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

Submission Title: [Characterization of Ultra-Wideband Channels: Small-Scale Parameters for Indoor & Outdoor Office Environments.]

Date Submitted: [14 July, 2004]

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Re: [Response to Call for Contributions by 15.4a Channel Modeling Subgroup]

Abstract: [This contribution describes the channel model adopted by IEEE 802.15.4a channel modeling subgroup for evaluating small-scale parameters from the empirical data collected in indoor & outdoor office environments. It consists of detailed characterization of statistical ultra-wideband channel models in 3-6GHz frequency range.]

Purpose: [For IEEE 802.15.SG4a to adopt the statistical channel model and use it in link budget calculations for validation of throughput and range requirements of UWB PHY proposals.]

Characterization of Ultra-Wideband Channels: Small-Scale Parameters for Indoor & Outdoor Office Environments

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Outline

- Motivation
- Equipment Setup
- Environments
- Statistical UWB Channel Model
- PDP: Data Processing
- Extraction of Parameters
- Amplitude Statistics
- Conclusion

Motivation

- To extract statistical parameters of UWB channels from empirical data collected in indoor and outdoor office environments.
- These parameters will be used
  - To simulate various UWB channels' propagation behavior.
  - To validate the range and throughput requirements of 15.4a UWB PHY proposals in various environments.
  - To help to design appropriate modulations and coding schemes to combat the ill-effects of multipaths.

Equipment Setup

- Measurements were taken in frequency domain using VNA (Agilent 8753E)
  - Center Frequency: f_c = 4.5GHz
  - Bandwidth: BW = 3GHz
  - Frequency bins: N = 1601
  - Delay resolution: 👎♦ 🖬 (1/BW) = 0.33ns
  - Frequency step: 👎f = BW/(N-1) =1.875MHz
  - Max. excess delay: ♦$_{max}$ = 1/ 👎f = 533.3ns (160m)
  - Sweeping time: t_{sw} = 600ms
  - Max. Doppler shift: $f_{d,max}$ = 1/ t_{sw}
  - IF bandwidth: IF_{BW} = 3.7kHz
  - Antenna type: Omni-directional Cone antennas(3-6GHz)
  - Antenna heights: 1.2m

Equipment Setup

- Fig. (1) shows the equipment setting. Frequency domain data are collected by a laptop with Agilent IntuLink VNA software via GPIB interface.
- This measurement setup (without antennas) is calibrated using the 8753E calibration kit.
- For the outdoor measurements, an amplifier with 10 dBm gain was used at the Tx.

Equipment Setup

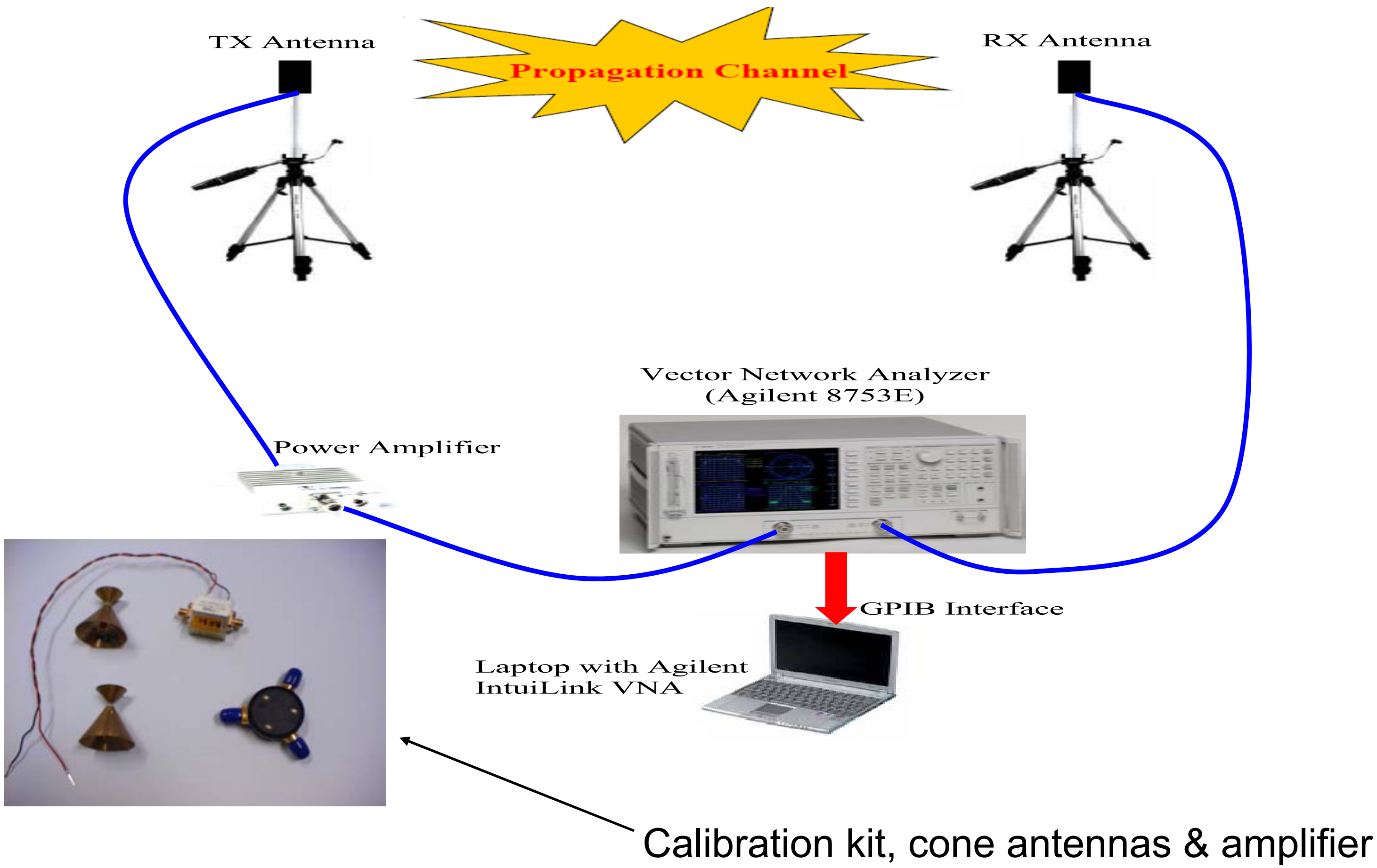


Fig. (1): Equipment Setup

Environments (Indoor Office)

- Indoor office environments: OFF_LOS, OFF_SOFT_NLOS and OFF_HARD_NLOS.
  - Tx-Rx separations ranging from 5m to 18m.
  - Number of locations: OFF_LOS - 39, OFF_SOFT_NLOS - 48 and OFF_HARD_NLOS -17.
  - At each location, measurements are taken over a square grid of K (= 9 or 49) spatial points (5cm inter-distance).
  - Figs. (2), (3) & (4) show the Tx/Rx locations for OFF_LOS, OFF_NLOS and RM_NLOS measurements respectively.

OFF_LOS Tx/Rx Locations

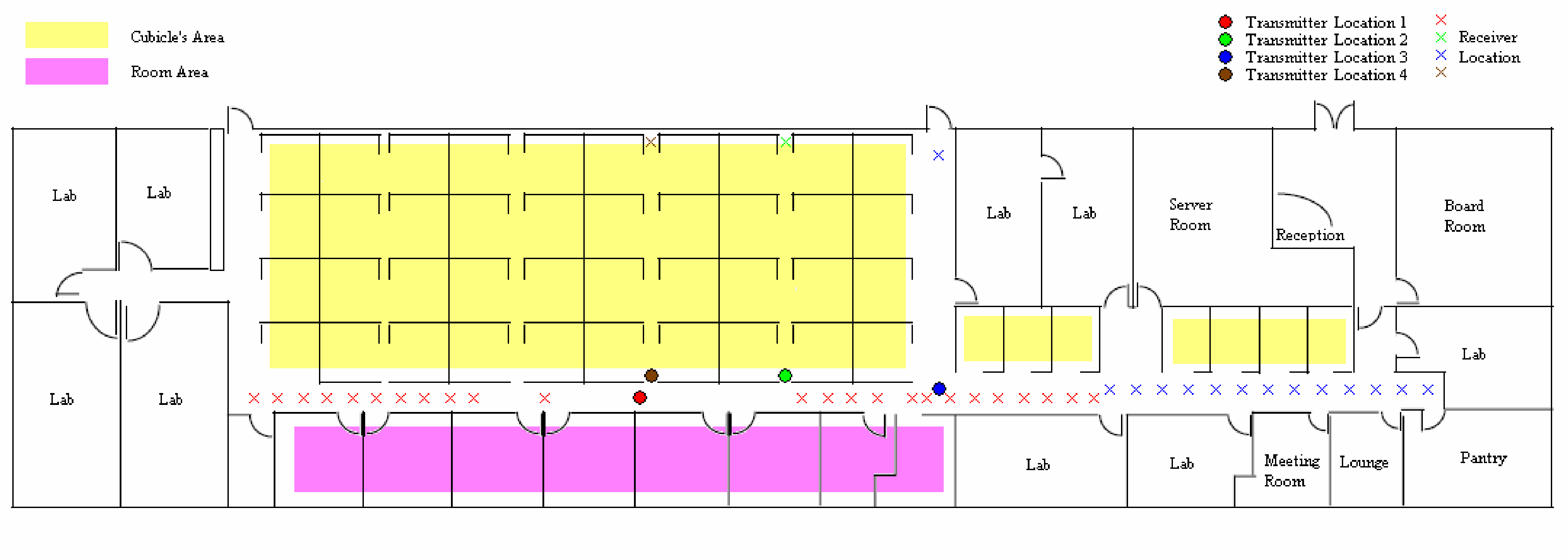


Fig. (2): Tx/Rx locations for OFF_LOS

OFF_SOFT_NLOS Tx/Rx Locations

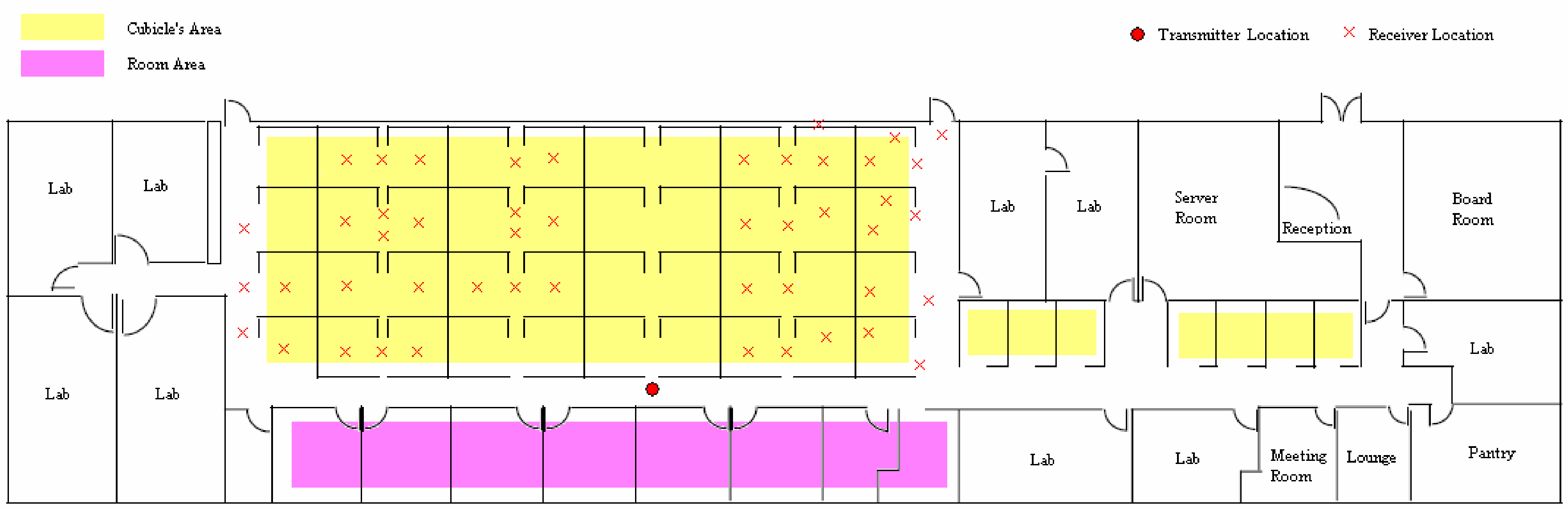


Fig. (3): Tx/Rx locations for OFF_SOFT_NLOS

OFF_HARD_NLOS Tx/Rx Locations

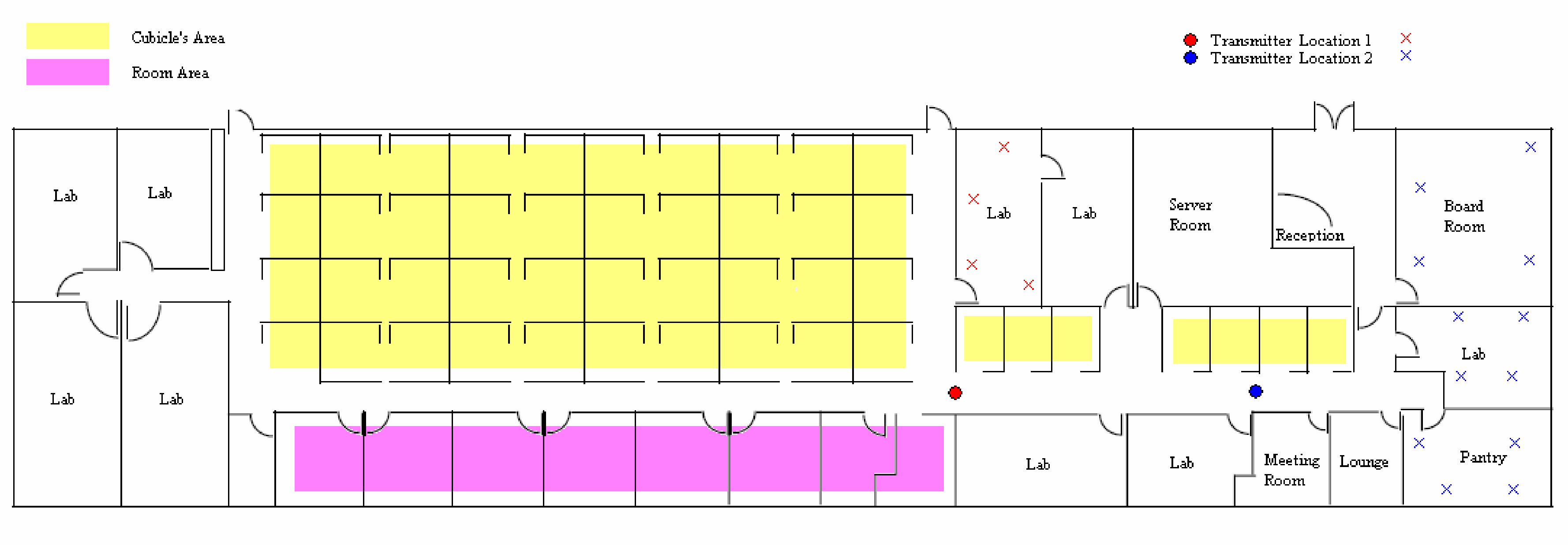


Fig. (4): Tx/Rx locations for OFF_HARD_NLOS

Environments (Outdoor Office)

- Outdoor office environments: OUT_LOS .
  - Tx-Rx separations ranging from 3m to 24m
  - Number of locations: OUT_LOS-41 locations.
  - At each location, measurements were taken over a square grid of K (= 9 or 49) spatial points (5cm inter-distance) .
  - Figs. (5) shows the Tx/Rx locations for OUT_LOS measurements.

OUT_LOS Tx/Rx Locations

Fig.(5a): OUT_LOS environment

OUT_LOS Tx/Rx Locations

Fig.(5b): OUT_LOS environment

Environments

- OFF_SOFT_NLOS environment: There are cubicles between the Tx & Rx, where the cubicles are made of gypsum material.
- OFF_HARD_NLOS environment: Tx & Rx are separated by 1 or 2 walls which are made of gypsum material.
- OUT_LOS environment: In the middle of two buildings (metal plated concrete walls with small/large glass windows) and has some trees around.

Statistical UWB Channel Model

- 802.15.4a channel modeling sub-committee adopted the following discrete-time model for the channel measurements campaign:

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

where $a_{k,l}$: tap weight of the k^{th} component

T_l: delay of the l^{th} cluster

$\tau_{k,l}$: delay of the k^{th} MPC relative to the l^{th} cluster

K: total number of MPCs in a cluster

L: total number of clusters

$\tau_{0,l} = 0$

Distributions of Arrival Times

- The distributions of the cluster and ray (MPC) arrival times are given by Poisson processes (similar to S-V model):

$$p(T_l|T_{l-1}) = \Lambda \exp[-\Lambda(T_l - T_{l-1})], l>0 \quad (2)$$

$$p(\tau_{k,l}|\tau_{k,l-1}) = \lambda \exp[-\lambda(\tau_{k,l} - \tau_{k,l-1})], k>0 \quad (3)$$

where Λ: cluster arrival rate

λ: ray arrival rate

Power Delay Profile (PDP)

- Average PDP at $T_l + \tau_{k,l}$ is described by the following exponential function:

$$E\{|a_{k,l}|^2\}=E\{|a_{0,0}|^2\}\exp\left[-\frac{T_l}{\Gamma}\right]\exp\left[-\frac{\tau_{k,l}}{\gamma}\right] \quad (4)$$

$$\Rightarrow \ln\left[\frac{E\{|a_{k,l}|^2\}}{E\{|a_{0,0}|^2\}}\right]=-\left(\frac{1}{\Gamma}\right)T_l-\left(\frac{1}{\gamma}\right)\tau_{k,l} \quad (5)$$

Parameters of Interest

- Therefore, we need to extract the following parameters to characterize the Multipath statistics of the channel:

Γ - cluster arrival rate

γ - ray arrival rate

Λ - cluster arrival rate

λ - ray arrival rate

$a_{k,l}$ - tap weight

PDP: Data Processing

- Time domain impulse responses are obtained from the frequency domain data by using the simple IFFT.
- A threshold value, PW_{TH} is defined as the power level above the noise floor. In this report, the default value of PW_{TH} = 10dB. Any MPC with the power level < (noise power + PW_{TH}) is ignored.
- The reference delay, $T_0 = \tau_{0,0} = 0$, for each impulse response, is obtained by setting it to be the earliest path arrival which is within 10 dB from the peak power and 10ns (50ns for NLOS data) for LOS data.
- A PDP is obtained from each impulse response. Number of clusters and their respective arrival times, w.r.t. T_0 , are manually obtained from each PDP.

Extraction of Parameters: Γ

- For each PDP, select the first path of each cluster and divide those paths by $|a_{0,0}|^2$,thus, the power of the first path becomes one.
- All the cluster arrivals (from all the PDPs) are superimposed and plotted on a semi-log graph (see eq.(5), where $\tau_{0,l} = 0$) as shown in figs. (6-9) for various office environments.
- Γs are obtained from the plots by applying a least square curve fitting program.

Γ: OFF_LOS

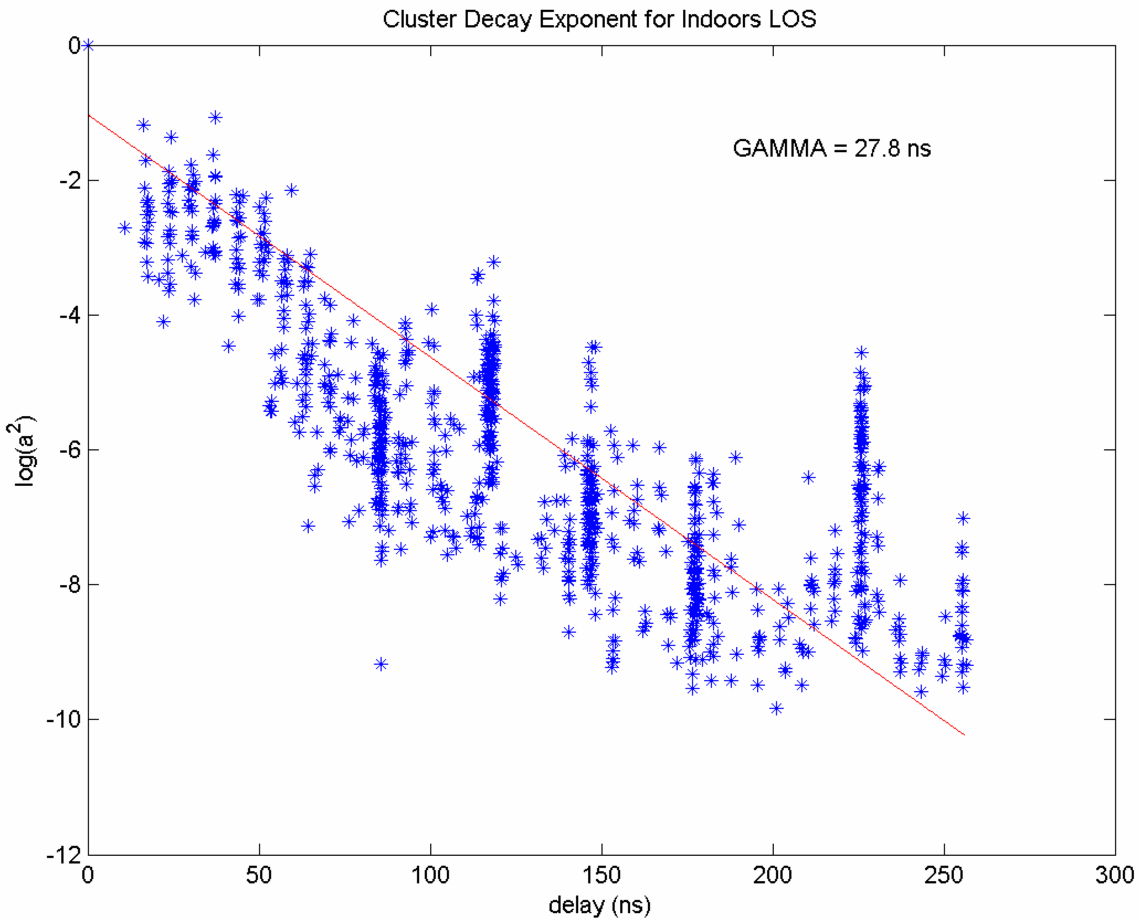


Fig. (6): Γ = 27.8 for OFF_LOS

Γ: OFF_SOFT_NLOS

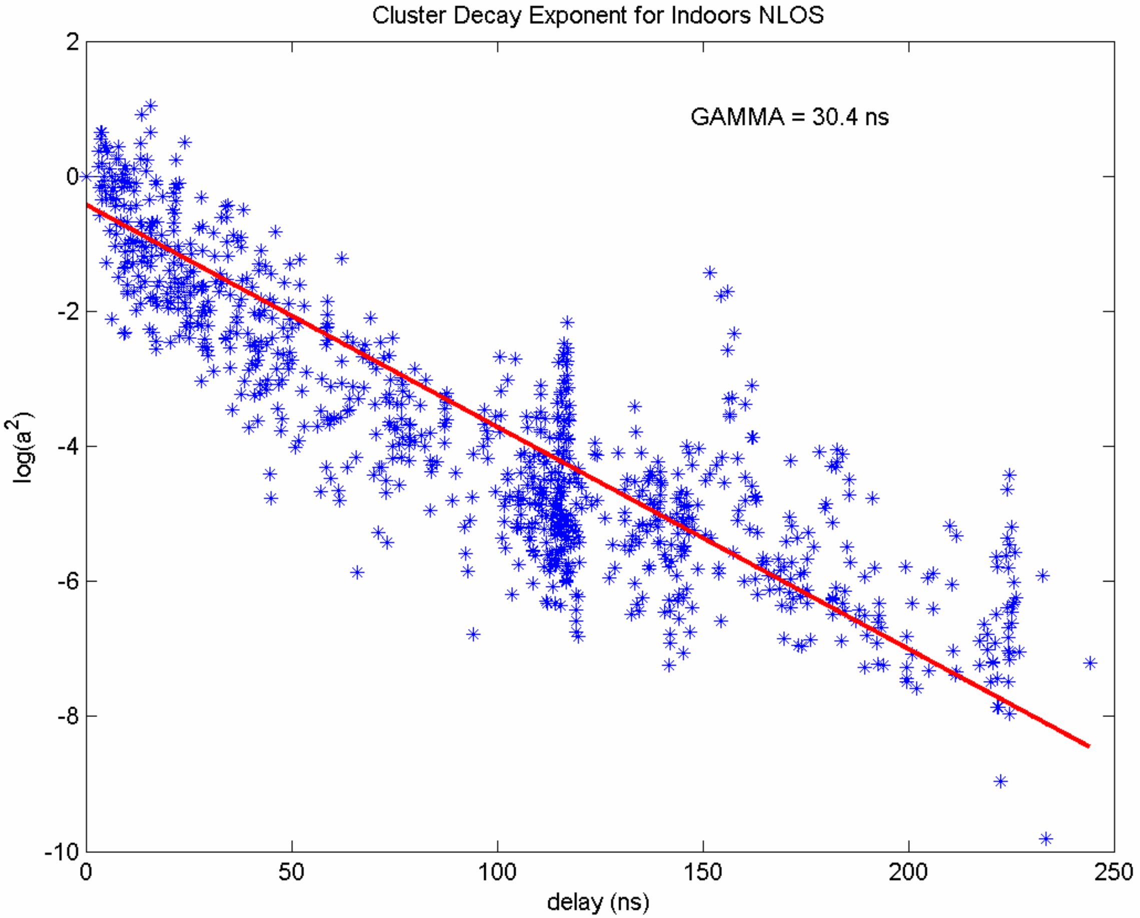


Fig. (7): Γ = 30.4 for OFF_SOFT_NLOS

Γ:OFF_HARD_NLOS

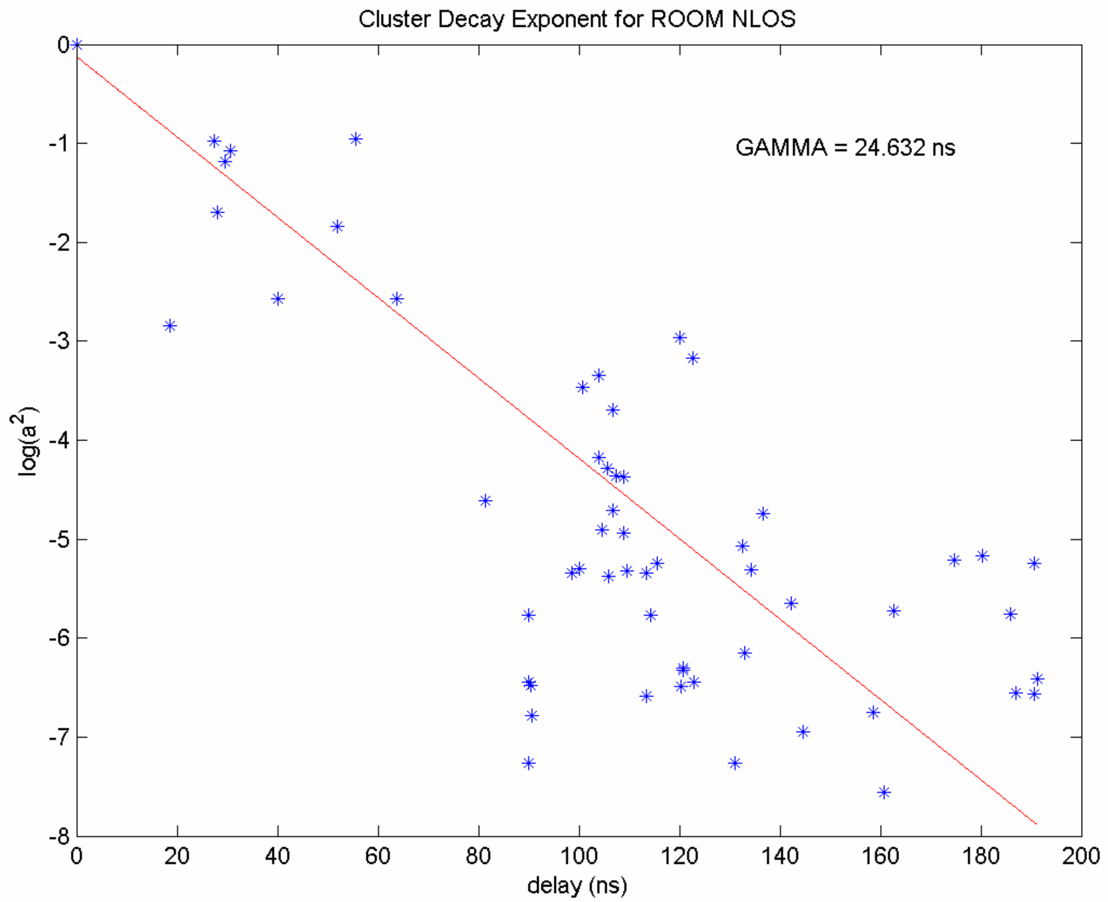


Fig. (8): Γ = 24.6 for OFF_HARD_NLOS

Γ: OUT_LOS

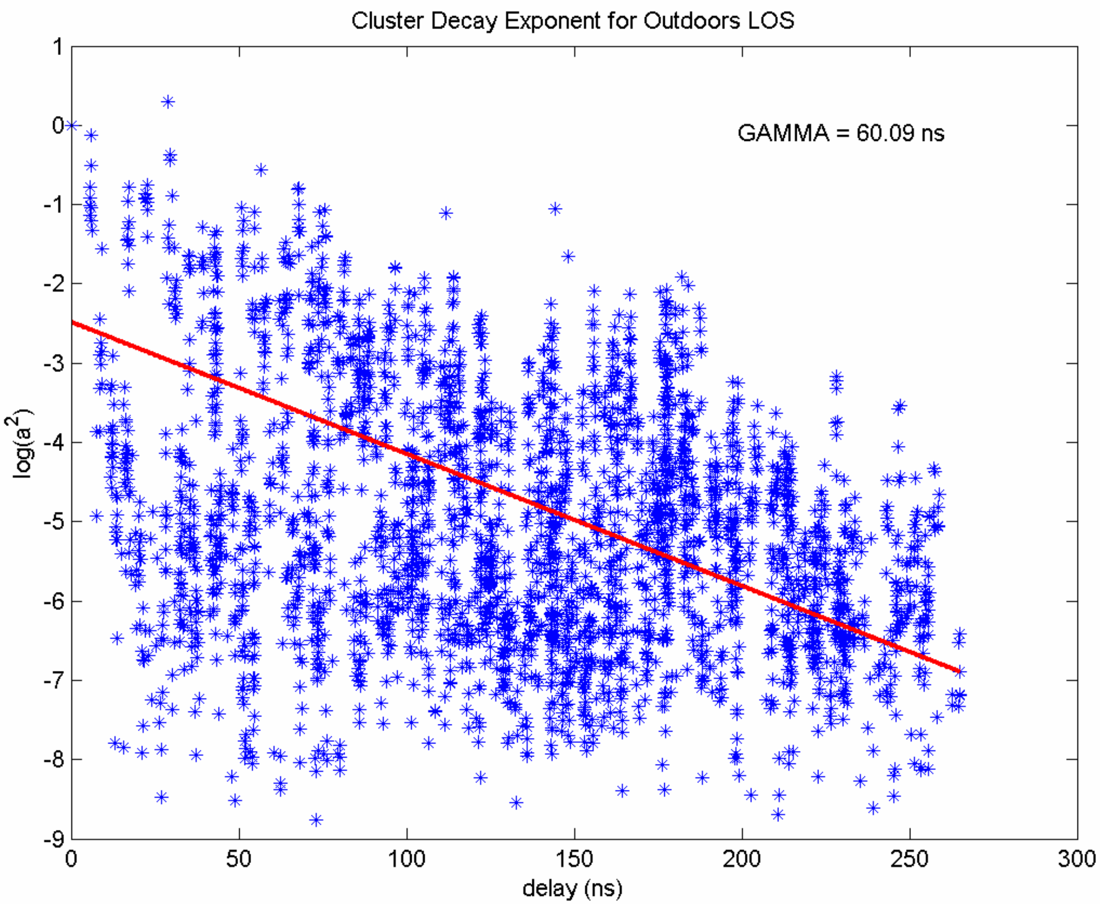


Fig. (9): Γ = 60.1 for OUT_LOS

Extraction of Parameters: γ

- In this report, it is assumed that all the clusters decay at a constant rate, γ.
- Normalize all the MPCs in a cluster w.r.t. to the power of the first path of that cluster, thus, the power of the first path of each cluster becomes one.
- Superimpose all the clusters and plot the power vs delay on a semi-log graph as shown in figs. (10-14) for various environments.
- γs are obtained from the plots by applying a least square curve fitting program.

γ: OFF_LOS

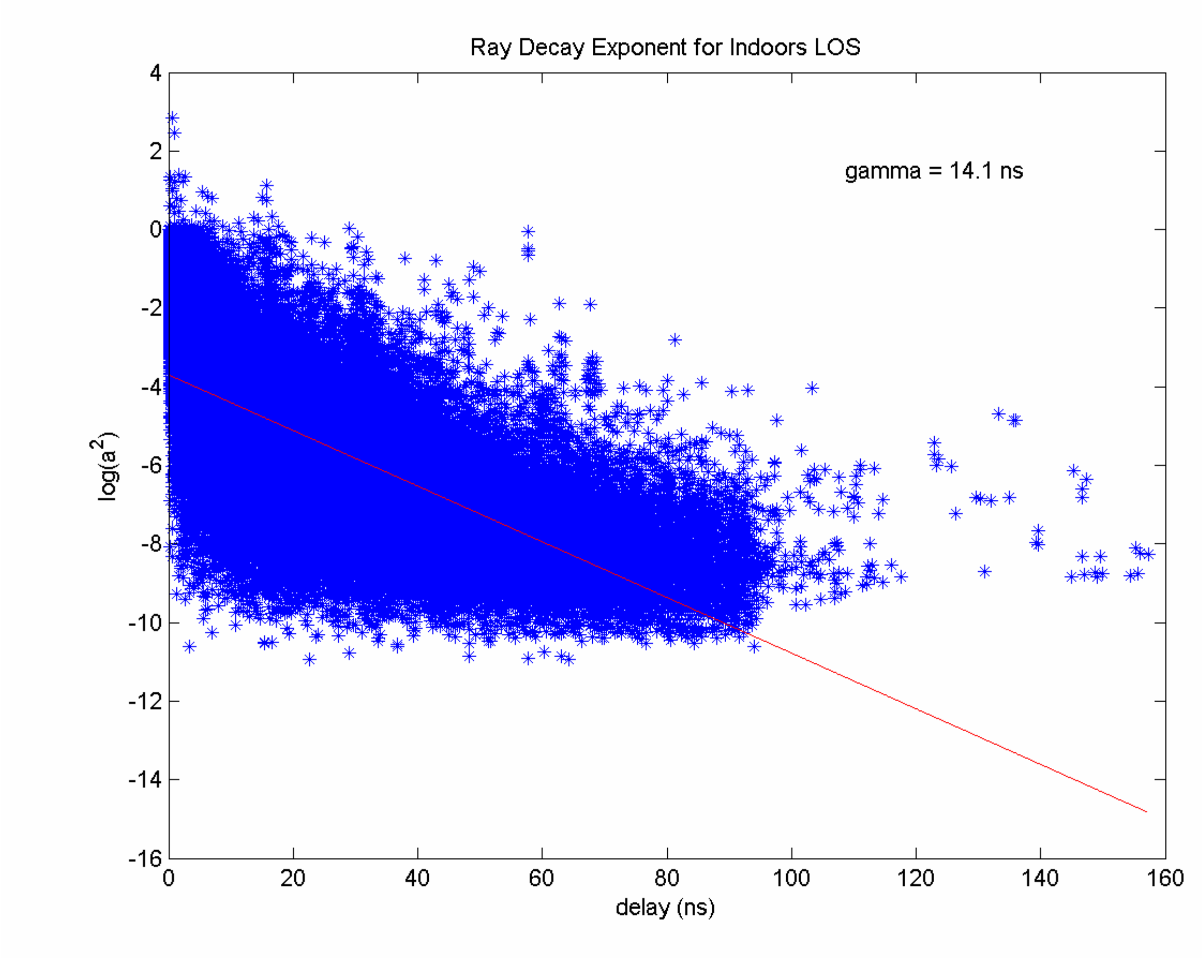


Fig. (10): γ = 14.1 for OFF_LOS

γ: OFF_SOFT_NLOS

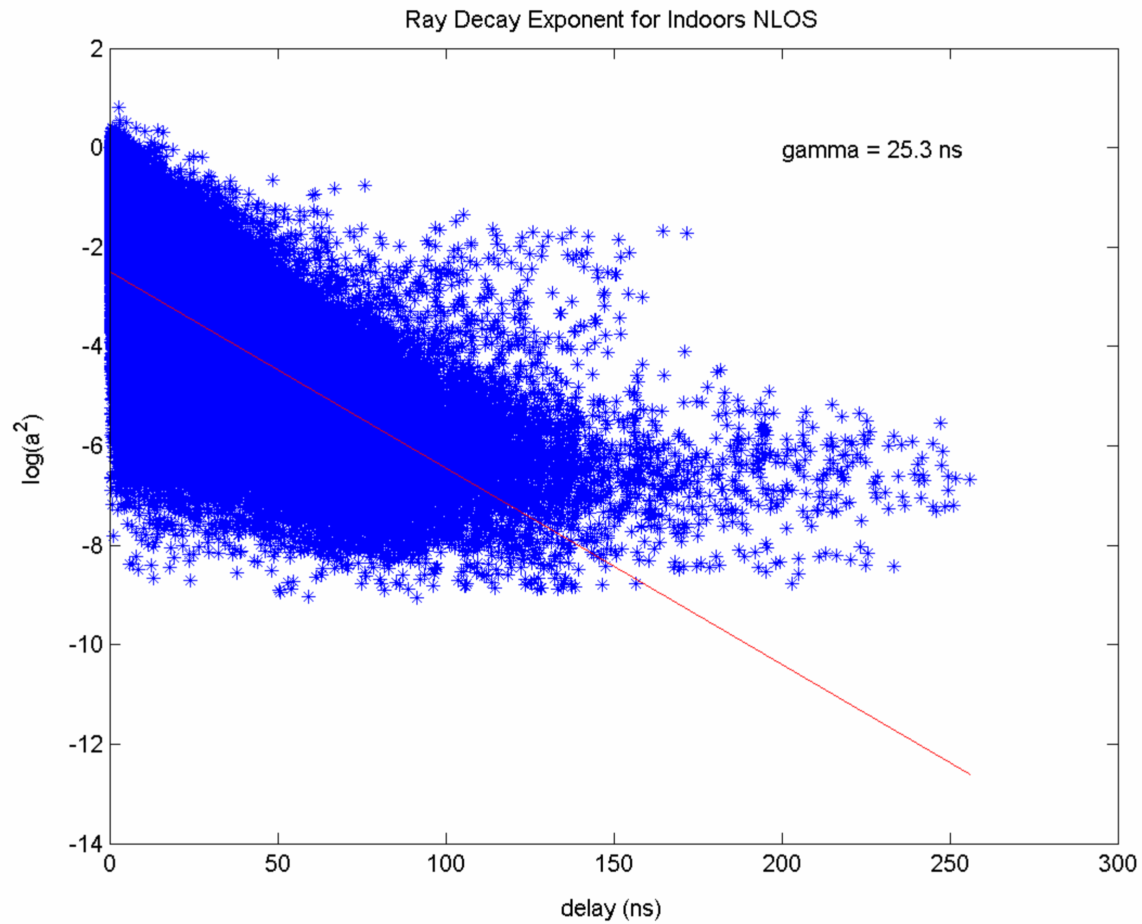


Fig. (11): γ = 25.3 for OFF_SOFT_NLOS

γ: OFF_HARD_NLOS

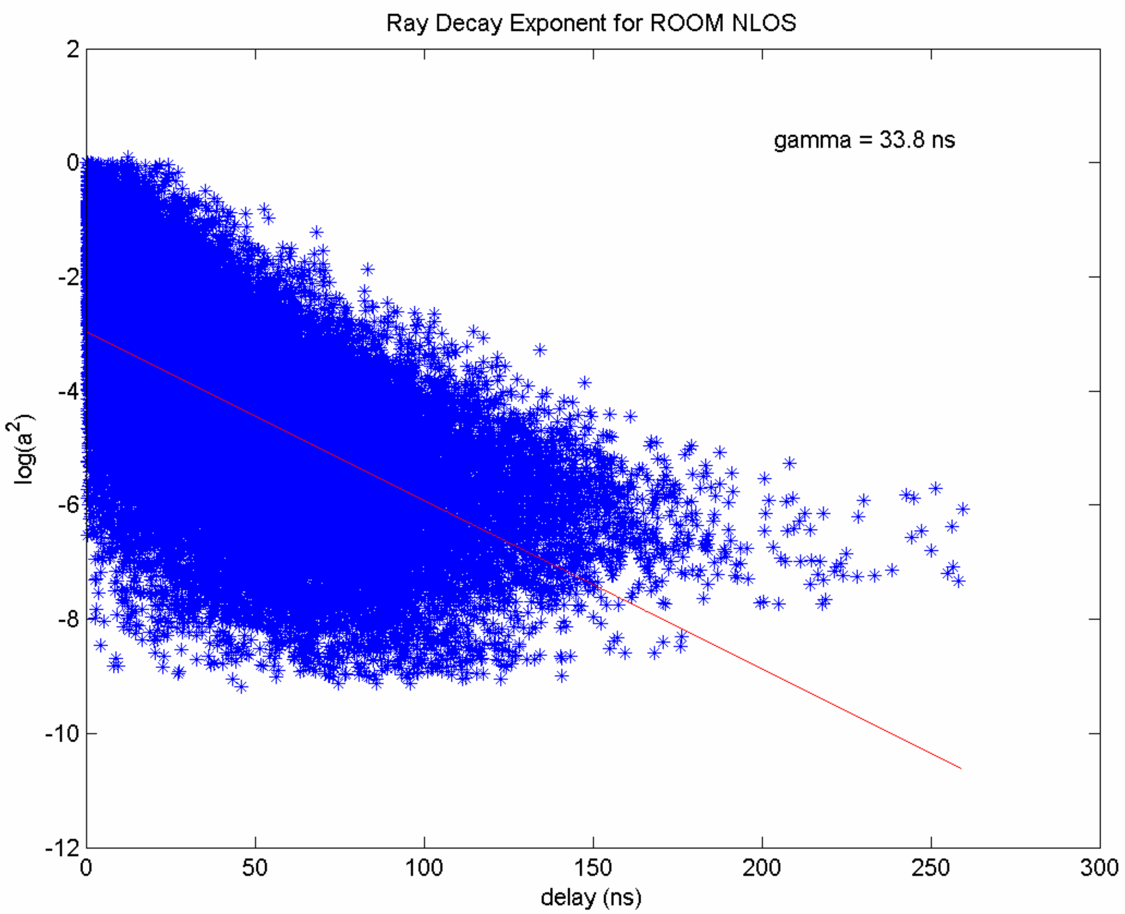


Fig. (12): γ = 33.8 for OFF_HARD_NLOS

γ: OUT_LOS

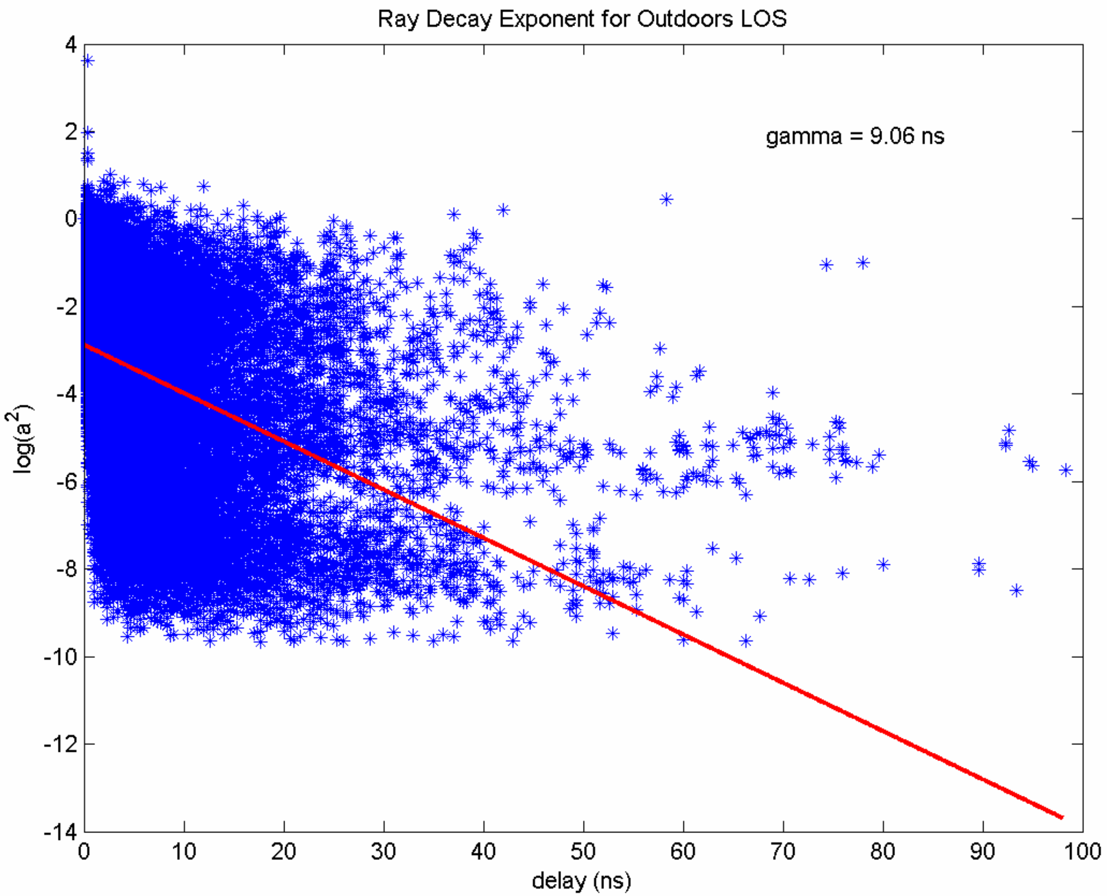


Fig. (1): γ = 9.1 for OUT_LOS

Extraction of Parameters: Λ

- Cluster arrivals are described by the Poisson process (eq. (2)).
- With $T_0 = 0$, the empirical CDF are obtained from the measured data.
- An LMS criteria is used to fit the best exponential CDF (CDF of a Poisson process is an exponential function) to the empirical CDF.
- Figs. (14-17) shows the values of Λ for various office environments.

Λ: OFF_LOS

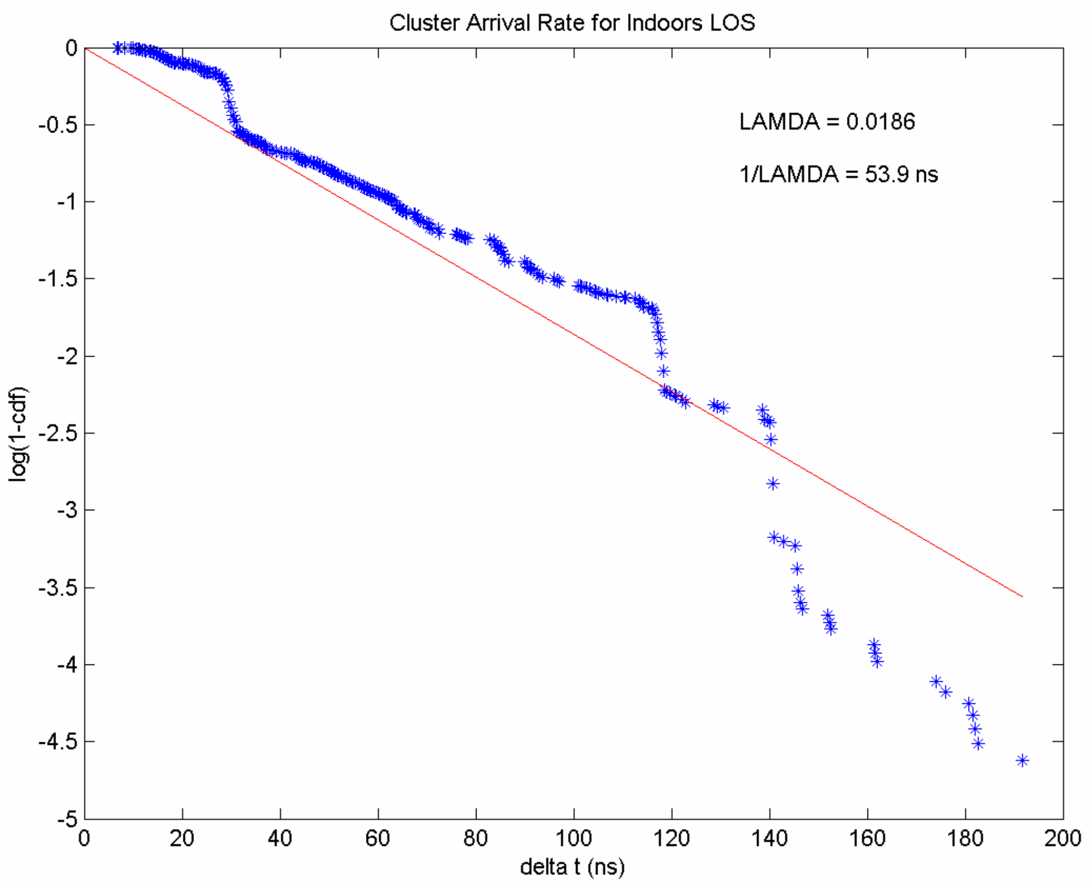


Fig. (14): $\Lambda = 0.0186$ for OFF_LOS

Λ: OFF_SOFT_NLOS

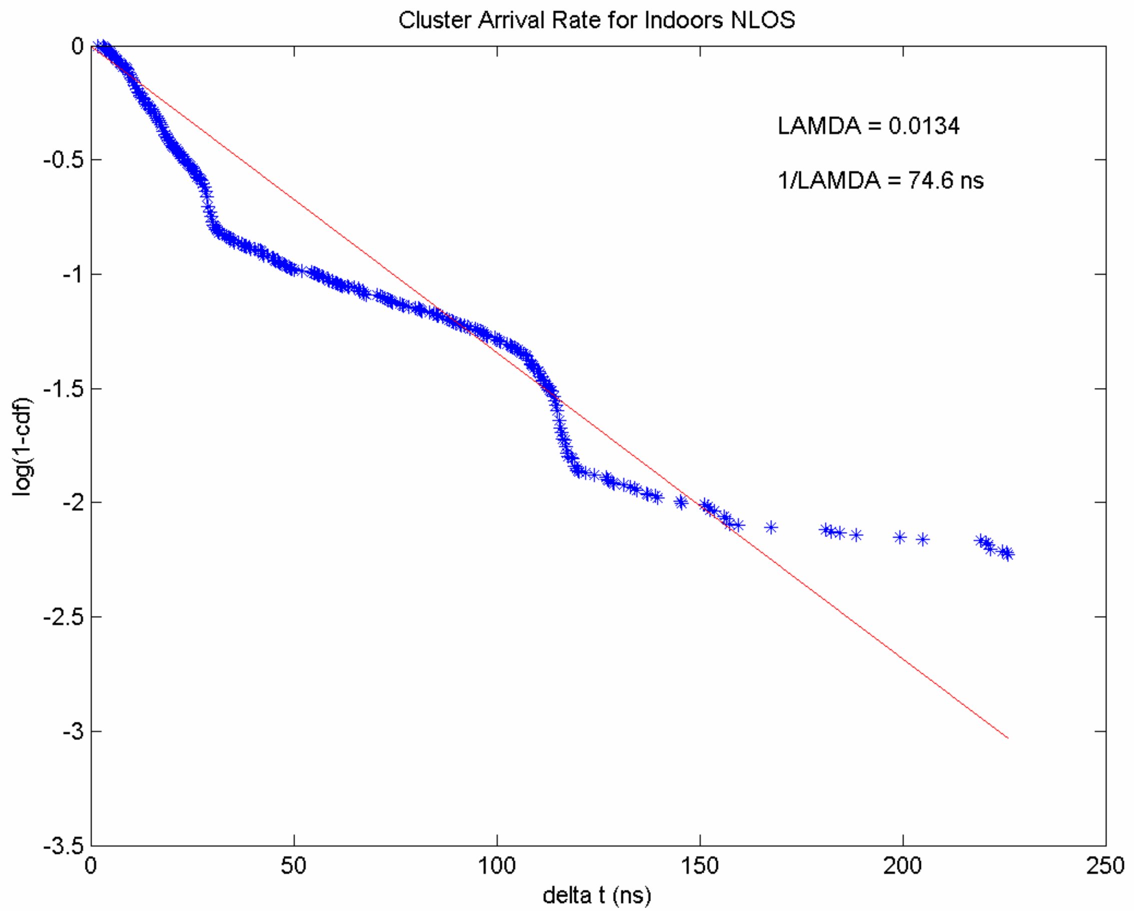


Fig. (15): Λ = 0.0134 for OFF_SOFT_NLOS

Λ: OFF_HARD_NLOS

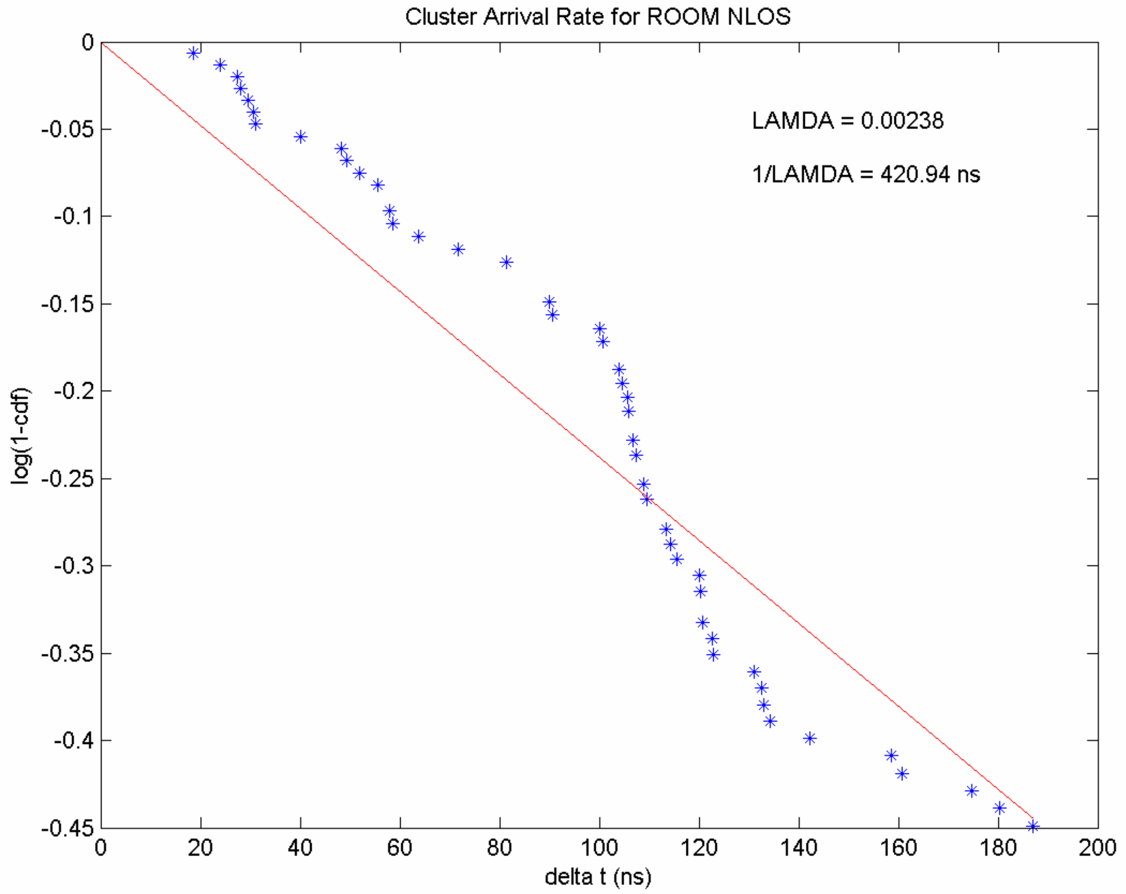


Fig. (16): Λ = 0.0024 for OFF_HARD_NLOS

Λ: OUT_LOS

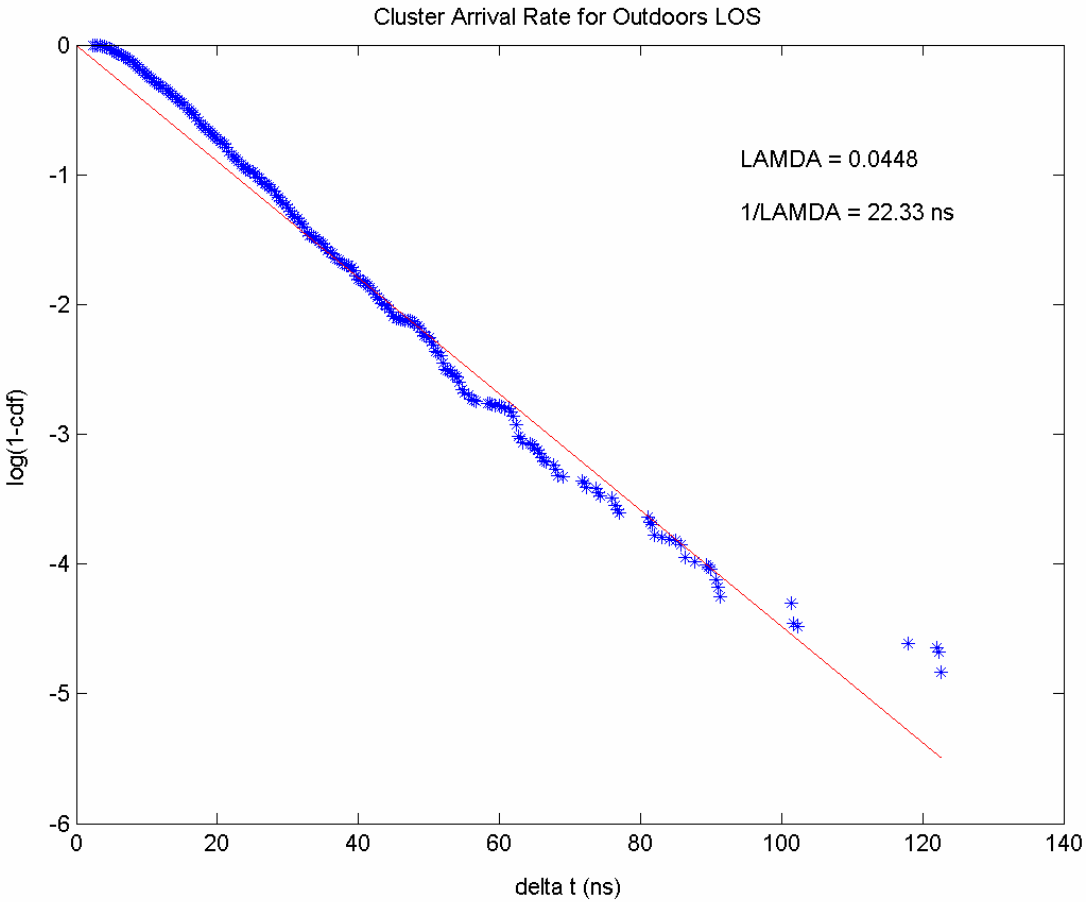


Fig. (17): Λ = 0.0448 for OUT_LOS

Extraction of Parameters: λ

- Ray arrivals are also described by the Poisson process (eq. (3)).
- Set the arrival time of the first path of each cluster to zero and adjust the arrival times of the other paths accordingly.
- An LMS criteria is used to fit the best exponential CDF (CDF of a Poisson process is an exponential function) to the empirical CDF.
- Figs. (18-21) shows the values of λ for various office environments.

λ: OFF_LOS

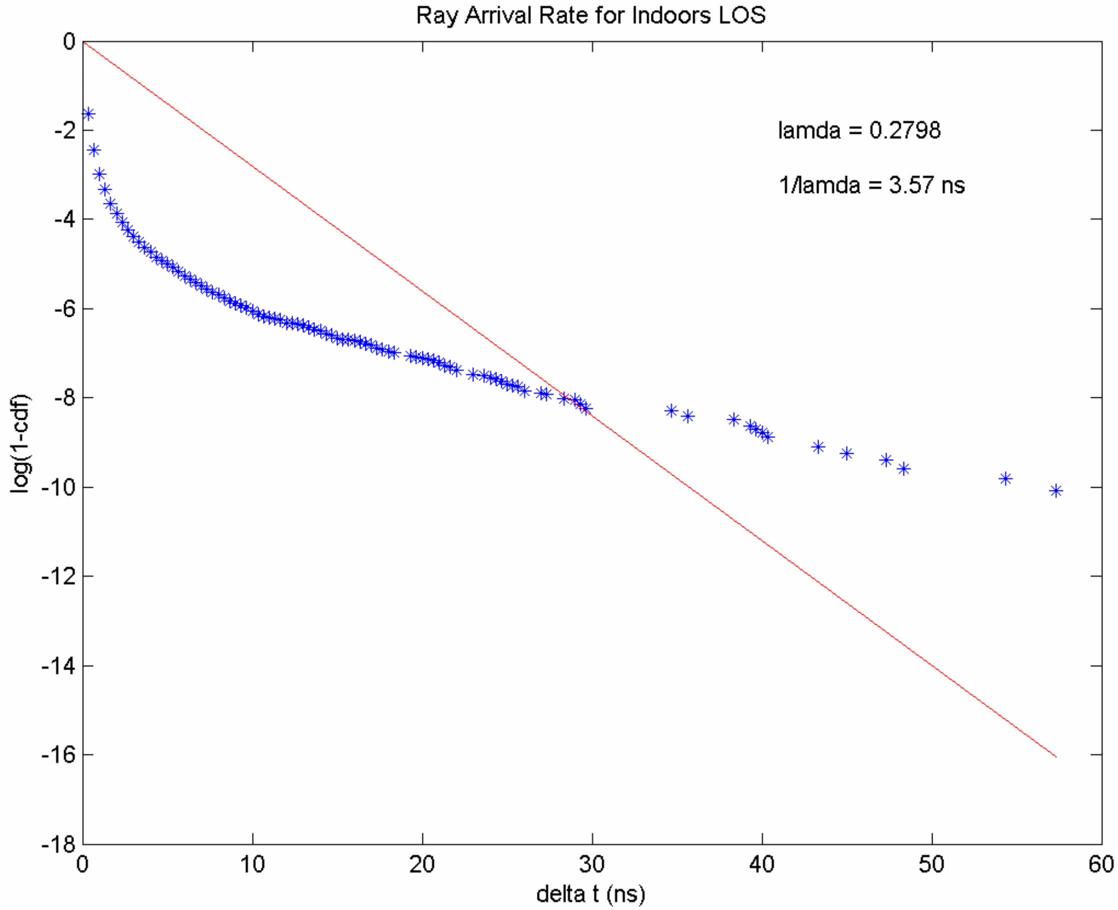


Fig. (18): λ = 0.28 for OFF_LOS

λ: OFF_SOFT_NLOS

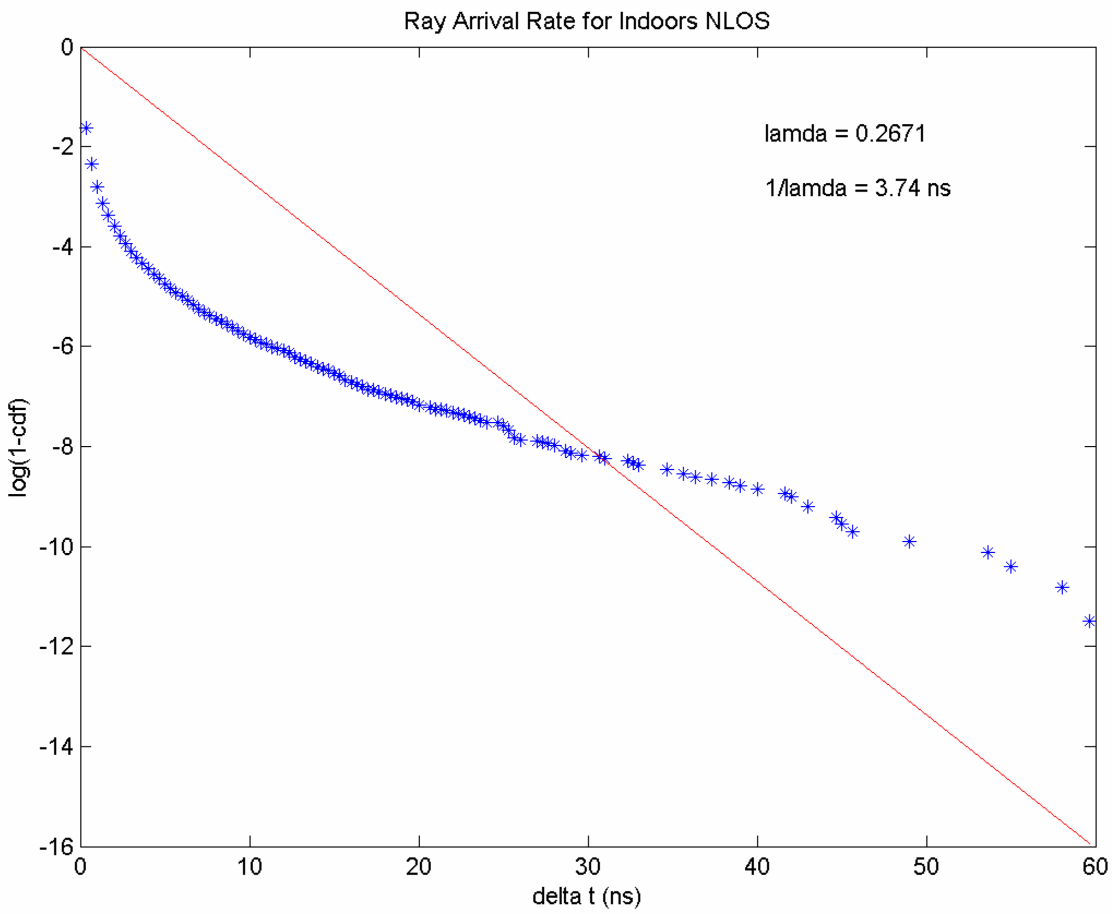


Fig. (19): λ = 0.267 for OFF_SOFT_NLOS

λ: OFF_HARD_NLOS

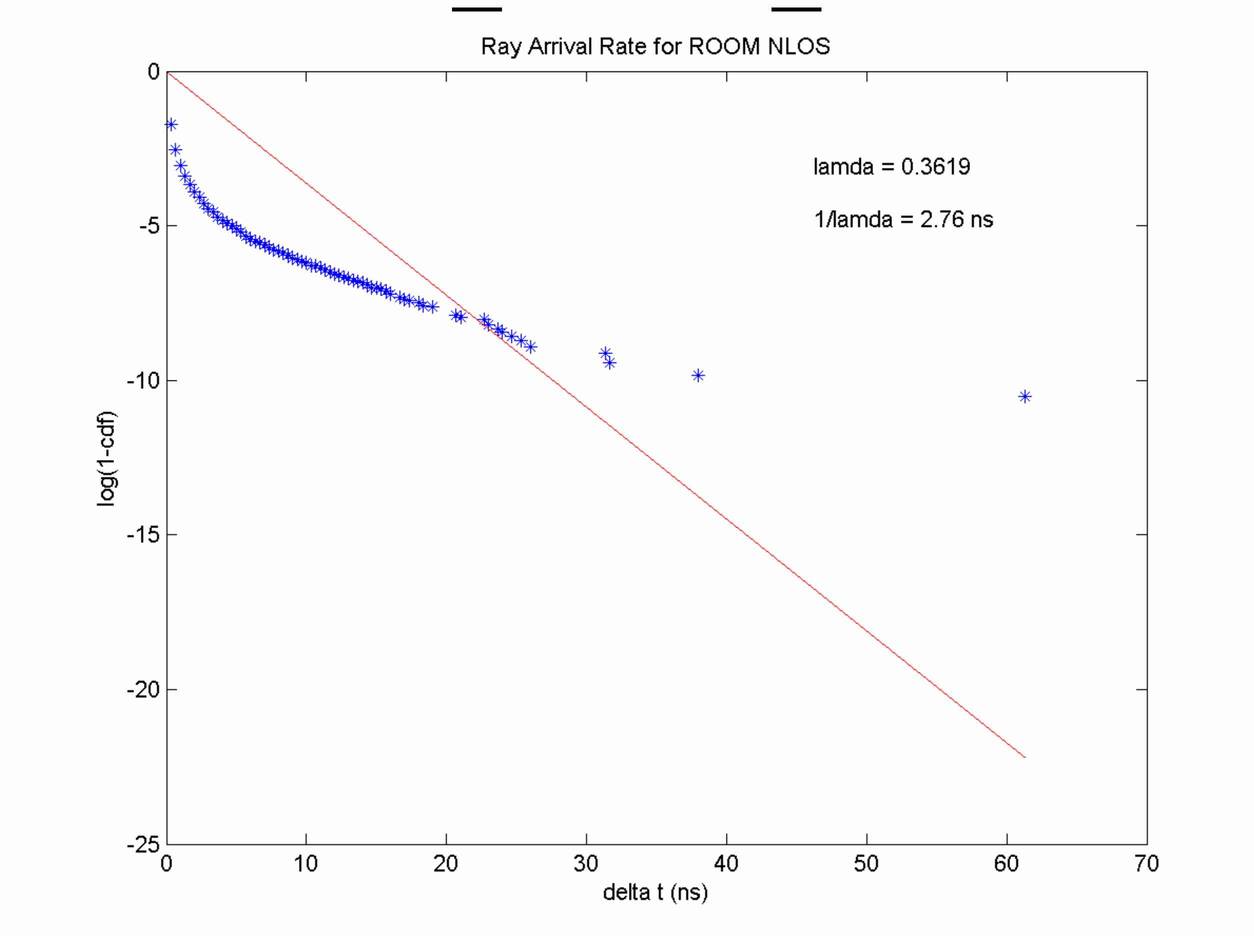


Fig. (20): λ = 0.362 for OFF_HARD_NLOS

λ: OUT_LOS

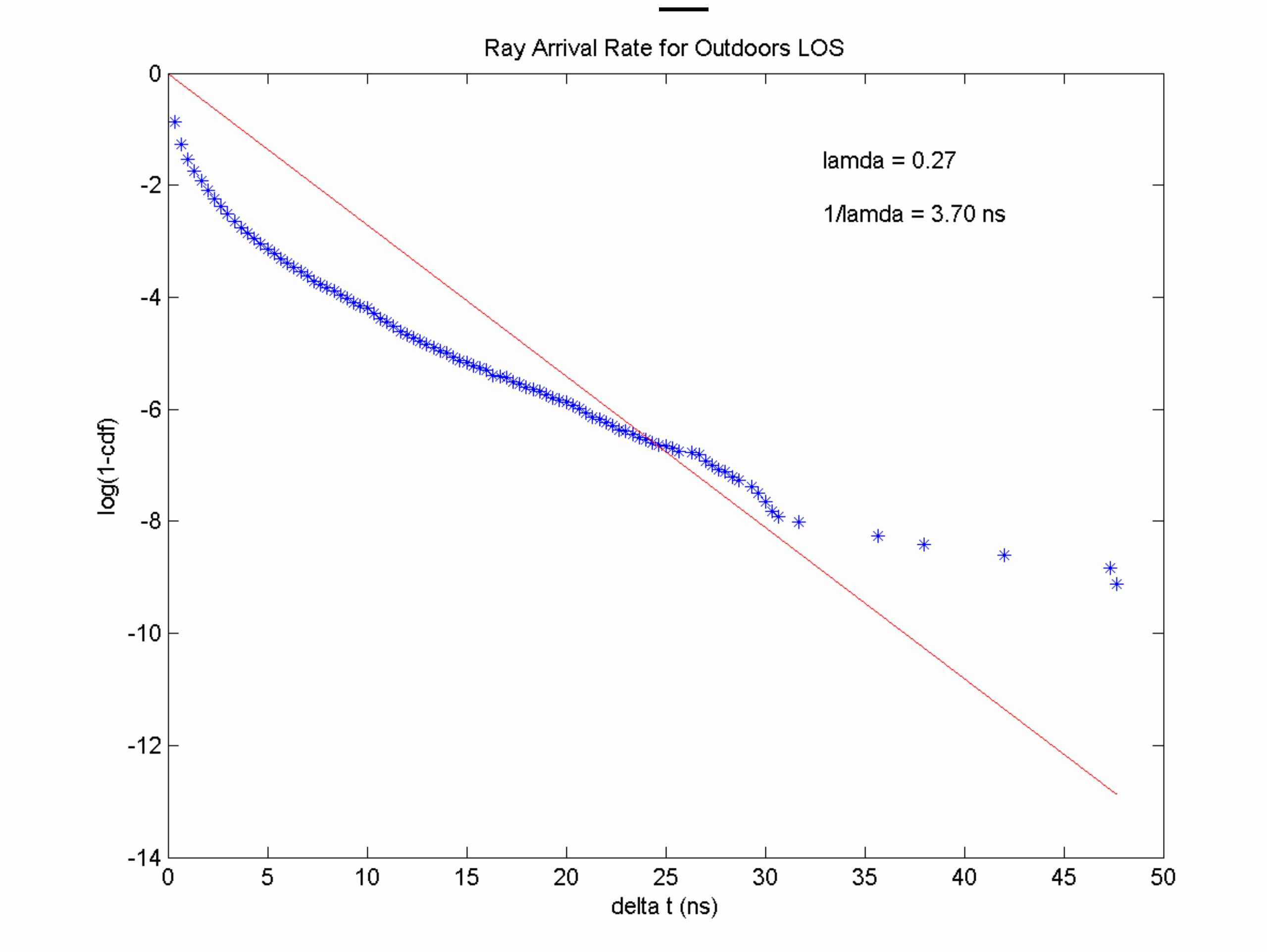


Fig. (21): λ = 0.27 for OUT_LOS

Proposed New Distributions of Arrival Times

- The distributions of the ray (MPC) arrival times are given by a mixture of Poisson processes :

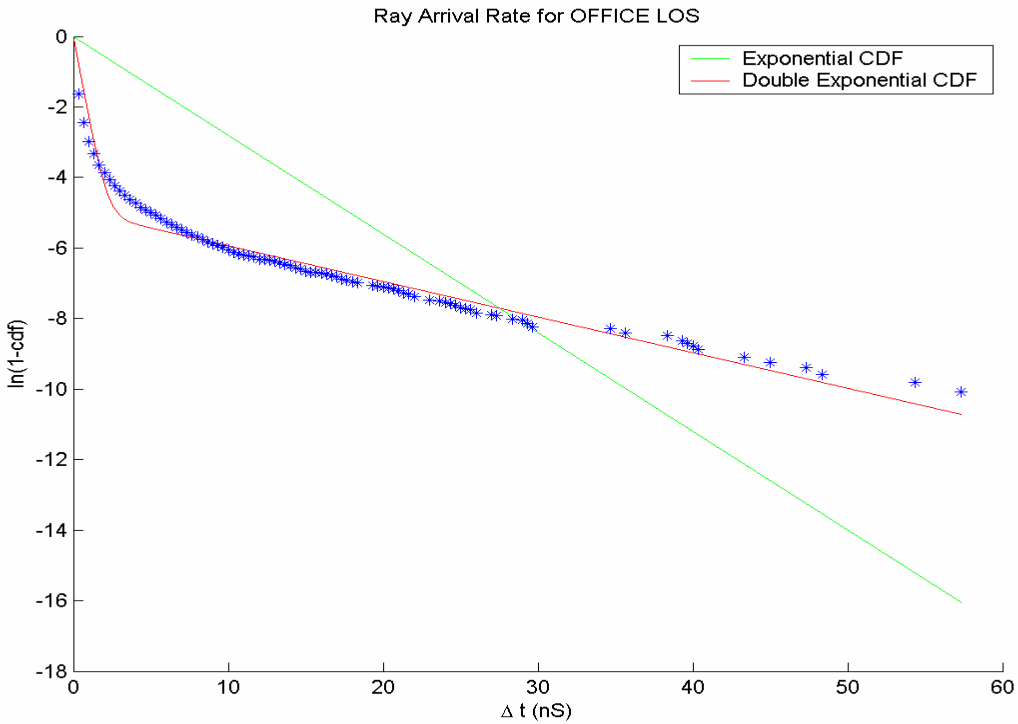
$$p(\tau_{k,l}|\tau_{k,l-1}) = \beta\lambda_1 \exp[-\lambda_1 (\tau_{k,l}-\tau_{k,l-1})] + (1-\beta)\lambda_2 \exp[-\lambda_2 (\tau_{k,l}-\tau_{k,l-1})], k>0 \qquad (4)$$

where Λ: cluster arrival rate

λ_1, λ_2: ray arrival rate

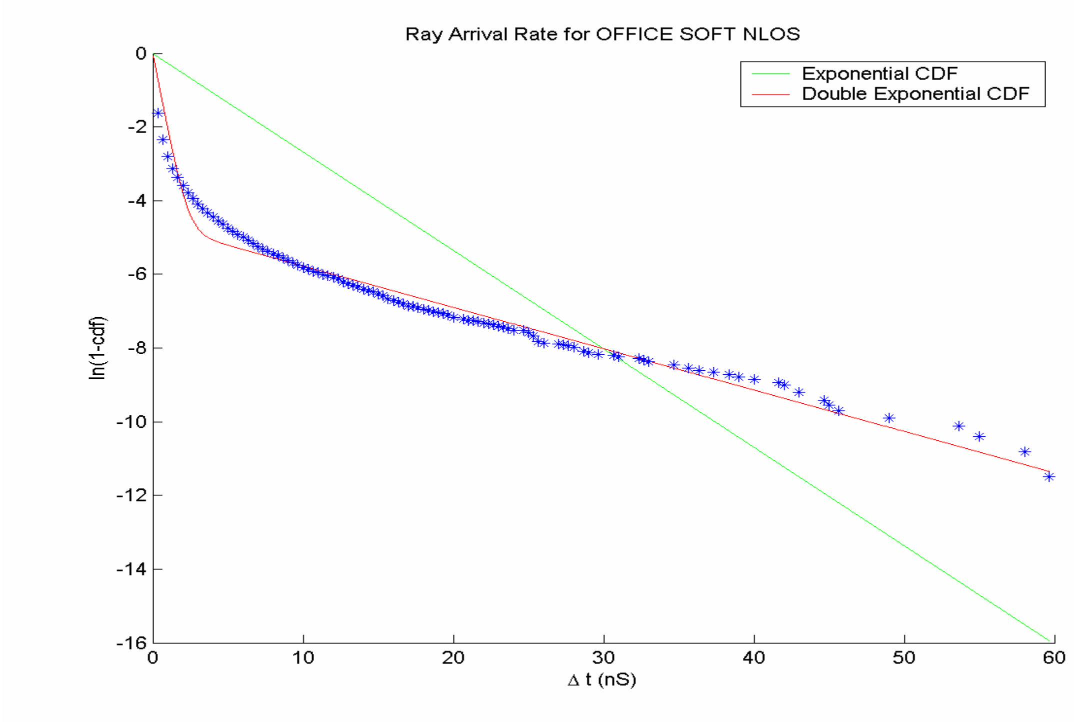
β: mixing probability

β, λ_1 and λ_2: OFF_LOS



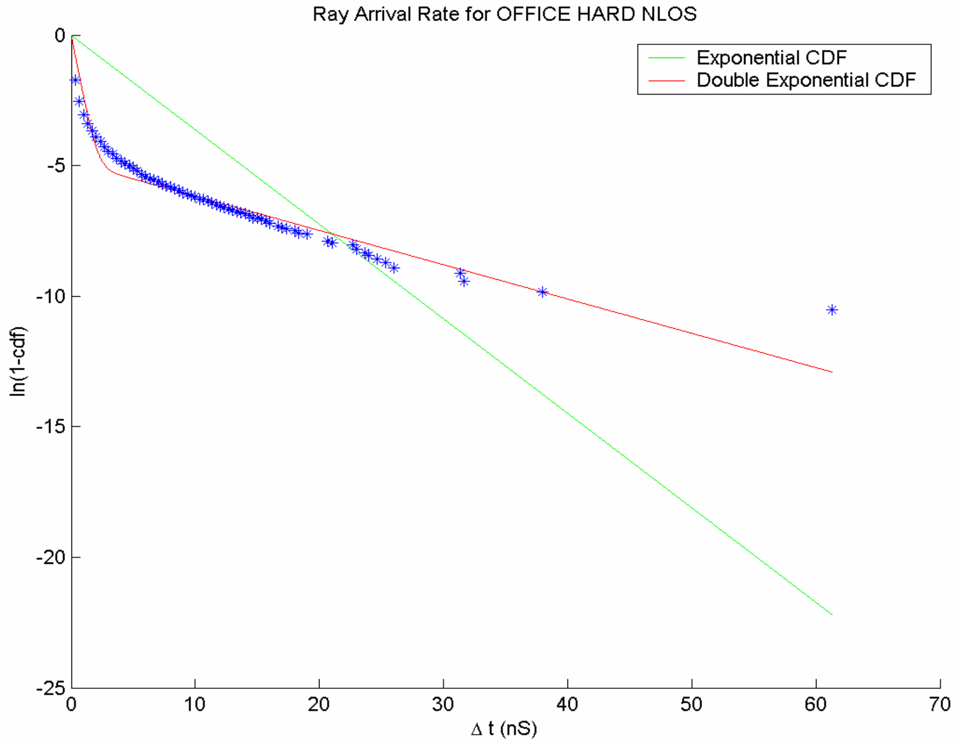
Fig(): OFF_LOS; β=0.0184, λ_1= 0.19 and λ_2=2.97

β, λ_1 and λ_2: OFF_SOFT_NLOS



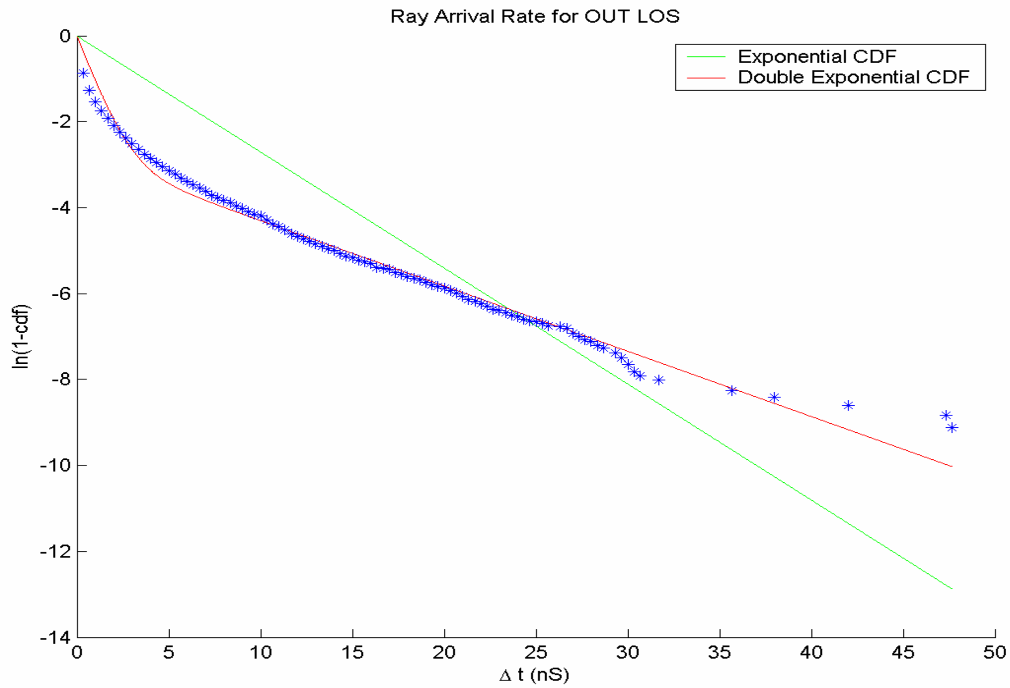
Fig(): OFF_SOFT_NLOS; β=0.0096, λ_1= 0.11 and λ_2=2.09

β, λ_1 and λ_2: OFF_HARD_NLOS



Fig(): OFF_HARD_NLOS; β=0.0078, λ_1= 0.13 and λ_2=2.41

β, λ_1 and λ_2: OUT_LOS



Fig(): OUT_LOS; β=0.00620, λ_1= 0.15 and λ_2=1.13

Extraction of Parameters: τ_m , τ_{rms}

- Mean excess delay, τ_m and root square mean excess delay, τ_{rms} can be calculated from

$$i^{th} \text{ order moment: } \tau^i = \frac{\sum_{l=0}^{L}\sum_{k=0}^{K} a_{k,l}^2 \tau_{k,l}^i}{\sum_{l=0}^{L}\sum_{k=0}^{K} a_{k,l}^2}$$

$$\tau_m = \tau^1, \quad \tau_{rms} = \sqrt{\tau^2 - (\tau^1)^2} \qquad (6)$$

Parameters Extracted From PDPs

- Parameters extracted from PDPs for various environments are tabulated in tab. (1) below:

Parameters	OFF_LOS	OFF_SOFT_NLOS	RM_HARD_NLOS	OUT_LOS
Mean # of clusters	5.4	3.6	2.5	13.6
Γ (ns)	27.8	30.4	24.6	60.1
γ (ns)	14.1	25.3	33.8	9.1
Λ (1/ns)	0.0186	0.0134	0.0024	0.0448
λ (1/ns)	0.28	0.27	0.36	0.27
(β, λ_1, λ_2)	(0.0184, 0.19, 2.97)	(0.0096, 0.11, 2.09)	(0.0078, 0.13, 2.41)	(0.0620, 0.15, 1.13)
τ_m (ns)	5.8	15.7	16.3	24.1
τ_{rms} (ns)	15.6	23.6	18.7	55.1

Tab. (1): PDP parameters

Amplitude Statistics: $a_{k,l}$

- For OFF_LOS measurements, 6 locations are selected with transmitter-receiver distances of 8, 12 and 16m (2 locations per distance).
- For OFF_SOFT_NLOS, 6 locations are selected with T-R distances of 8, 10 and 12m.
- For OUT_LOS, 6 locations are selected with T-R distances of 8, 10, 12 and 14m (2 locations for 8m and 10m, 1 each for 12m and 14m).
- For each location, measurements are made for receiver in K = 49 spatial points, defined on a 7x7 grid with 5cm separation to capture the small-scale fading.

Passband CIR

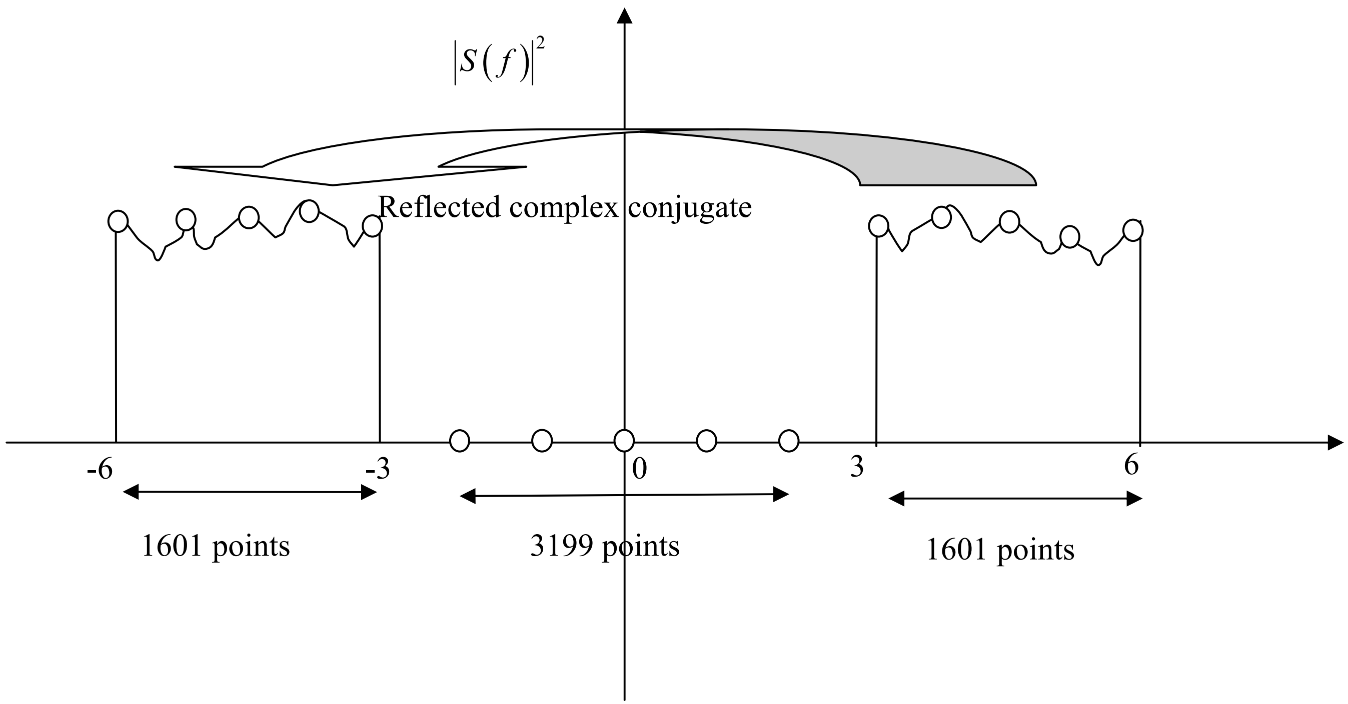


Fig. 21: Zero padding to obtain passband CIR

Data Processing on Passband CIR

- The reflected complex conjugate was padded with trailing 3199 (2x1601-3) zeros and the original complex frequency response to yield 6401-point complex frequency response data over 12 GHz.
- Inverse Fourier transform was then performed on the 6401-point complex frequency response to obtained 6401-point time domain complex CIR. The squared magnitude of the complex CIR would then yield the PDP.
- Since our measured data is from 3-6 GHz, i.e. 3 GHz bandwidth, binning of 4 time samples into 1 mulitpath component (MPC) needs to be performed.

Data Processing on Passband CIR

- For the aligned data, 4 samples are added (note this is power decay profile) to form a MPC.
- The binned data is then normalized to get rid of path loss and shadowing effect so that its sum is equal to 1.
- The normalized binned data is then square rooted (element-wise) to obtain the CIR.

Data Processing on Passband CIR

- The process of extracting the small-scale statistics involves fitting the data (obtained from the 49 spatial points in a location) in each bin to each of the 4 hypothesized distributions, namely **Rayleigh, Ricean, log-normal and Nakagami.**
- The parameters of the hypothesized distributions are obtained from the data via maximum likelihood estimation (MLE).
- The criteria for evaluating the fit of the distribution is based on hypothesis testing using **chi-square and Cramer-Von Mises** tests at 5% and 10% significance level.

Data Processing on Passband CIR

- K-S and Cramer-Von tests come under question as the parameters of the hypothesized distributions are obtained from the data.
- Chi-square test overcomes such limitation by decreasing the degrees of freedom for each parameter estimated.

Data Processing on Passband CIR

- For each bin, the maximum number of samples is 49 while a minimum number of 39 is set before the bin is considered “fit” for testing.
- The number 39 is chosen because the minimum expected count in each group is 10 for chi-square test to yield an accurate result (5 for satisfactory accuracy).
- A sample size of 39 can form 4 groups which gives 4-1=3 degrees of freedom. For Ricean, log-normal and Nakagami, 2 parameters are estimated which further gives 3-2=1 degree of freedom. Hence, at least 39 samples must be present in a bin to carry out an accurate chi-square test.

Amplitude Statistics: $a_{k,l}$

- The results of the distribution fitting are summarized in the following tables.

	Chi-square		Cramer-Von Mises	
	10%	5%	10%	5%
Rayleigh	19.5	30.3	21.1	34.3
Ricean	67.3	76.1	96.0	98.4
Lognormal	53.0	64.8	39.4	53.8
Nakagami	84.1	91.6	99.2	100

Tab.(2): Hypothesis test results for OFF_LOS

Statistics of $a_{k,l}$

	Chi-square		Cramer-Von Mises	
	10%	5%	10%	5%
Rayleigh	26.5	36.4	25.8	40.4
Ricean	62.6	75.2	96.7	99.7
Lognormal	53.3	63.6	41.7	54.0
Nakagami	82.8	89.4	99.3	100

Tab.(3): Hypothesis test results for OFF_SOFT_NLOS

Amplitude Statistics: $a_{k,l}$

	Chi-square		Cramer-Von Mises	
	10%	5%	10%	5%
Rayleigh	9.0	12.8	12.8	17.9
Ricean	60.3	67.9	85.9	92.3
Lognormal	55.1	69.2	61.5	65.4
Nakagami	75.6	83.3	92.3	96.2

Tab.(4): Hypothesis test results for OUT_LOS

Fitting of CDFs

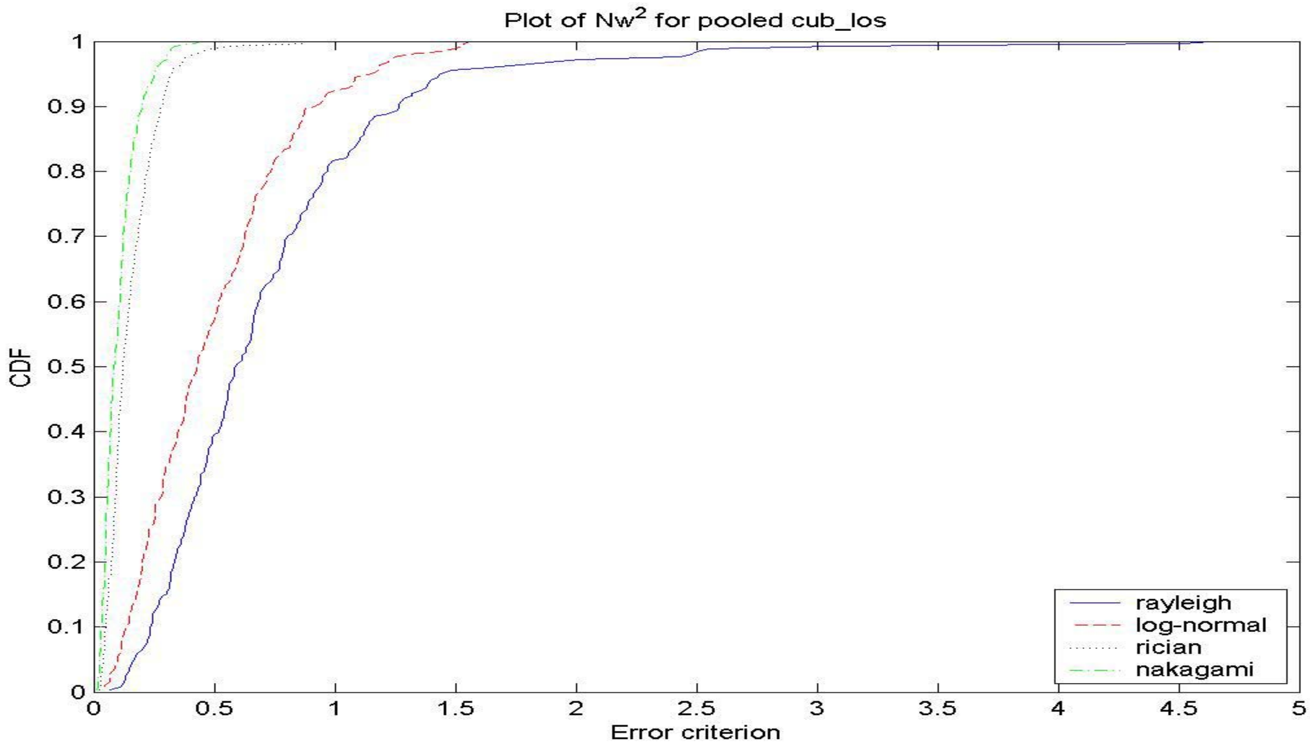


Fig. (22): CDF fitting for OFF_LOS

Fitting of CDFs

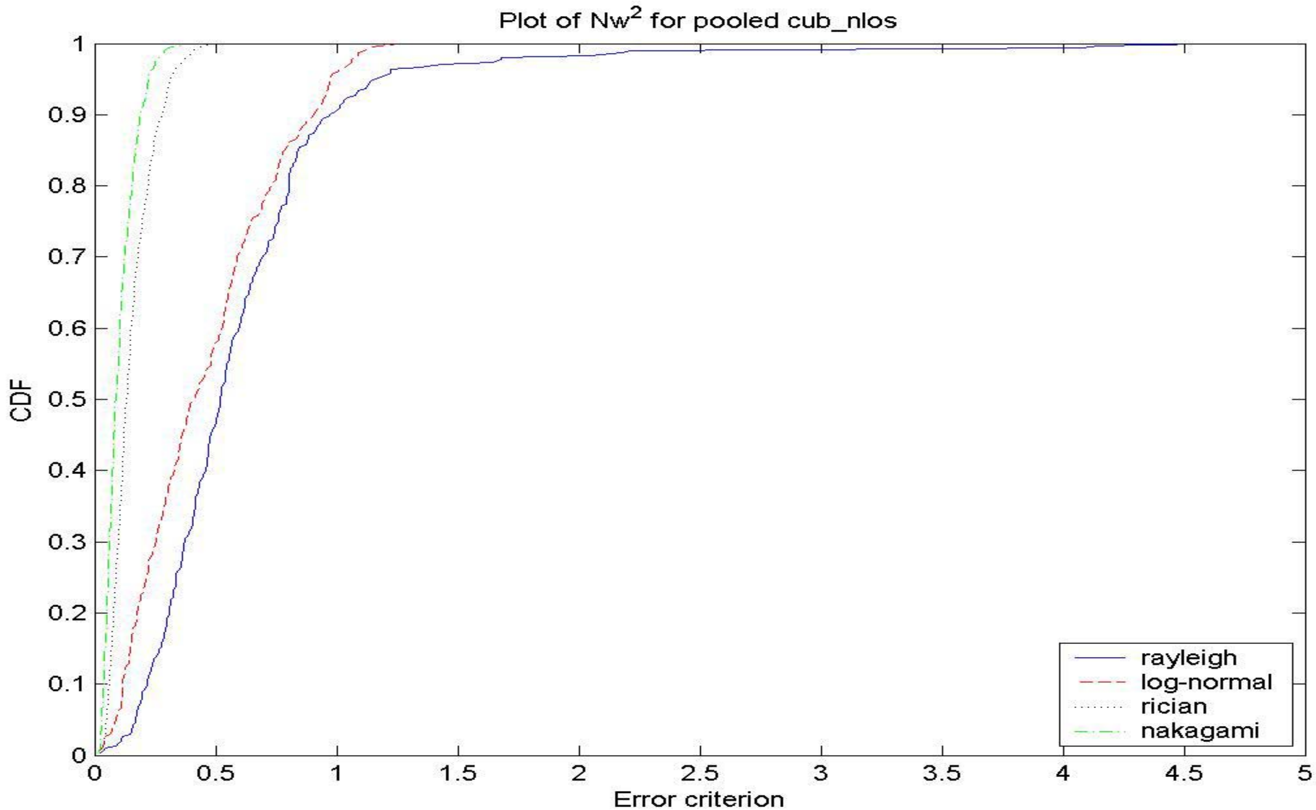


Fig. (22): CDF fitting for OFF_SOFT_NLOS

Fitting of CDFs

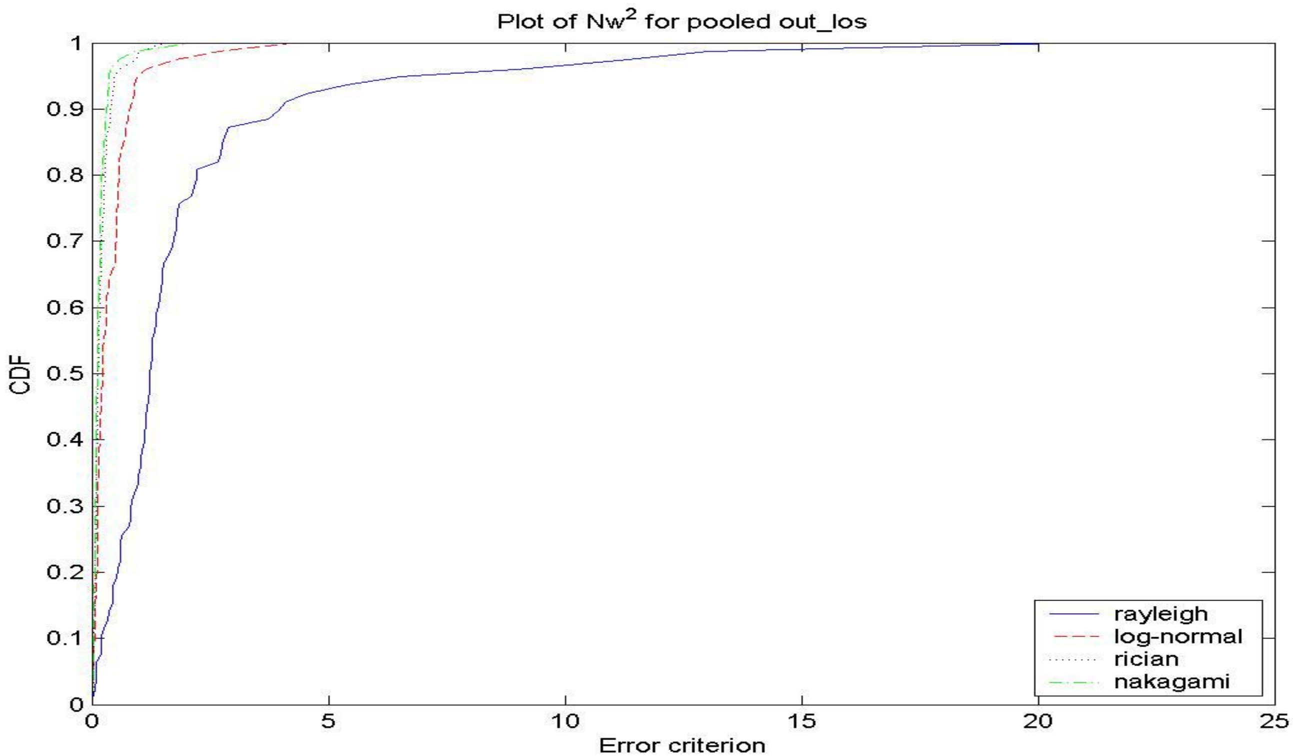


Fig. (23): CDF fitting for OUT_LOS

Nakagami m Factor

- Phenomenon of decreasing m with increasing delay was not observed.
- Instead, it was observed that, at the first few delays, the values of m are larger. For outdoor LOS cases, m values are large compared to that of the indoor LOS.
- Variations of 'm' with delays are plotted in figs.(24-26).
- It is found that the CDFs of these m values for all the scenarios fit well into a log-normal distributions as shown in figs. (27-29).

Nakagami m Factor

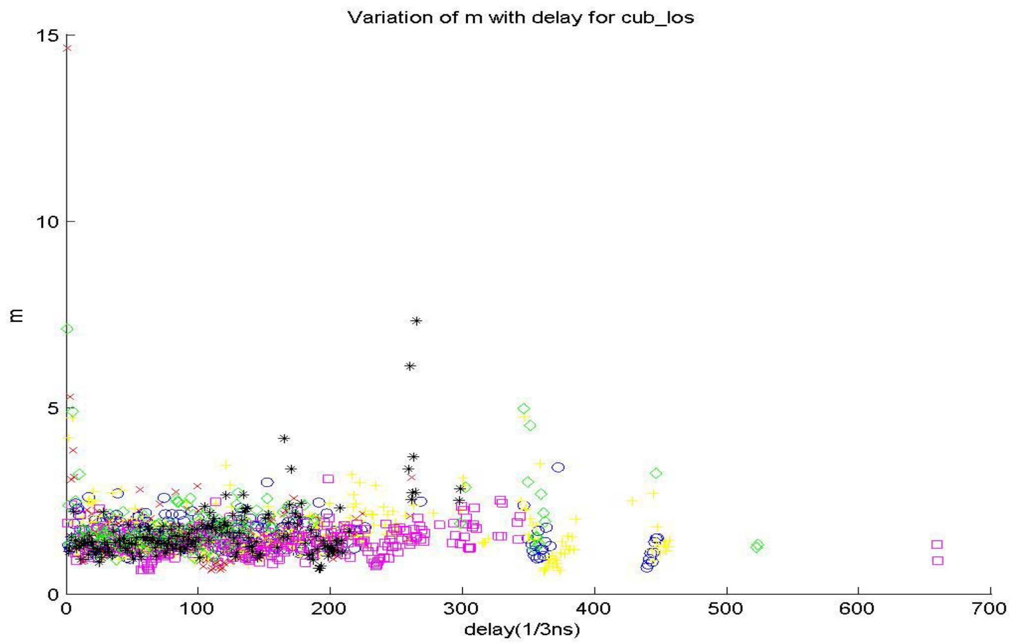


Fig. (24): m vs delay for OFF_LOS

Nakagami m Factor

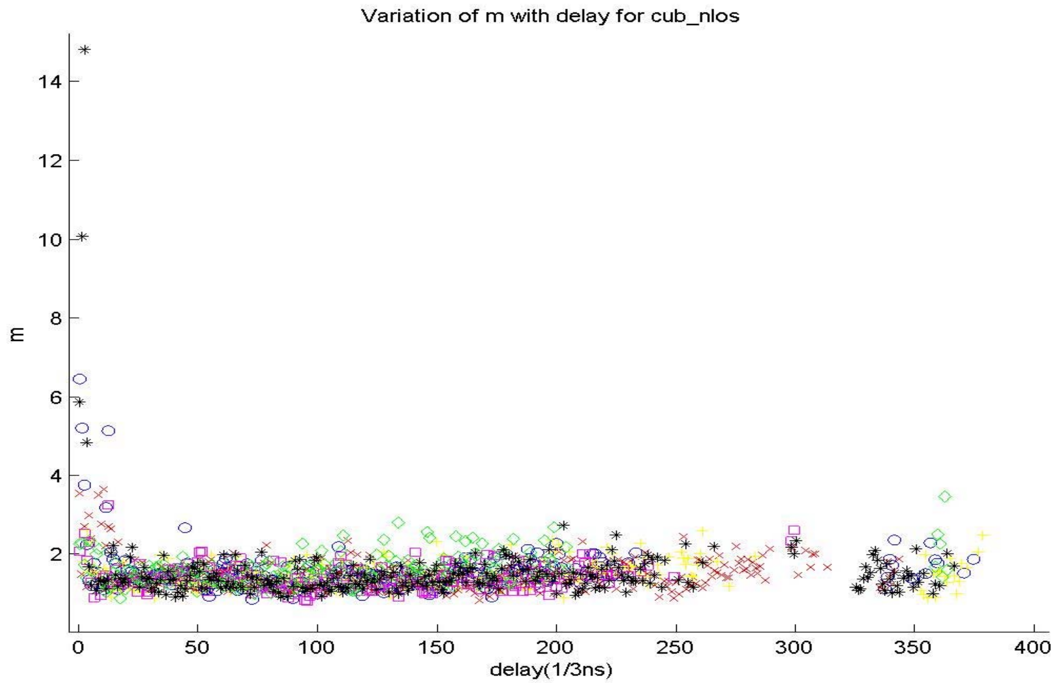


Fig. (25): m vs delay for OFF_SOFT_NLOS

Nakagami m Factor

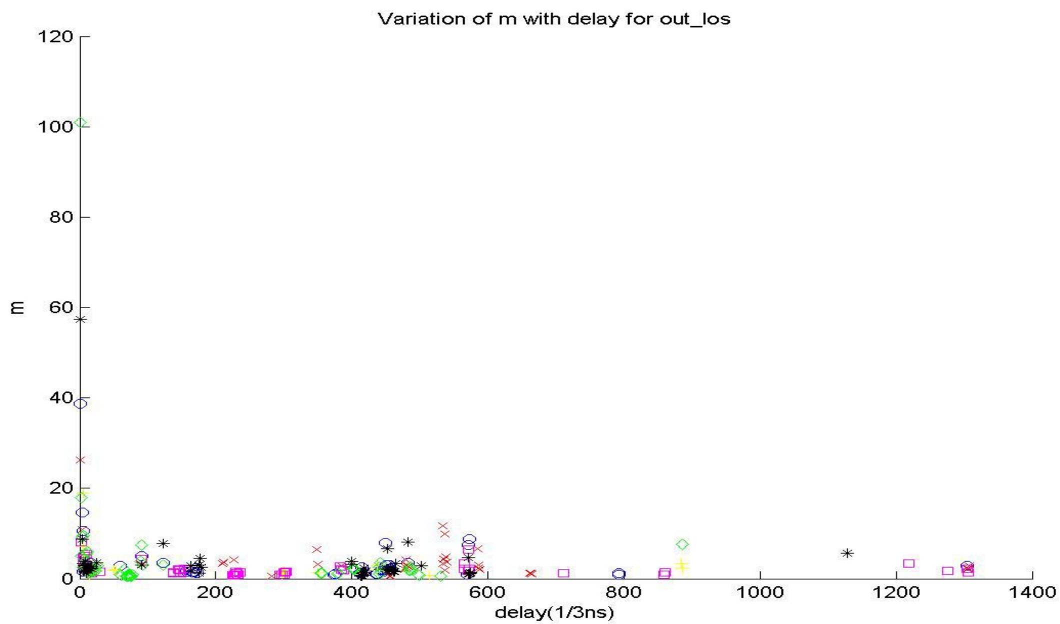


Fig. (26): m vs delay for OUT_LOS

Nakagami m Factor

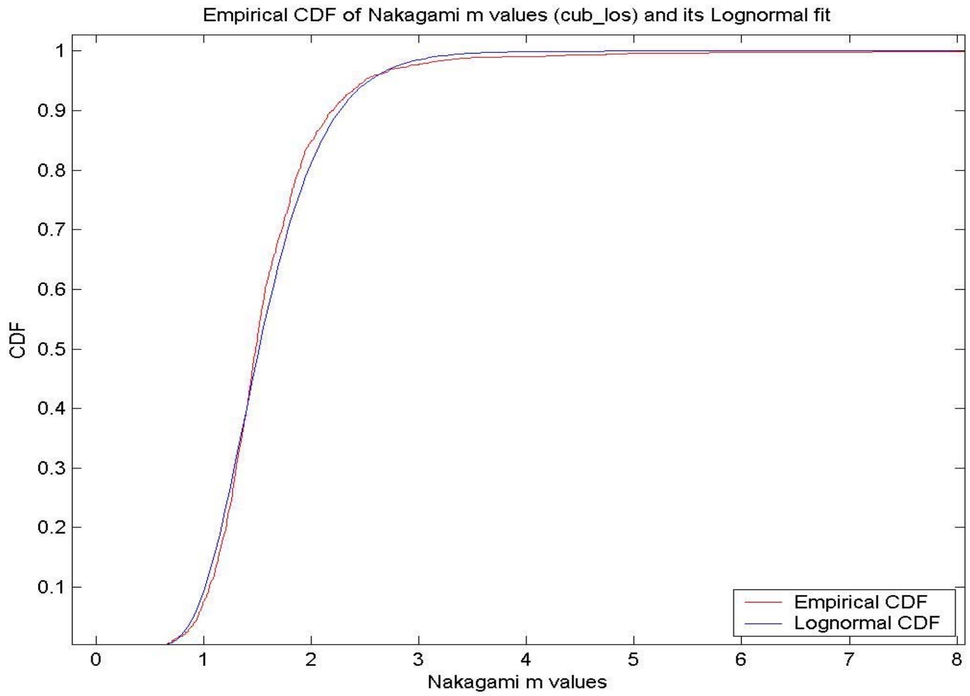


Fig. (27): cdf of 'm' OFF_LOS: μ_m = 0.41, σ_m =0.31

Nakagami m Factor

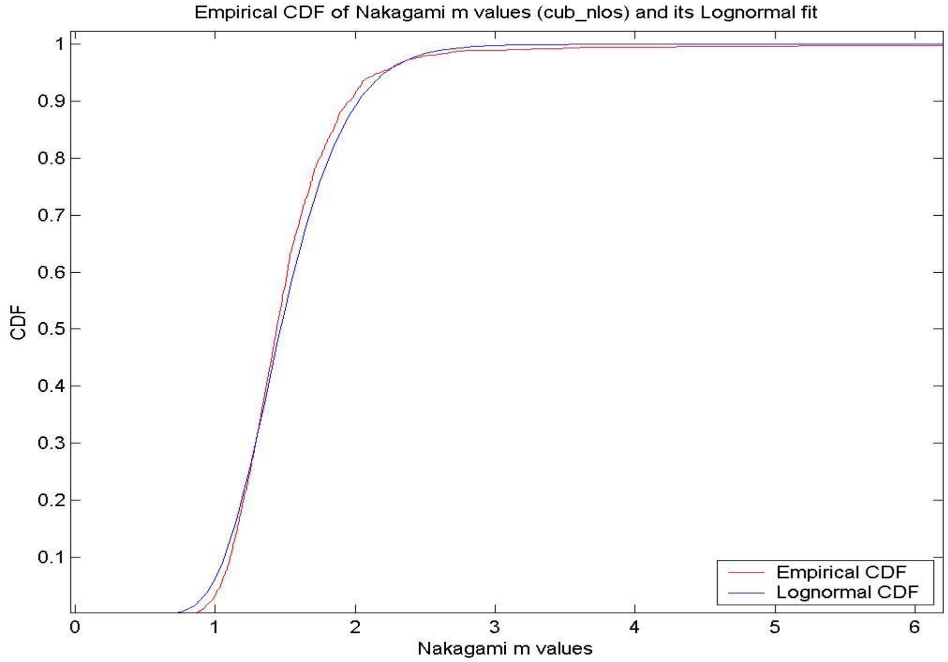


Fig. (28): cdf of 'm' OFF_SOFT_NLOS : μ_m = 0.38, σ_m =0.25

Nakagami m Factor

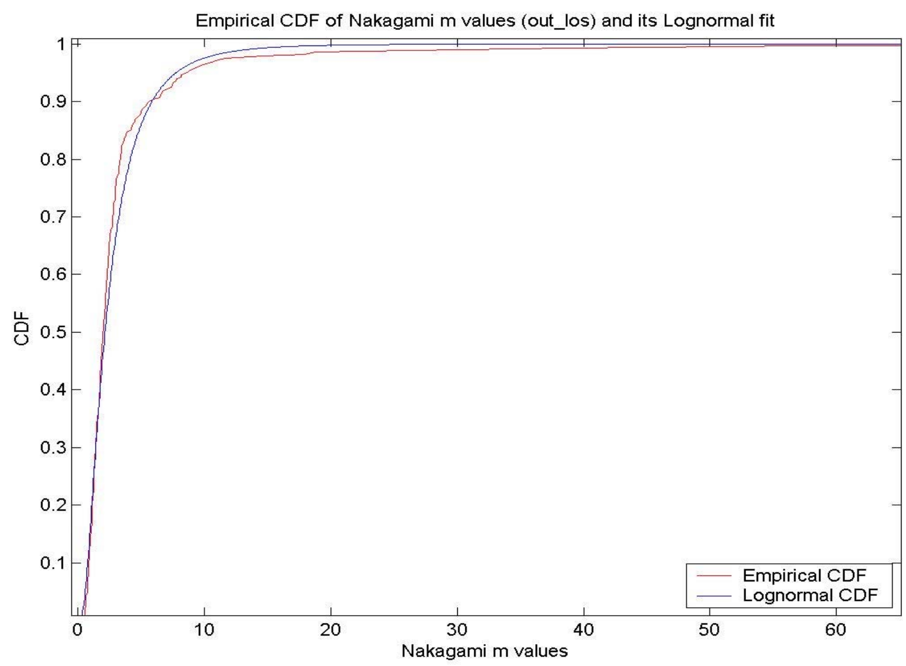


Fig. (29): cdf of 'm' OUT_LOS: μ_m = 0.78, σ_m =0.78

Parameters: UWB channels In Indoor & Outdoor Office Environments

	OFF_LOS	OFF_SOFT_NLOS	OFF_HARD_NLOS	OUT_LOS
Large-Scale Parameters				
ν	1.78	1.76	2.12	1.76
σ (dB)	1.45	2.43	4.21	0.83
PL_0 (dB)	36.62	52	46.35	43.29
δ (μ_δ , σ_δ) (freq. dependent PL)	(0.1156, 0.0063)	(0.4208, 0.0079)	(0.1904, 0.0070)	(0.1477, 0.0066)
r (μ_r , σ_r) ((freq. dependent PL)	(0.4752, 0.1243)	(1.8277, 0.1526)	(0.88349, 0.1345)	(0.6350, 0.1241)
Small-Scale Parameters				
Γ (ns)	27.8	30.4	24.6	60.1
γ (ns)	14.1	25.3	33.8	9.1
Λ (1/ns)	0.0186	0.0134	0.0024	0.0448
λ (1/ns)	0.28	0.27	0.36	0.27
(β, λ_1, λ_2)	(0.0184, 0.19, 2.97)	(0.0096, 0.11, 2.09)	(0.0078, 0.13, 2.41)	(0.0620, 0.15, 1.13)
Mean Excess Delay, τ_m (ns)	5.8	15.7	16.3	24.1
RMS Delay Spread, τ_{RMS} (ns)	15.6	23.6	18.7	55.1
Energy concentration	99.1%	96.9%	97.8%	93.3%
Mean Number of Clusters	5.4	3.6	2.5	13.6
Amplitude Statistics, a_k	Nakagami Distribution	Nakagami Distribution	N/A	Nakagami Distribution
Nakagami m-factor (fit well into a log-normal distribution)				
Mean	0.42	0.38	N/A	0.78
Variance	0.31	0.25	N/A	0.77

Tab(5): UWB Channel Parameters

Conclusion (1)

- We performed channel measurements and extracted relevant small-scale parameters to characterize the UWB channels in indoor and outdoor office environments.
- Unlike the conventional way, we set our threshold from the noise floor (10 dB above the noise floor) instead of from the peak power level.
- It is observed that the outdoor environments have larger delay spreads compared to that of the indoor environments.
- In the outdoor environments, the mean number of clusters is much larger than the indoor environments.

Conclusions (2)

- The results shows that the Nakagami distributions fit the amplitudes statistics very well in all three environments.
- In all three environments, the distribution of Nakagami m values fit well into a log-normal distribution.
- The results also show that the ray arrival rates for all the propagation environments studied in this report can be better modeled by mixture of Poisson processes.