful approach.**

Model Selection using Akaike's Information Criterion (AIC)

A measure for the difference of distributions is **relative entropy**. AIC is an unbiased estimate of the relative entropy difference between a candidate model and the true distribution, given as

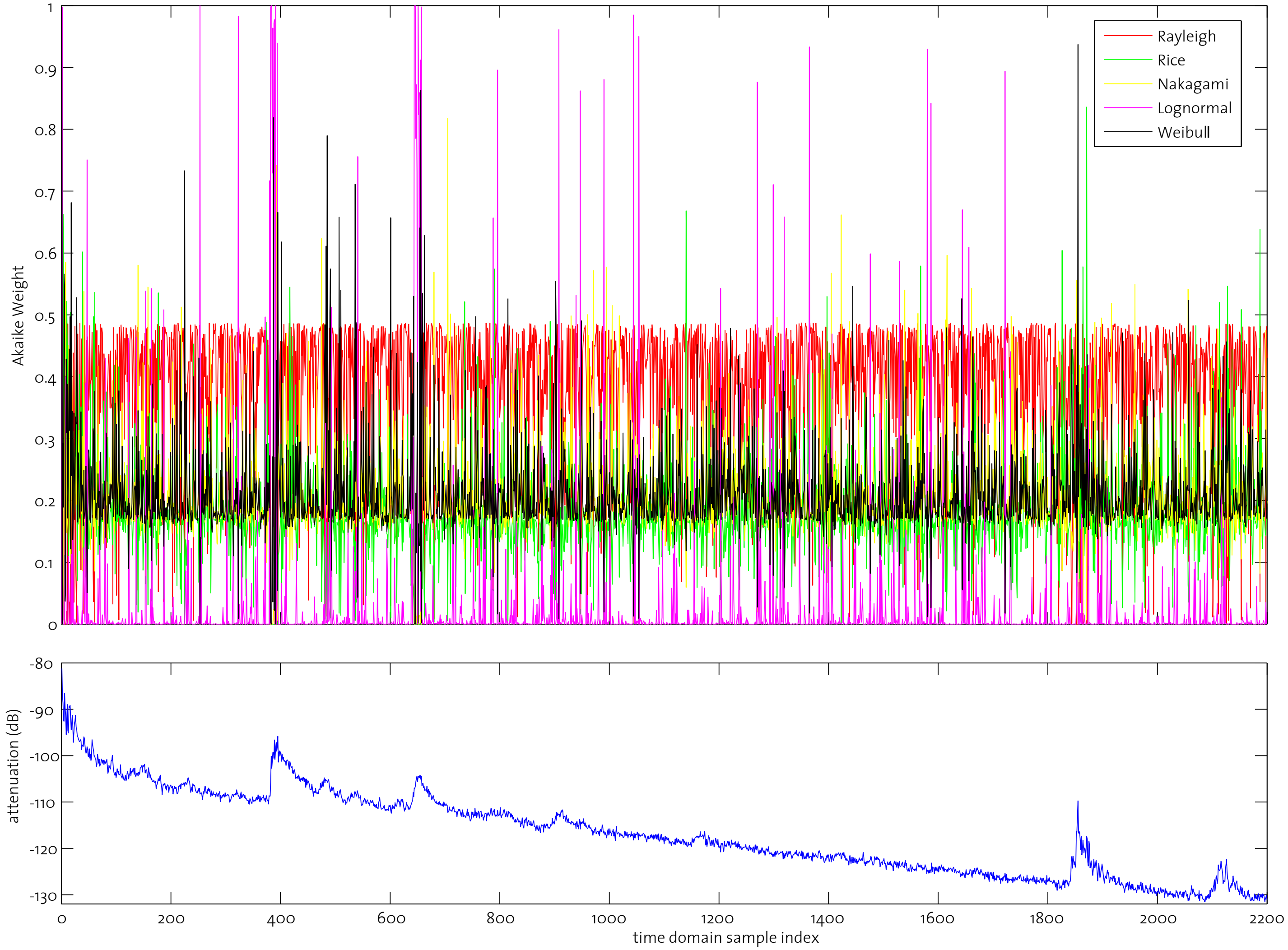
$$-2 \log q_i(\mathbf{y} \,|\, \hat{\boldsymbol{\Theta}}(\mathbf{y})) + 2K$$

with $q_i(\cdot \,|\, \boldsymbol{\Theta})$ the parameterized PDF of candidate model i, i.i.d. data vector $\mathbf{y}$ and ML parameter estimate $\hat{\boldsymbol{\Theta}}(\mathbf{y})$.

From this, it is possible to compute the **probability for each candidate model of providing the best fit**, called **Akaike weight** w_i.

Advantage: no ambiguities due to confidence level selection, test power and binning.

Akaike Weights, Averaged Impulse Response — Lobby LOS



Fading Model Selection

We computed Akaike Weights for all scenarios

- Rayleigh provides on average the best fit
- Rayleigh is not good at the start of a cluster
- LOS component is often Weibull distributed
- Lognormal is almost always the worst model

Conclusion: there is not single true model, but Rayleigh still seems to be an appropriate and convenient choice for UWB, except for the first taps in each cluster.

Small Scale Parameters - Time Dispersion

Mean delay and **delay spread** often used to characterize time dispersiveness of the channel. They are **not** the most general description.

Estimates can be computed as

$$\bar{\tau} = \sum_{l=1}^{L} \tilde{h}[l] l \qquad \text{mean delay}$$

$$s = \sqrt{\sum_{l=1}^{L} (l - \bar{\tau})^2 \tilde{h}[l]} \qquad \text{delay spread}$$

where the $\tilde{h}$ is the magnitude of the power normalized impulse response. Mean and standard deviation can now be computed over all small scale positions on the virtual array.

Mean Delay and Delay Spread Statistics — Lobby LOS

	Mean Delay		Delay Spread	
Distance	$\mu_{\bar{T}}$	$\sigma_{\bar{T}}$	μ_s	σ_s
27 m	27.13 ns	1.74 ns	49.5 ns	2.08 ns
24 m	27.15 ns	2.86 ns	49.23 ns	3.37 ns
21 m	30.99 ns	2.30 ns	53.62 ns	2.25 ns
18 m	29.86 ns	2.11 ns	52.23 ns	1.64 ns
15 m	27.26 ns	1.75 ns	49.20 ns	1.63 ns

Mean Delay and Delay Spread Statistics — Lobby OLOS

	Mean Delay		**Delay Spread**	
Distance	$\mu_{\bar{\tau}}$	$\sigma_{\bar{\tau}}$	μ_s	σ_s
27 m	49.82 ns	7.78 ns	74.08 ns	7.04 ns
24 m	46.86 ns	6.33 ns	71.07 ns	5.91 ns
21 m	45.61 ns	5.70 ns	71.23 ns	4.43 ns

Mean Delay and Delay Spread Statistics — Corridor

LOS Setting

	Mean Delay		Delay Spread	
Distance	$\mu_{\bar{T}}$	$\sigma_{\bar{T}}$	μ_s	σ_s
12.5 m	7.55 ns	0.88 ns	21.08 ns	1.65 ns
10.5 m	10.68 ns	1.69 ns	24.70 ns	2.19 ns
8.5 m	9.93 ns	2.15 ns	23.74 ns	2.86 ns

NLOS Setting

Mean Delay		Delay Spread	
$\mu_{\bar{T}}$	$\sigma_{\bar{T}}$	μ_s	σ_s
24.44 ns	1.16 ns	31.11 ns	1.87 ns

Small Scale Parameters - The Saleh-Valenzuela Model

The proposed 802.15.4a channel model is continuous time and **specular**:

$$h(t) = \sum_{l=0}^{L-1} \sum_{k=0}^{K-1} a_{k,l} \delta(t - T_l - \tau_{k,l,})$$

with L **clusters** and **K** rays per cluster. Ray and cluster arrivals are described by **Poisson processes** with interarrival probabilities

$$\mathbb{P}(T_l \,|\, T_{l-1}) = \Lambda \exp\{-\Lambda(T_l - T_{l-1})\}.$$

Ray and cluster power decay are **exponential**

$$\mathbb{E}\left[|a_{k,l}|^2\right] = \mathbb{E}\left[|a_{0,0}|^2\right] \exp\left\{-\frac{T_l}{\Gamma}\right\} \exp\left\{-\frac{\tau_{k,l}}{\gamma}\right\}.$$

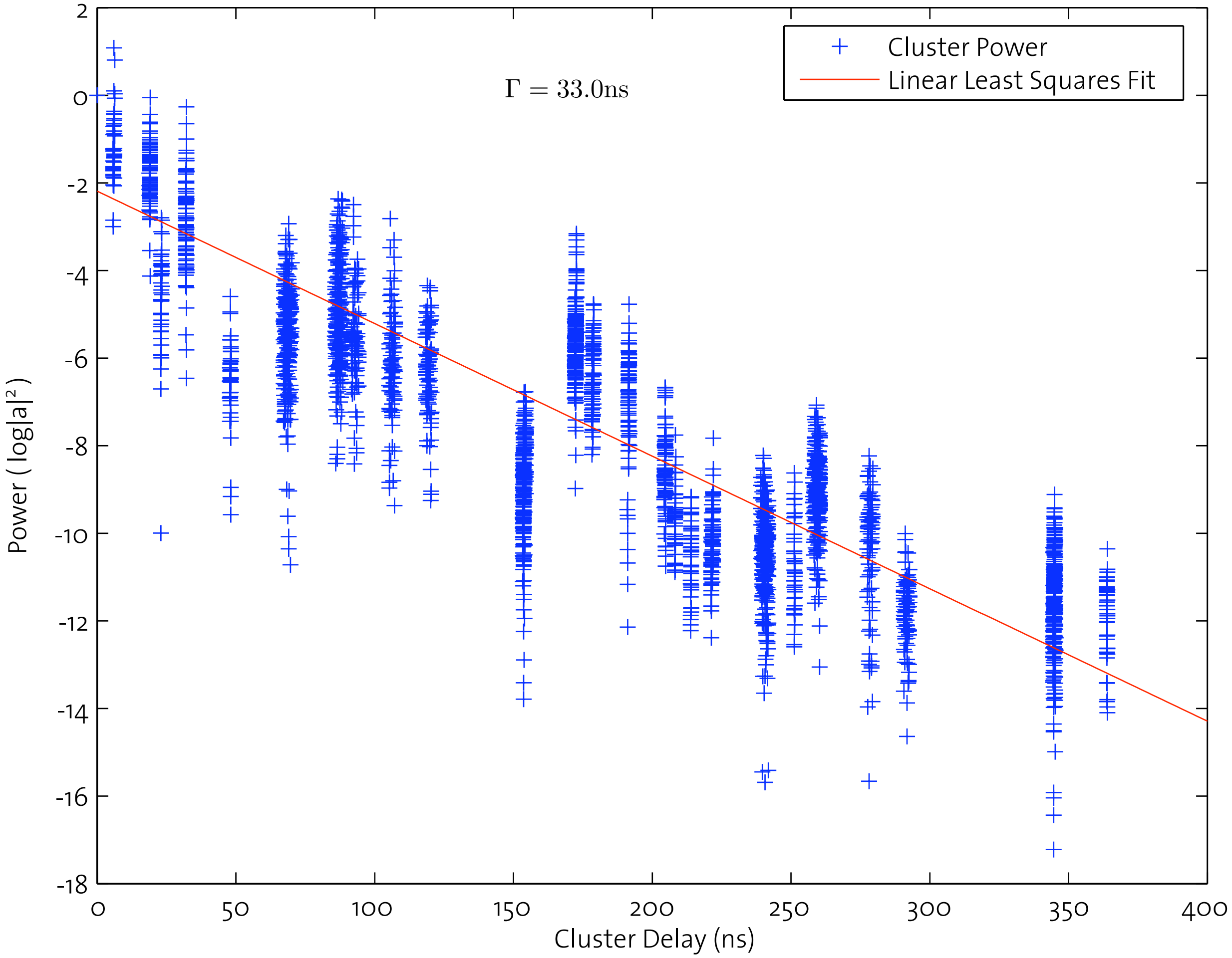
Saleh-Valenzuela Model Parameter Extraction

Our discrete time model does not fit this framework ⇒ cannot extract all parameters since there are no rays. Using the methodology presented by Balakrishnan in doc. 802.15-04-0342-00-004a, we computed

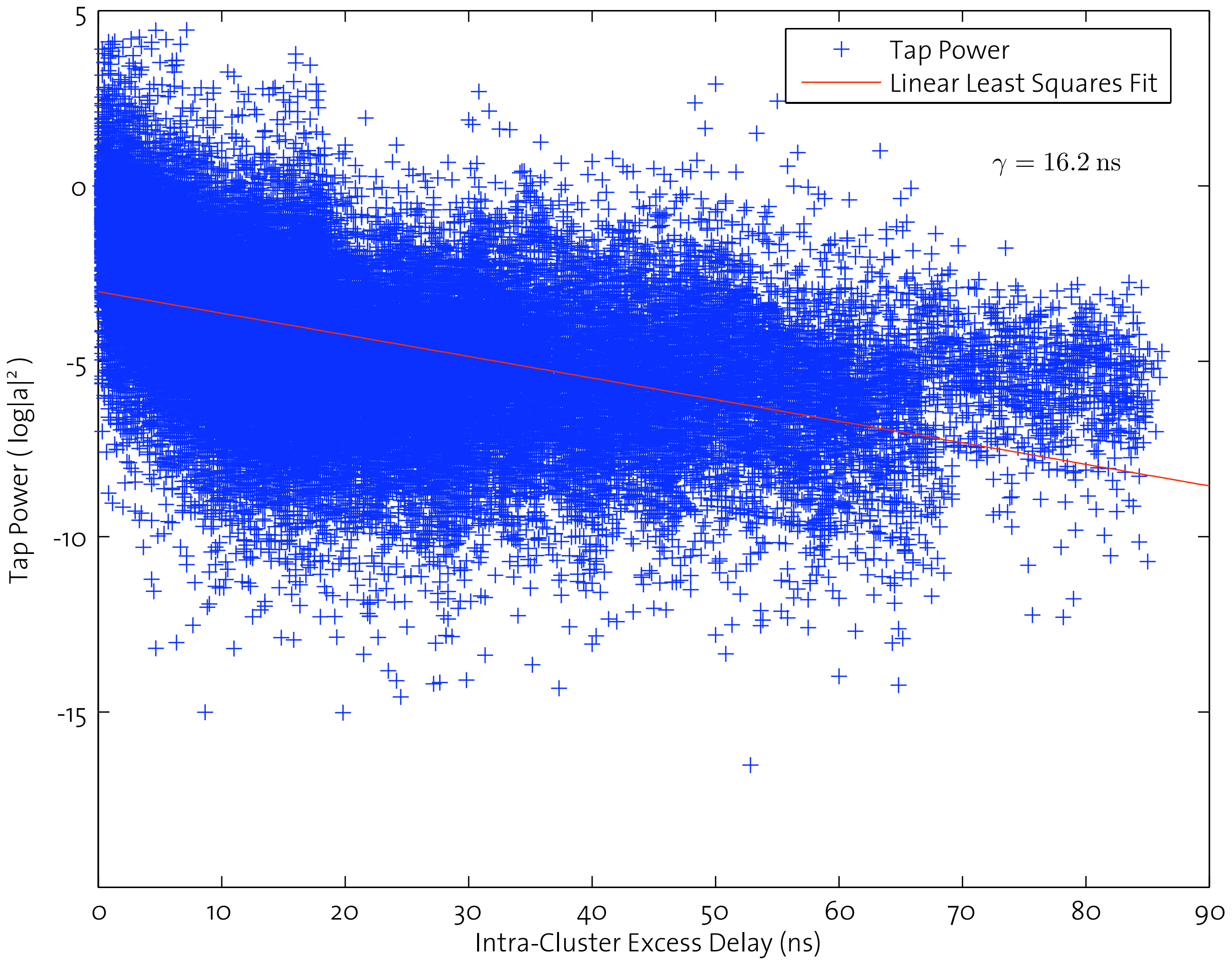
- Cluster decay coefficient Γ
- Inter-cluster decay coefficient γ
- Cluster interarrival time Λ

The model fit is not always satisfactory, as can be seen in the following plots. We only extracted S-V parameters for the LOS scenarios, where clusters were observable.

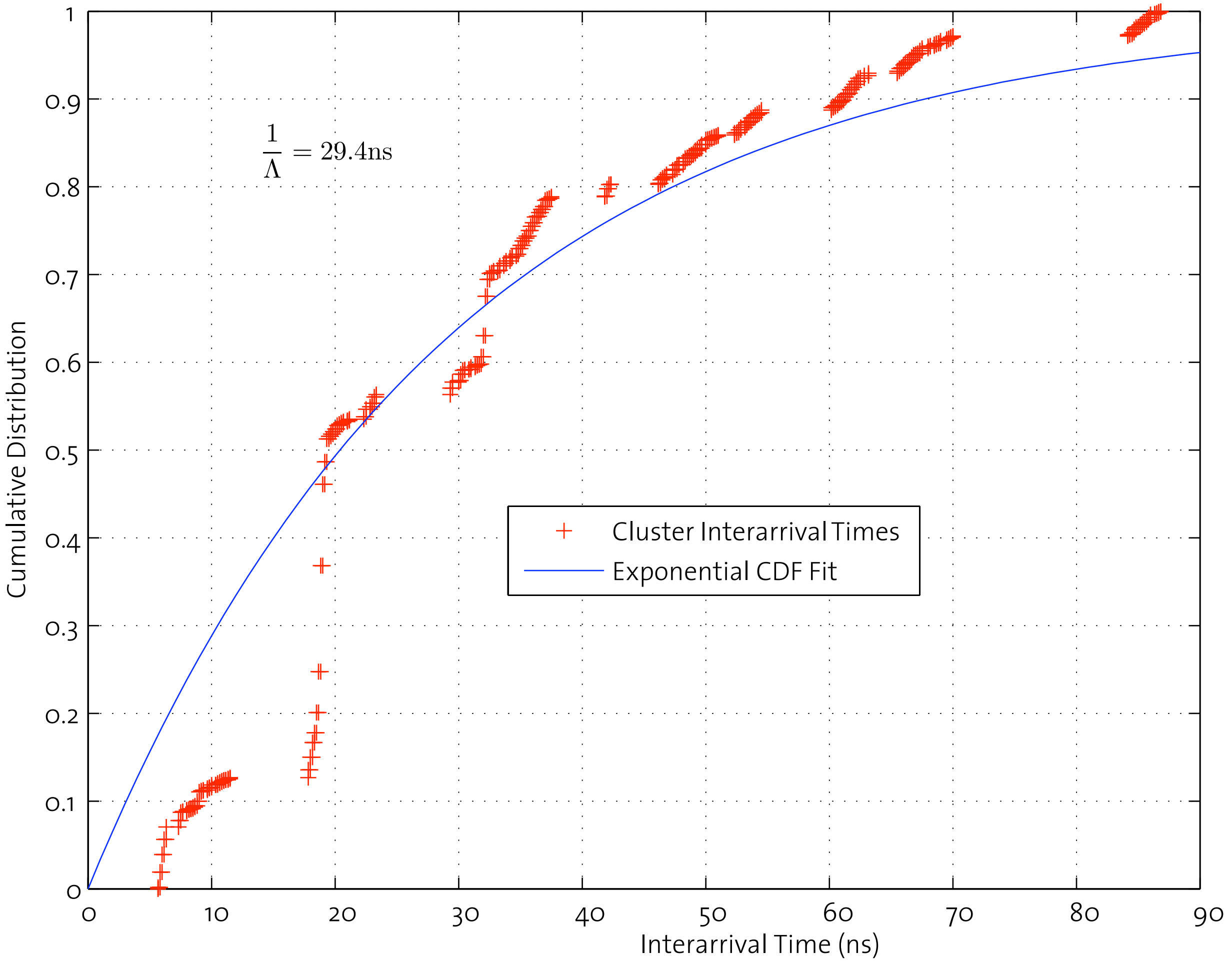
Cluster Decay — Corridor LOS



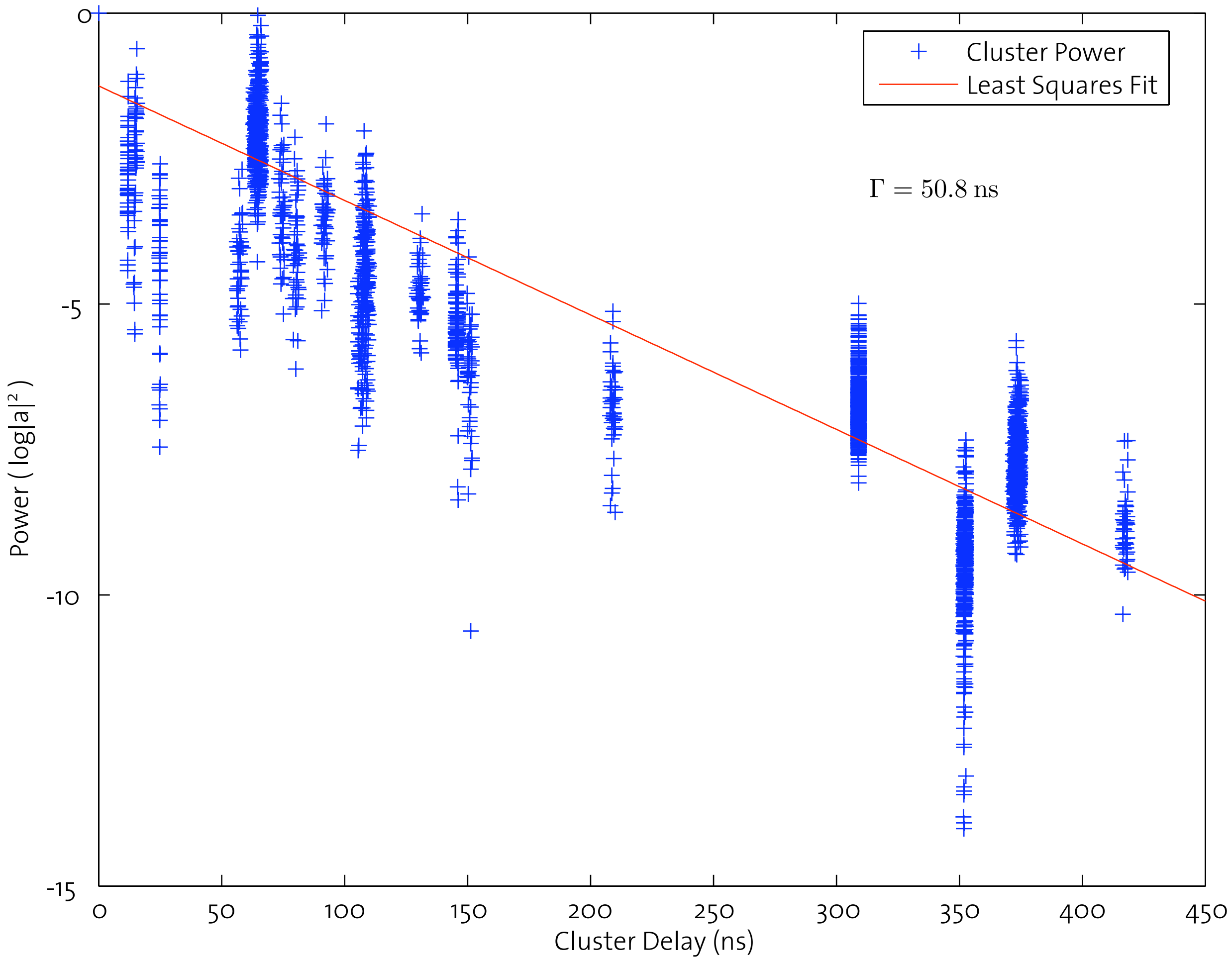
Intra-Cluster Decay — Corridor LOS



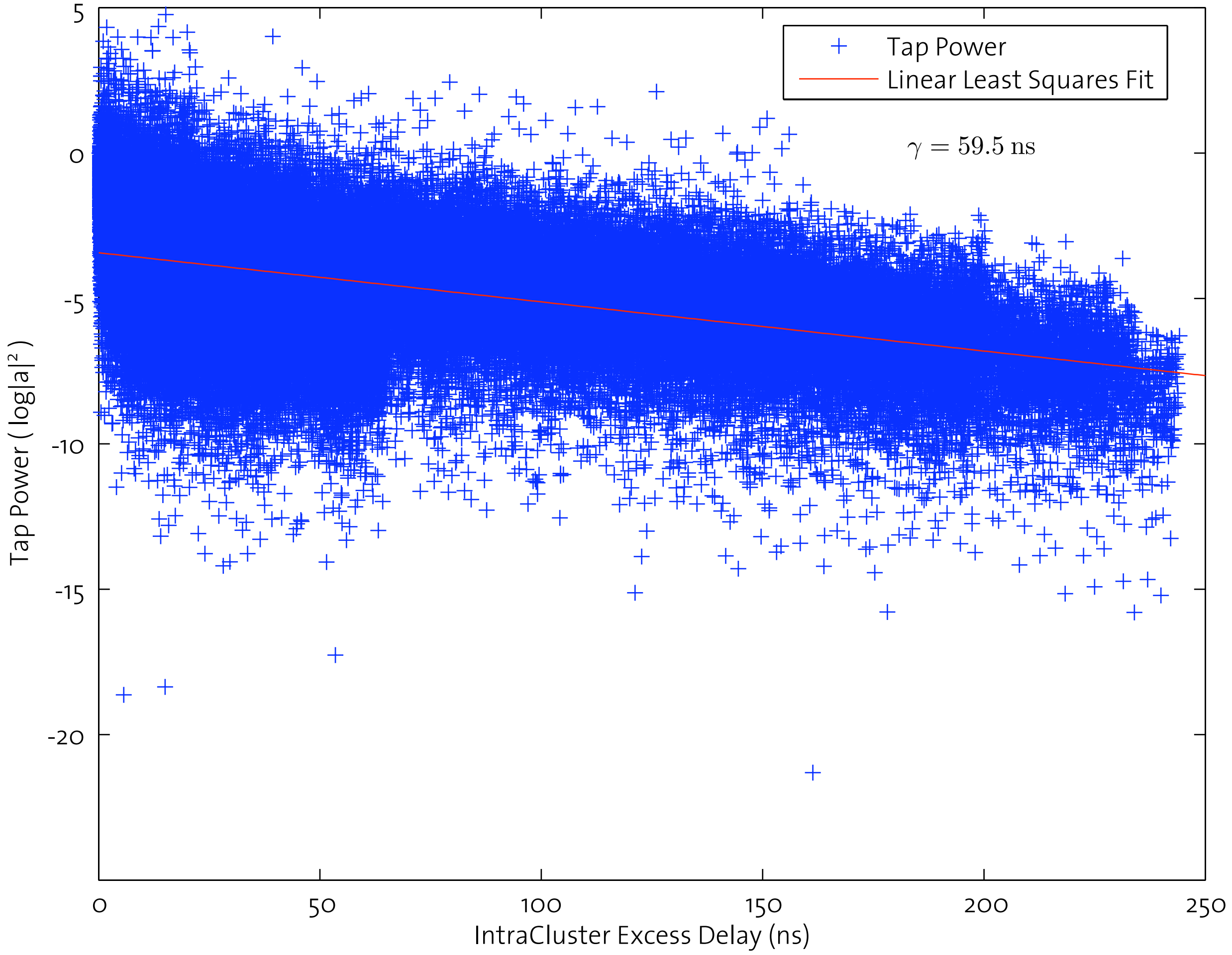
Cluster Interarrival Times — Corridor LOS



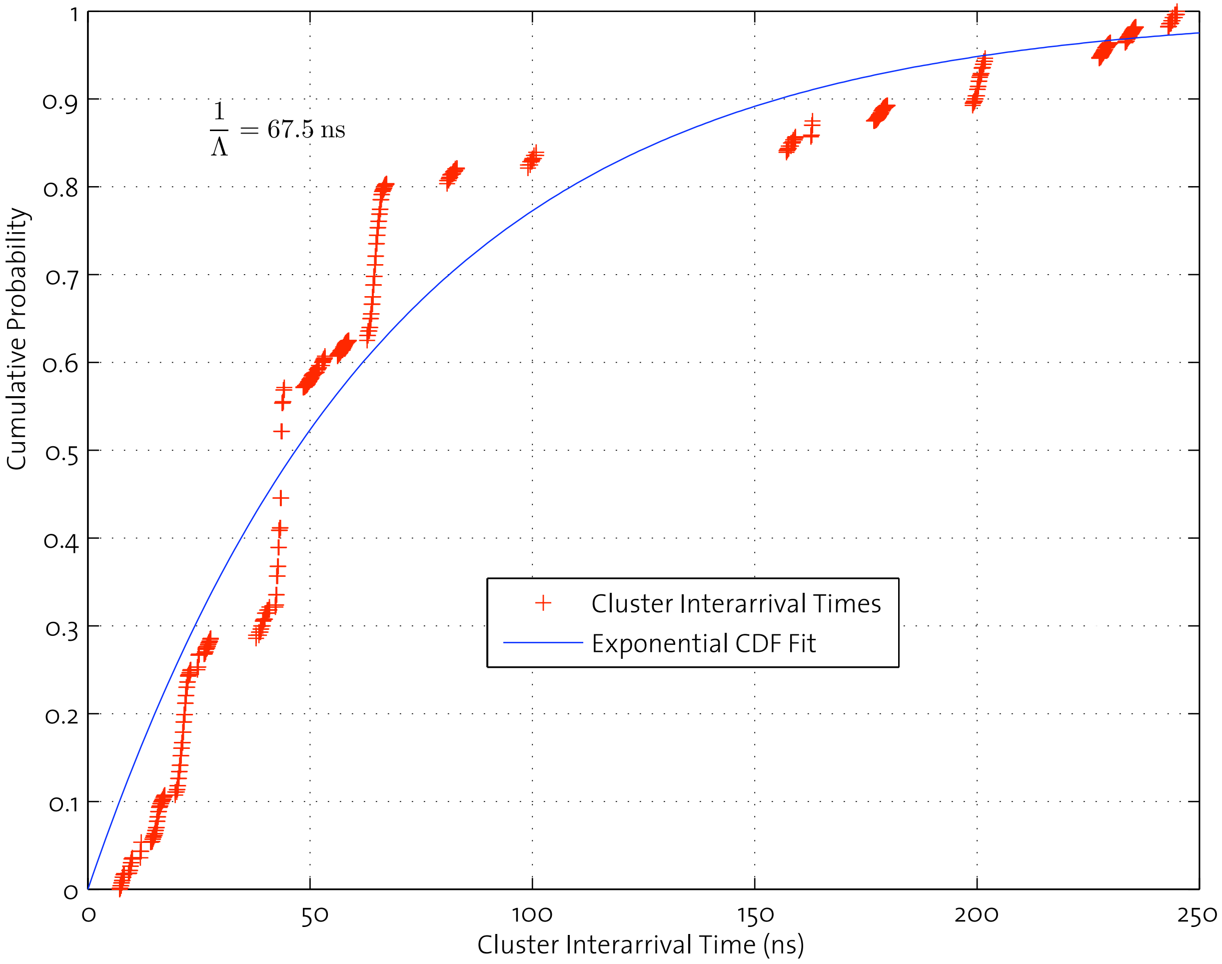
Cluster Decay — Lobby LOS



Intra-Cluster Decay — Lobby LOS



Cluster Interarrival Times — Lobby LOS



Large Scale Parameters — Path Loss

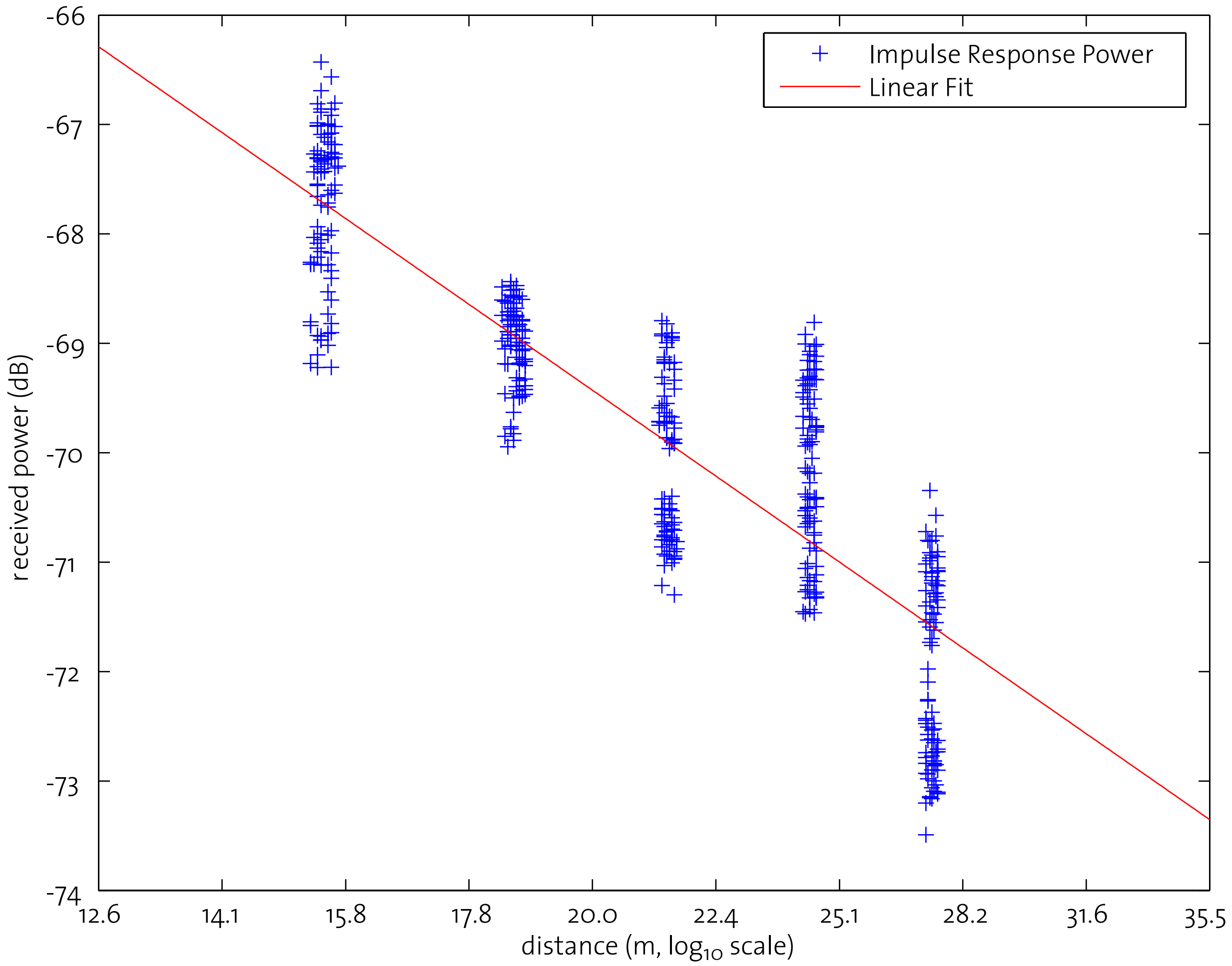
The simplest pathloss model consists of a single slope with exponential decay

$$10 \log P(d) = G_0 + 10\nu \log \frac{d}{d_0}, \quad d \geq d_0$$

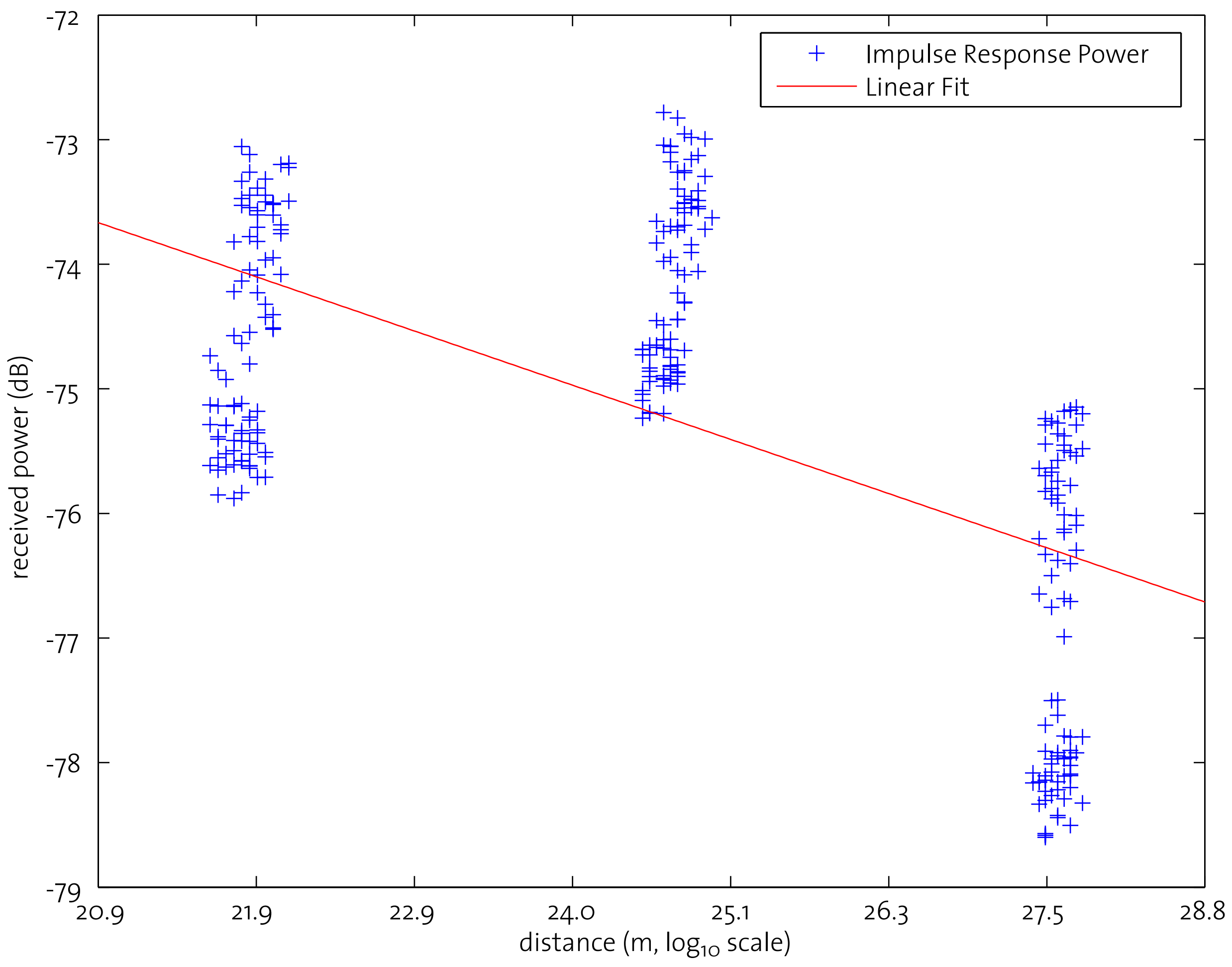
with $d_0 = 1m$, an arbitrarily chosen reference distance, and G_0 the reference loss at d_0.

Our measurements are not targeted at pathloss extraction; only in three settings enough large scale data points are available to yield crude estimates, as can be observed from the following scatter plots.

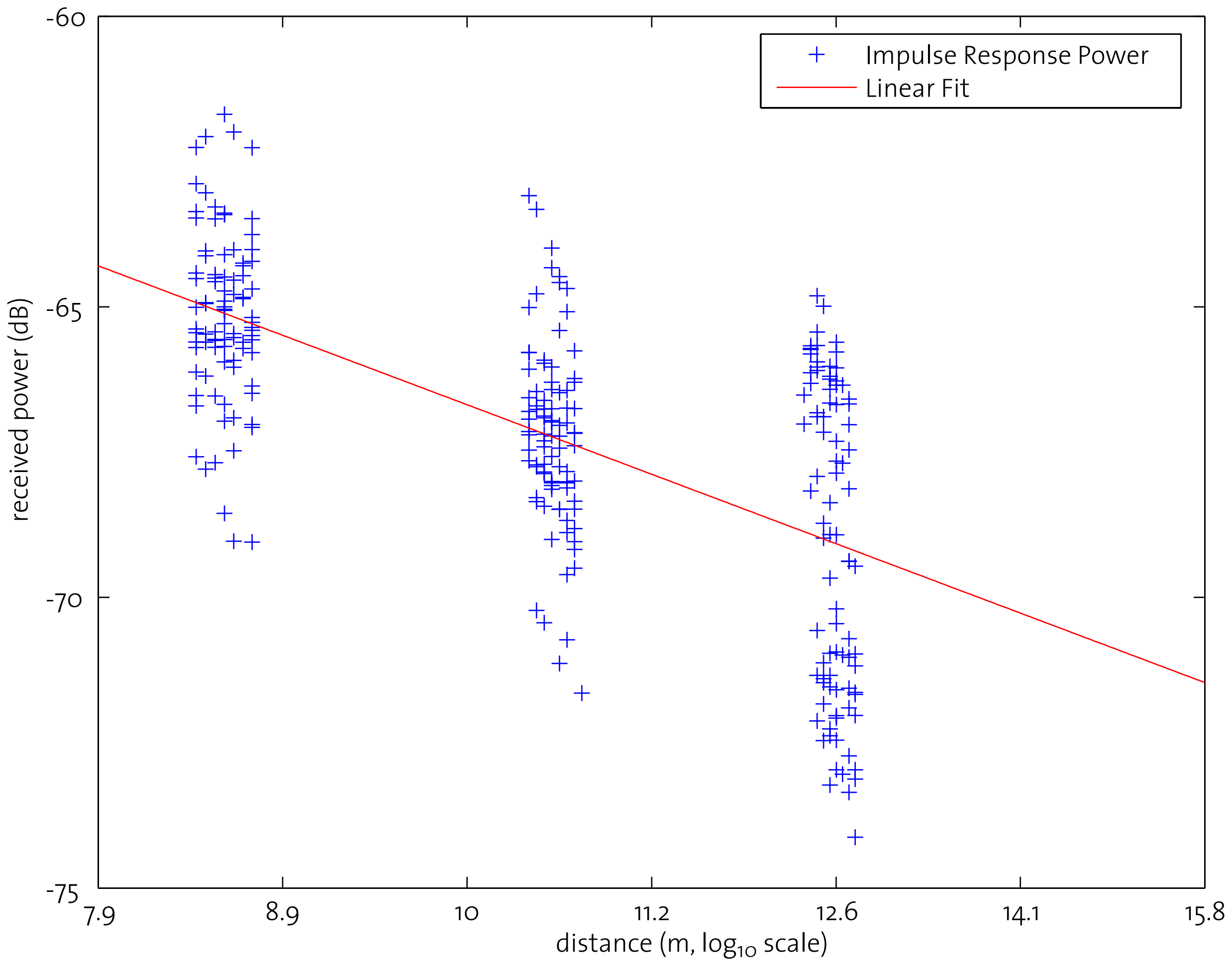
Path Loss Fit — Lobby LOS



Path Loss Fit — Lobby OLOS



Path Loss Fit — Corridor LOS



Pathloss Coefficients

Setting	ν	G_0
Lobby LOS	1.6	-49 dB
Lobby OLOS	2.2	-45 dB
Corridor LOS	1.2	-51 dB