Probabilistic Omnidirectional Path Loss Models for Millimeter-Wave Outdoor Communications

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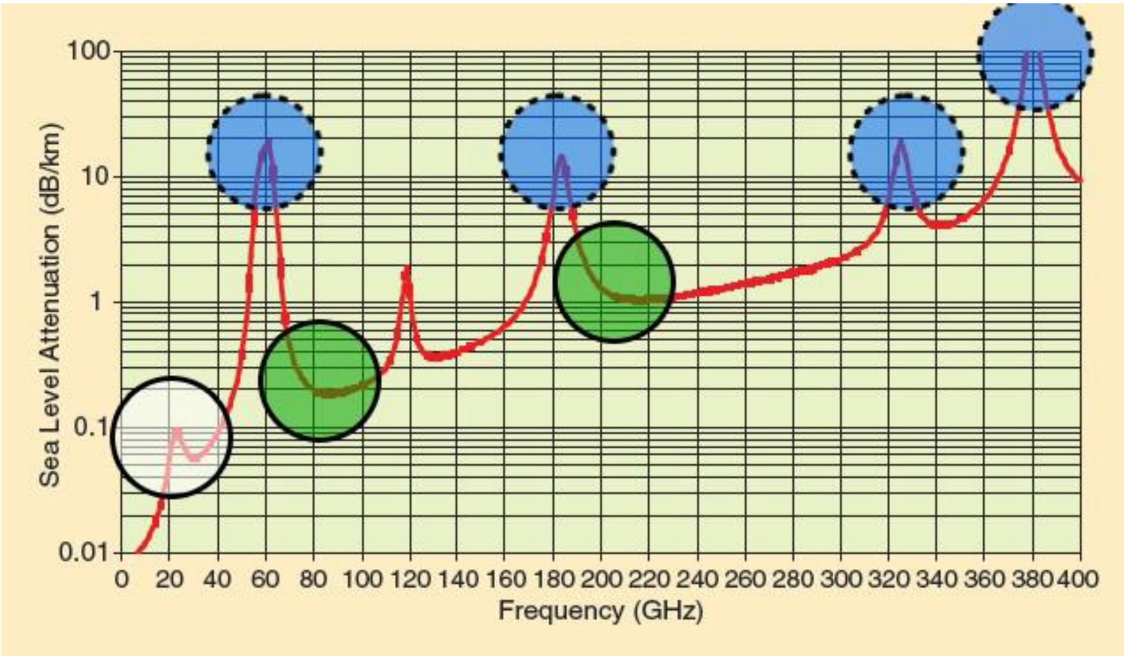
CONTENTS

Previous Work

Propagation path loss models have been synthesized from the collected unique pointing angle (directional) ***28 GHz*** and ***73 GHz*** mmWave measurements in New York City reported in [3], [4],using both the traditional close-in free space reference distance model, and the floating-intercept least-squares regression model [2], [5].

Measurements Parameters



- Researchers have shown that at **the mmWave bands** of **28 GHz, 38 GHz, and the 73 GHz** E-band, there will be a negligible degree of atmospheric attenuation for inter-site distances up to 200 m [3], [5], [10], [11].

Fig. 1. **Air attenuation at different frequency bands** [3].
The white circle shows at 28 and 38 GHz air attenuation is very small, providing feasibility of millimeter wave communication at such frequencies.
The green circles show the attenuation similar to attenuation in current communication systems, comparably larger than the white circle.
The blue circles indicate frequencies with high attenuation, thus viable for indoor communication.

Floating-intercept model

- Fitting a minimum mean square error (MMSE) best fit line to the measured path losses (with distances in log- scale), yielding a mathematically-based omnidirectional path loss model, applicable over the range of measured distance

Close-in free space reference distance model

- Arising from electromagnetic theory
- **using a constraint anchor point** at the close-in reference distance d_0 (assuming free space propagation up to d_0) when fitting the MMSE best fit line, where the slope of the best fit line and standard deviation beyond d_0 are commonly known as the **path loss exponent (PLE)** and **shadowing factor**, respectively.

Previous Work

Omnidirectional path loss at an arbitrary distance d may be estimated using the close-in free space reference distance model, as shown in Eq. 1:

$$\mathrm{PL}(d)[\mathrm{dB}] = \mathrm{PL}(d_0) + 10\,\overline{n}\log_{10}\left(\frac{d}{d_0}\right) + X_\sigma \quad (d \geq d_0) \quad (1)$$

where,

$$\mathrm{PL}[\mathrm{dB}](d_0) = 20\log_{10}\left(\frac{4\pi d_0}{\lambda}\right) \quad (2)$$

$$\lambda = \frac{c}{f_c} \quad (3)$$

where d_0 (m) is the free space reference distance, λ (m) is the carrier wavelength, $c = 3 \times 10^8$ m/s, f_c (Hz) is the RF carrier frequency, $\overline{n}$ is the path loss exponent, and X_σ is the typical log-normal random variable with 0 dB mean and standard deviation σ that models large scale fading [11]. Note that $\mathrm{PL}(d_0)$ in Eq. 1 models the frequency dependence through λ. In this work, we specify $d_0 = 1$ m for simplicity.

The floating-intercept model is currently used in standards work such as 3GPP and WINNER II, and is shown below:

$$\boxed{\mathrm{PL}[\mathrm{dB}] = \alpha + 10 \cdot \beta \log_{10}(d) + X_\sigma} \quad (4)$$

where X_σ is the log-normal random variable with 0 dB mean and standard deviation σ [12]. The WINNER II path loss model is a floating-intercept model, and is shown below [13]:

$$\mathrm{PL} = A\log_{10}(d[\mathrm{m}]) + B + C\log_{10}\left(\frac{f_c[\mathrm{GHz}]}{5.0}\right) + X \quad (5)$$

where A is a fitting parameter that includes the path loss exponent, B is the incercept, C is a path loss frequency-dependent parameter, and X is an environment-specific term [13]. This model is frequency-dependent between 2-6 GHz.

Works In The Paper

- we present omnidirectional path loss models based on the same New York City data from both **line-of-sight (LOS)** and **non-line-of-sight (NLOS)** locations,
- but consider a site-specific function that describes the probability of having a LOS path for a given transmitter-receiver (T-R) separation distance.
- In this new "hybrid" path loss model, the mean estimated path loss is **probabilistic**.

Definition of LOS and NLOS

The probability of LOS

- the probability that radiation from the transmitter (TX) will not be blocked by buildings or other obstructions, traveling along a straight and unobstructed propagation path in the urban environment (i.e., zero reflections) to the receiver (RX).

The NLOS probability

- the probability that the radiation will be obstructed by at least one object, and travel along an obstructed path to reach the RX (i.e., via scattering, or from one or more reflections).

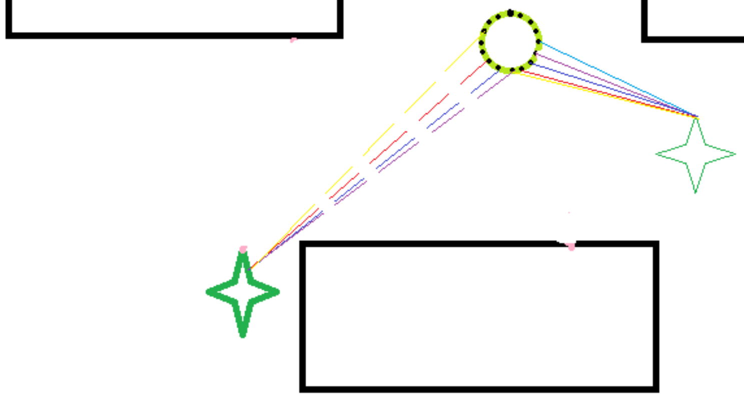
Obtained the LOS probabilities

To estimate the LOS probability for a T-R separation distance R

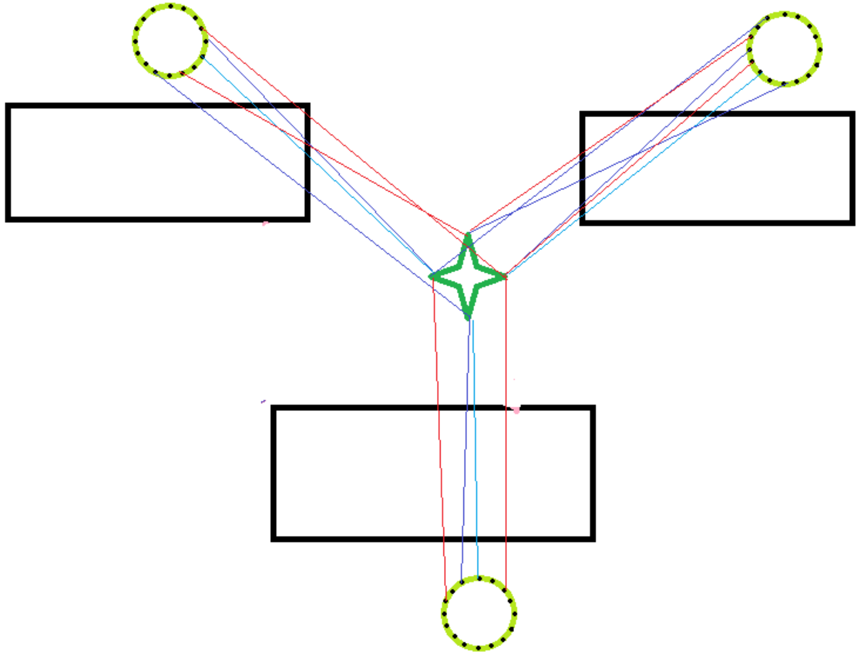
- **a circle** was discretized **in 100 evenly-spaced points** on the circumference around each TX location in the environment database.
- For each position along the circle external to a building or obstruction, ray-tracing was used to **draw a line** from the RX to the TX.
  - If that line to the TX penetrated through **at least one building**, the corresponding initial position at radius R on the circle was denoted as a **NLOS** position.
  - If the line to the TX was **unobstructed**, then that position was counted as a **LOS** position.
- This was repeated for all positions along the circle circumference, and the **ratio** of the number of LOS positions to the total number of positions along the circle provided the **LOS probability**. This was performed over radii ranging from **10 m to 200 m**, in increments of 1 m.

Obtained the LOS probabilities

PROBABILITY OF LOS



a LOS position



a NLOS position

Obtained the LOS probabilities

Raytracing techniques

- all buildings near the transmitters were represented in a 3-dimensional (3-D) database
- The 3-D geometric information was then exported from Google SketchUp into XML format, and subsequently extracted to numerically discretize the environment in MATLAB.

LOS test

- determine whether any of the database objects (buildings) blocked the direct connection line (LOS) between the TX and RX.

Obtained the LOS probabilities

Parameters

- ➢ Distances between the TX and RX ranged from *10* m to *200* m
- ➢ RX height of *1.5* m.

3-D model and ignore

- ➢ buildings were modeled as 3-D cubes with perfectly smooth, flat surfaces,
- ➢ while smaller obstructions such as trees, lampposts, and vehicular traffic were ignored

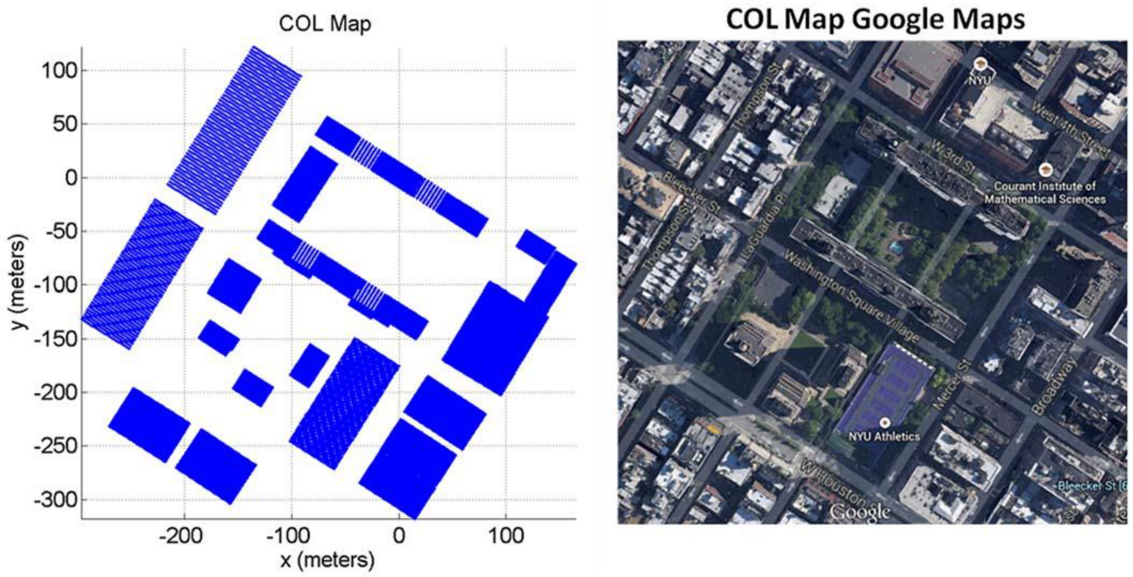
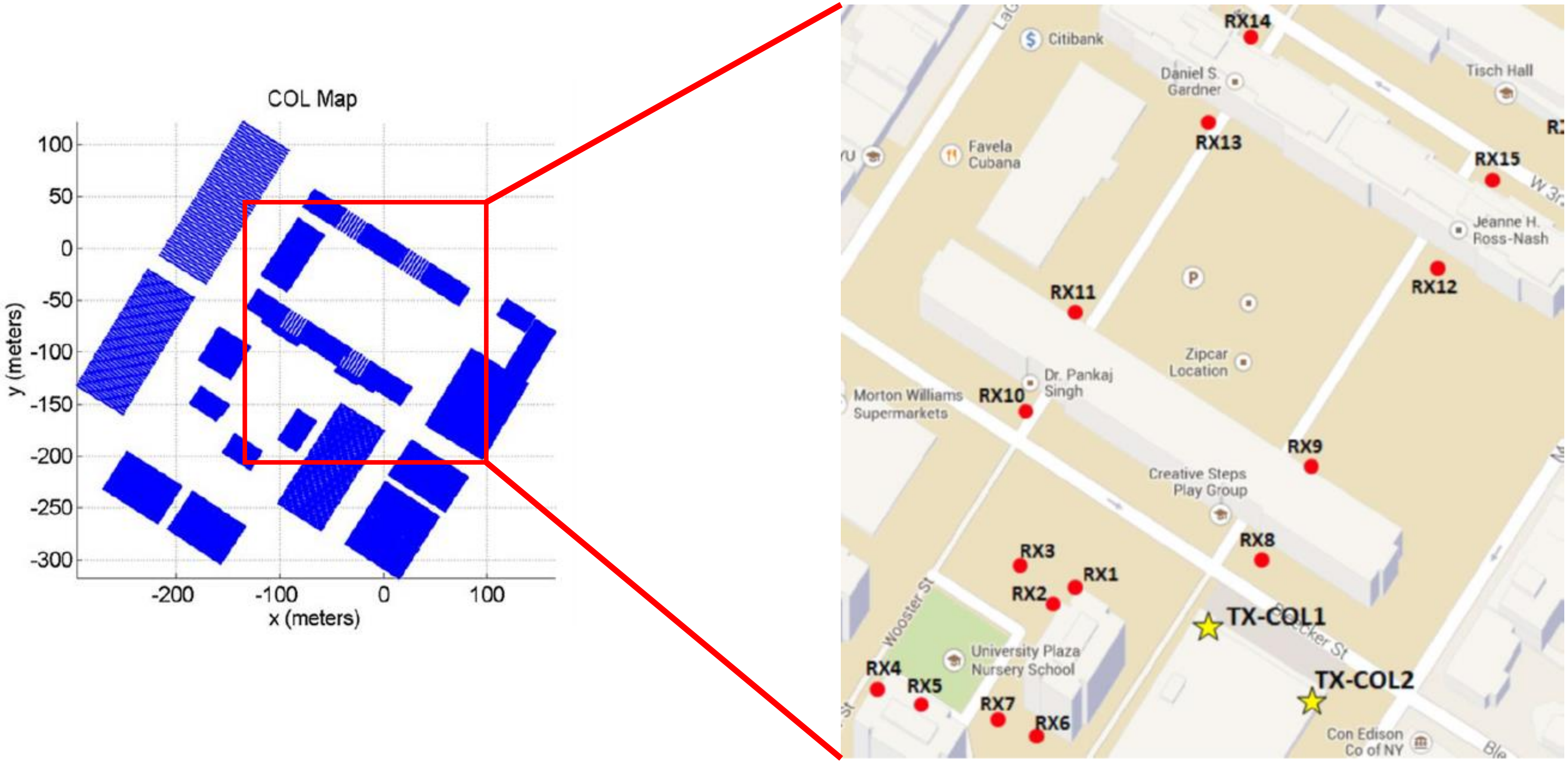


Fig. 1. Top view of the Coles (COL) Sports Center environment taken from Google Maps (right), and the corresponding environment (top view) reproduced in MATLAB (left). Buildings are represented by blue objects, and the white areas represent free space.

Obtained the LOS probabilities

PROBABILITY OF LOS



Obtained the LOS probabilities

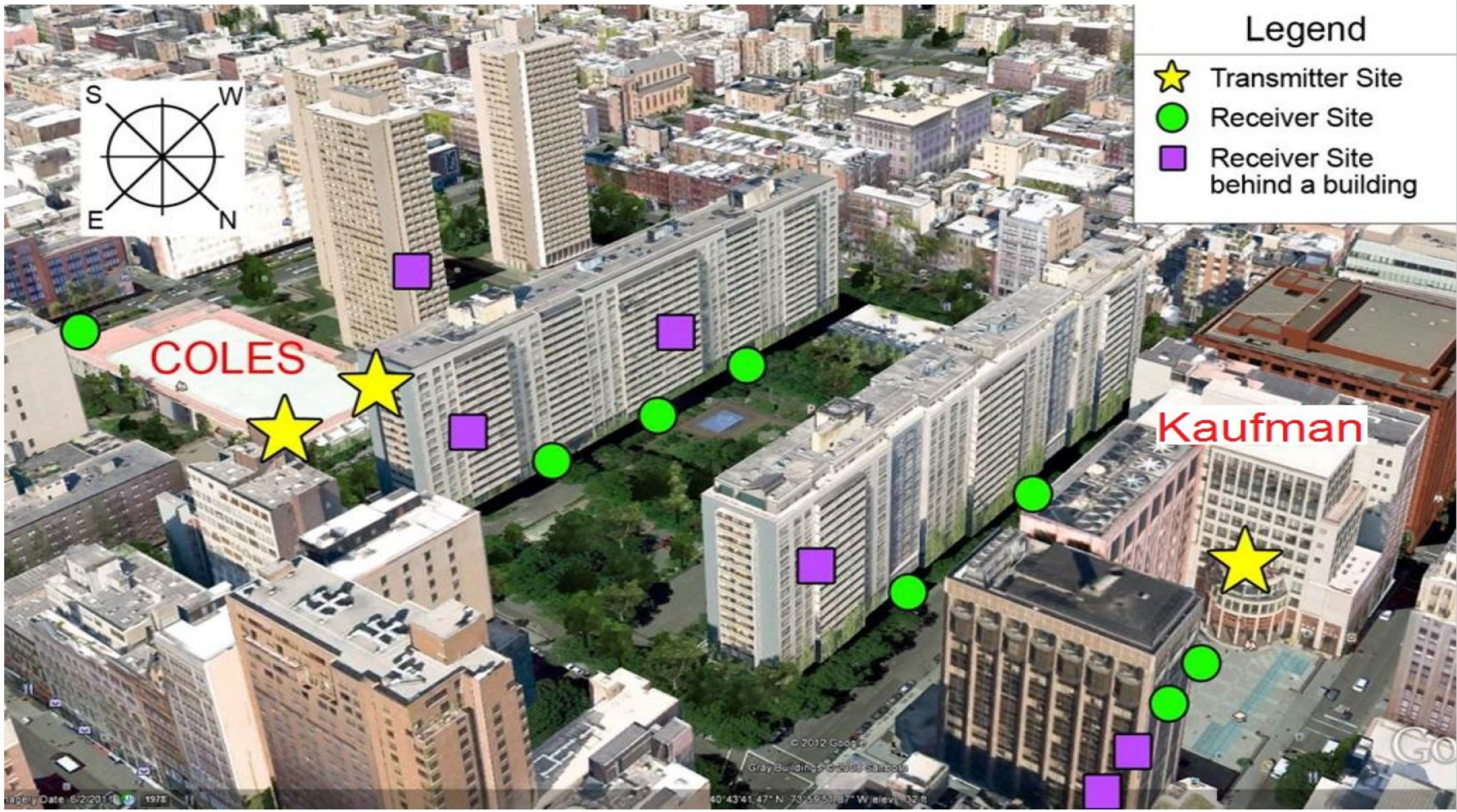
PROBABILITY OF LOS

- 4 TX sites
- 33 RX sites (35 w/ LOS)

- Pedestrian and vehicular traffic
- High rise-buildings, trees, shrubs

- TX sites:
  - TX-COL1 – 7 m
  - TX-COL2 – 7 m
  - TX-KAU – 17 m
  - TX-ROG – 40 m

- RX sites:
  - Randomly selected near AC outlets
  - Located outdoors in walkways



Obtained the LOS probabilities

PROBABILITY OF LOS

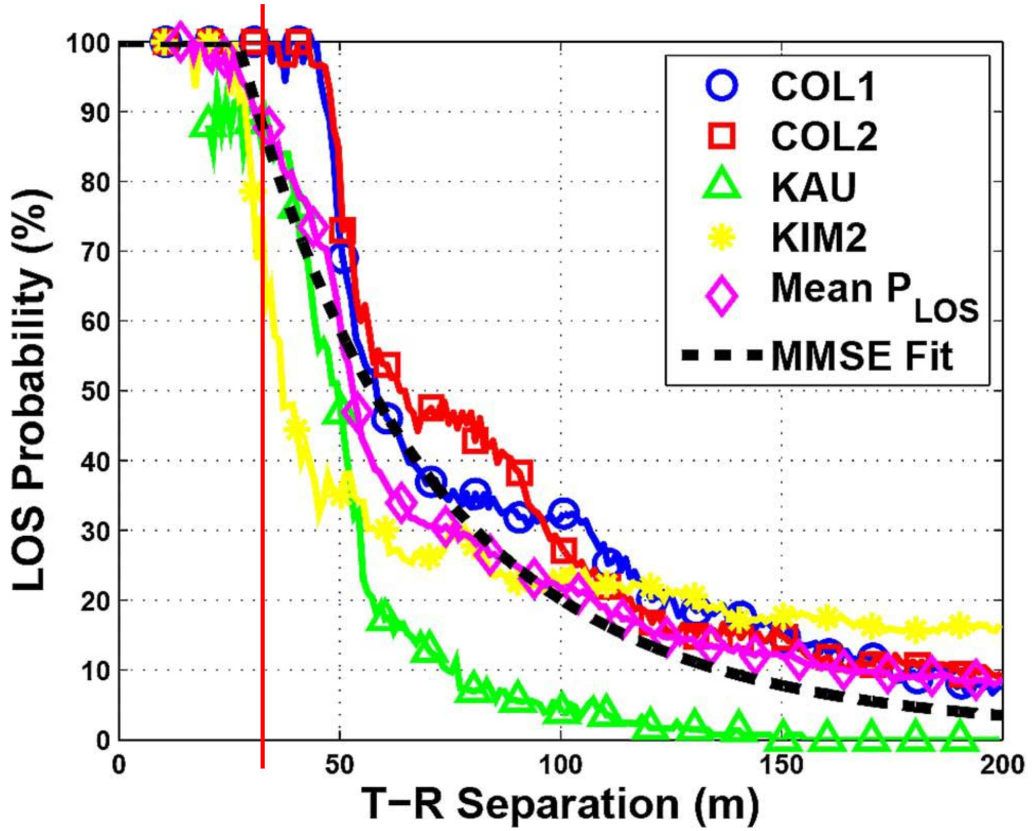


Fig. 2. LOS probability curves from ray-tracing as a function of T-R separation distance for **TX locations**

- As the T-R separation distance increases from ***10*** m to about ***30*** m, the probability of LOS remains constant with a value of ***100%***
- And it decreases monotonically after 30 m, as the environment becomes denser with more path obstructions.
- The mean LOS probability was computed from the four distinct LOS probability curves from the four physical TX locations used in [3] and [4].
- The mean LOS probability curve was fit to an analytical function.

Obtained the LOS probabilities **PROBABILITY OF LOS**

$$P_{\mathrm{LOS}}(d) = \left[\min\left(\frac{d_{\mathrm{BP}}}{d}, 1\right)\left(1 - e^{-\frac{d}{\alpha}}\right) + e^{-\frac{d}{\alpha}}\right]^2 \quad (1)$$

- d_{BP} is the breakpoint distance at which the LOS probability is no longer equal to **1**, α *(m)* is a decay parameter.

  - In this work, we applied the minimum mean square error (MMSE) method, which yielded values of d_{BP} = *27 m* and α = *71 m* that minimize the mean square error between the mean LOS curve in Fig. 2 and (1)

- Other cities and environments will likely have different values of d_{BP} and α , based on the density of buildings, the width of streets, and the heights of TX and RX antennas.

Measurements Parameters

Floating-intercept model

- provides a method for estimating path loss data in a given range of measured T-R separations, but can give non-realistic path loss results if extrapolated outside the measured range.
- But the slope of this model often has no physical basis

Close-in free space reference distance model

- physically based
- adequately estimates path loss data points,

but is sensitive to the selected free space reference distance anchor point d_0 when estimating the NLOS data, where the choice of d_0 is **subjective**

Measurements Parameters

- Establishing a standard free space reference distance of $d_0 = 1\ m$ for all mmWave measurements and path loss models **removes** this **subjectivity**, and offers a standard approach for propagation models at any mmWave frequency with any antenna.

- As long as measurements are obtained in the far field of an antenna, the measured data and corresponding path loss models may be recast with a $1\ m$ reference distance.

- By bringing both LOS and NLOS models **together** to improve path loss estimation, we propose here to combine LOS and NLOS propagation using the close-in free space reference distance model (for LOS) and a floating-intercept model (for NLOS), respectively, and weigh the LOS and NLOS path losses using a probabilistic distribution for the probability of LOS as a function of T-R separation.

Measurements Parameters

- A fixed reference distance of ***d_0 = 1 m*** , and the probability of LOS shown in (1).

- The LOS and NLOS path loss equation lines are of this form :

$$PL[\mathrm{dB}](d) = 20\log_{10}\left(\frac{4\pi d_0}{\lambda}\right) + 10\overline{n}\log_{10}\left(\frac{d}{d_0}\right) + X_\sigma \qquad d \geq d_0 \quad (2)$$

- ***PL_{LOS}*** is the LOS free space path loss

$$PL_{\mathrm{LOS}}[\mathrm{dB}](d) = 20\log_{10}\left(\frac{4\pi}{\lambda}\right) + 10\overline{n}_{\mathrm{LOS}}\log_{10}(d) + X_{\sigma,\mathrm{LOS}} \qquad d \geq 1\ \mathrm{m} \quad (3)$$

Measurements Parameters

$$PL_{\mathrm{NLOS,Close-In}}[\mathrm{dB}](d) = 20\log_{10}\left(\frac{4\pi}{\lambda}\right) + 10\overline{n}_{\mathrm{NLOS}}\log_{10}(d) + X_{\sigma,\mathrm{NLOS}}, \qquad d \geq 1 \text{ m} \qquad (4)$$

$$PL_{\mathrm{NLOS,Floating}}[\mathrm{dB}](d) = \alpha + 10\beta\log_{10}(d) + X_{\sigma,\mathrm{NLOS}} \qquad 30 \text{ m} < d < 200 \text{ m} \qquad (5)$$

- $PL_{NLOS,Close-In}$ and $PL_{NLOS,Floating}$ are the NLOS path losses computed using the ***1 m*** close-in free space reference distance and the floating-intercept models, respectively,
- λ is the carrier wavelength
- $\boxed{\overline{n}_{\mathrm{LOS}} \text{ and } \overline{n}_{\mathrm{NLOS}}}$ are the average (over distance) path loss exponents in LOS and NLOS, respectively·
- α and β are the intercept and slope of the floating-intercept model parameters
- X_σ is the lognormal random variable (normal in ***dB***) with standard deviation σ (***dB***) to model largescale shadowing.

Measurements Parameters

- The omnidirectional LOS path loss exponent and shadowing factor with respect to a ***1 m*** free space reference distance were computed to be
- $n_{LOS} = 2.1$ and $\sigma_{LOS} = 3.6$ dB at 28 GHz
- $n_{LOS} = 2.0$ and $\sigma_{LOS} = 4.8$ dB at 73 GHz
- For the NLOS ,
- $n_{NLOS} = 3.4$ and $\sigma_{NLOS} = 9.7$ dB at 28 GHz
- $n_{NLOS} = 3.4$ and $\sigma_{NLOS} = 7.9$ dB at 73 GHz
- The NLOS floating-intercept path loss equation lines produced the following parameters
- $\alpha = 79.2$ dB, $\beta = 2.6$ and $\sigma_{NLOS} = 9.6$ dB at 28 GHz
- $\alpha = 80.6$ dB, $\beta = 2.9$ and $\sigma_{NLOS} = 7.8$ dB at 73 GHz

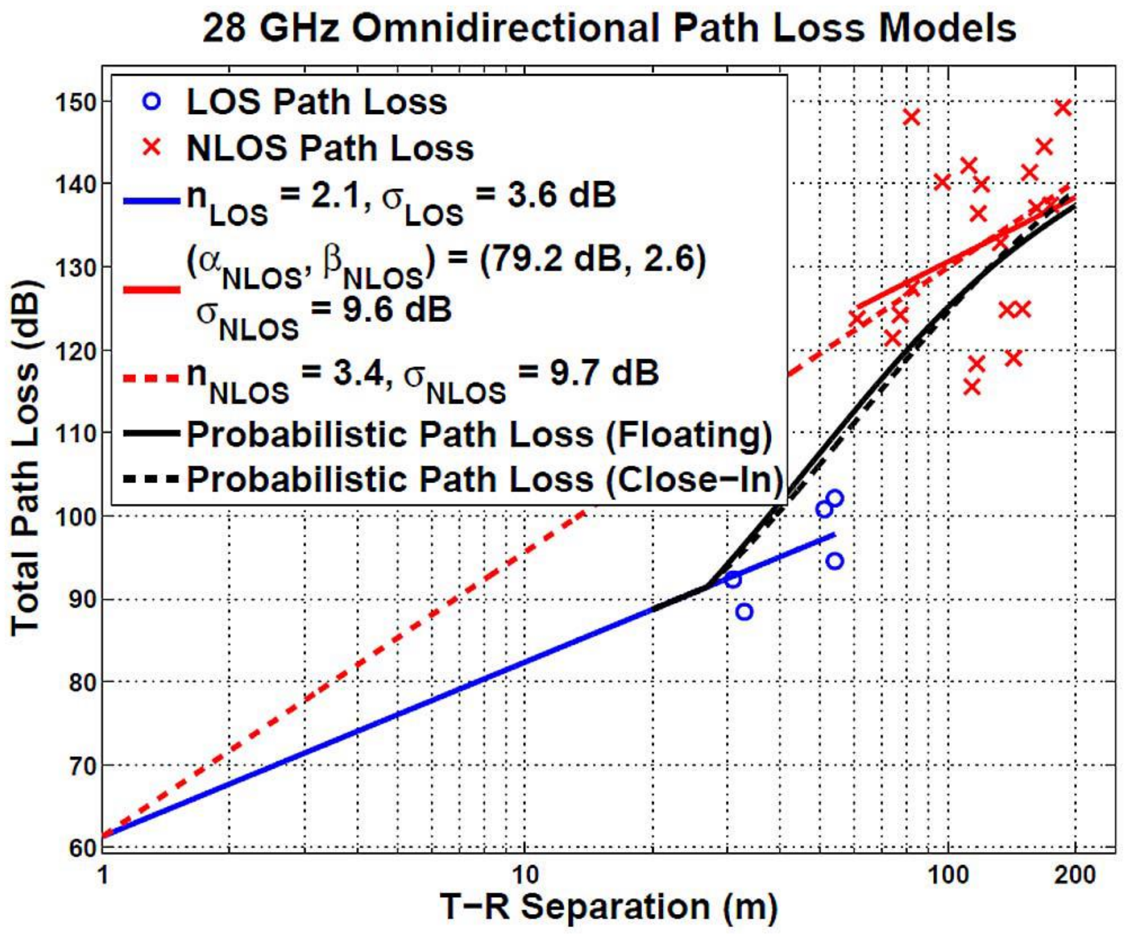
Measurements Parameters

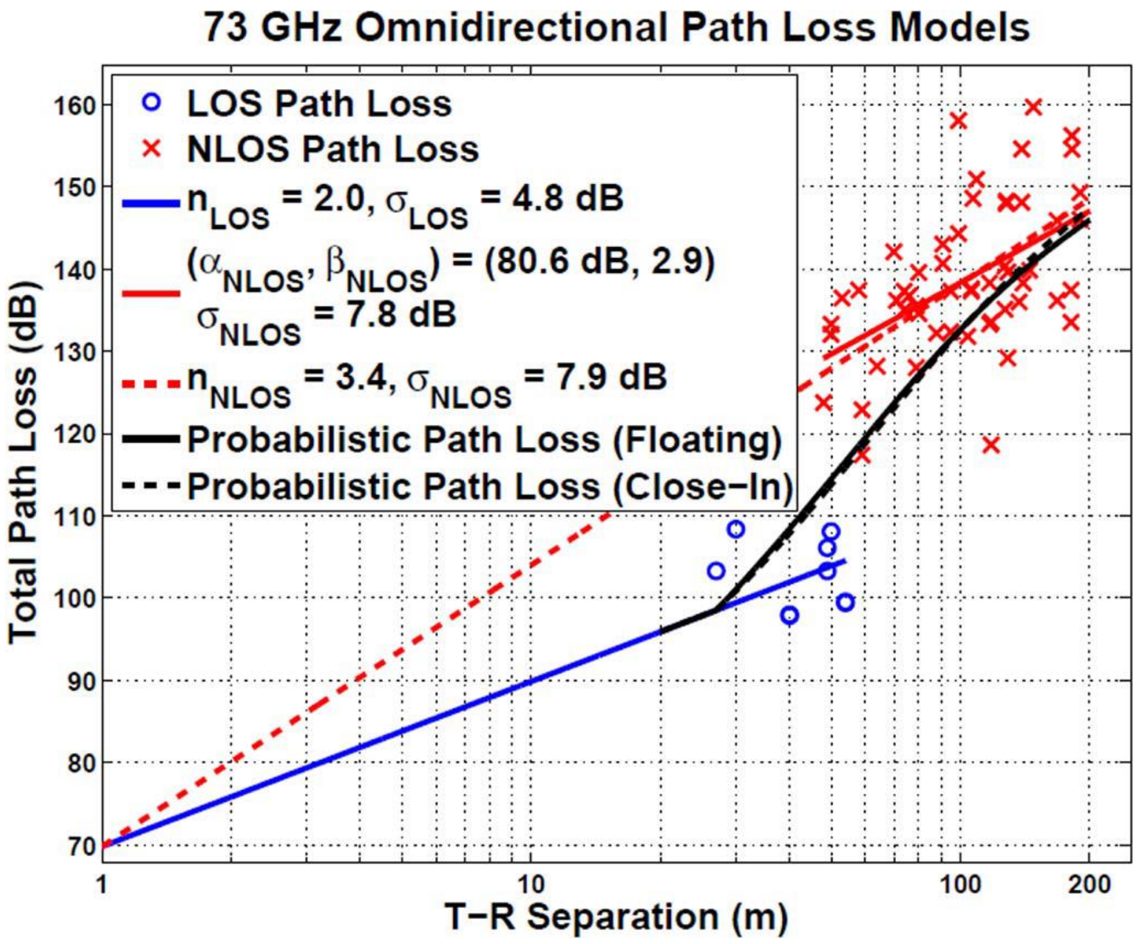
TABLE III: Close-in free space space reference distance ($d_0 = 1$ m) and floating intercept path loss models for base station-to-mobile (access) and base station-to-base station (backhaul) scenarios. PLE is the path loss exponent, α is the floating intercept in dB, β is the slope of the MMSE best fit line, and σ is the standard deviation in dB.

Omnidirectional Path Loss Models ($d_0 = 1$ m)										
		TX Height (m)	RX Height (m)	LOS		NLOS		NLOS (Floating) 30 m < d < 200 m		
				PLE	σ [dB]	PLE	σ [dB]	α [dB]	β	σ [dB]
28 GHz	Access	7; 17	1.5	2.1	3.6	3.4	9.7	79.2	2.6	9.6
73 GHz	Access	7; 17	2	2.0	5.2	3.3	7.6	81.9	2.7	7.5
	Backhaul		4.06	2.0	4.2	3.5	7.9	84.0	2.8	7.8
	Hybrid		2; 4.06	2.0	4.8	3.4	7.9	80.6	2.9	7.8

Measurements Parameters

PROBABILISTIC MODEL





Measurements Parameters

PROBABILISTIC MODEL

- Figs. 3 and 4 show the ***28 GHz*** and ***73 GHz*** omnidirectional path loss scatter plots and corresponding mean path loss equation lines,
- Using Eqs. (3), (4), and (5), in conjunction with (1), it is possible to implement a general probabilistic path loss model,

$$\mathrm{PL}_{\mathrm{Prob}}[\mathrm{dB}](d) = P_{\mathrm{LOS}}(d) \times \mathrm{PL}_{\mathrm{LOS}}(d) + (1 - P_{\mathrm{LOS}}(d)) \times \mathrm{PL}_{\mathrm{NLOS}}(d) \quad (6)$$

where ***$P_{LOS}(d)$, $PL_{LOS}(d)$, and $PL_{NLOS}(d)$*** are given in Eqs. (1), (3), and (4) or (5),

Measurements Parameters

PROBABILISTIC MODEL

$$P_{\mathrm{LOS}}(d) = \left[\min\left(\frac{d_{\mathrm{BP}}}{d}, 1\right)\left(1 - e^{-\frac{d}{\alpha}}\right) + e^{-\frac{d}{\alpha}}\right]^2 \quad (1)$$

$$PL_{\mathrm{LOS}}[\mathrm{dB}](d) = 20\log_{10}\left(\frac{4\pi}{\lambda}\right) + 10\overline{n}_{\mathrm{LOS}}\log_{10}(d) + X_{\sigma,\mathrm{LOS}} \qquad d \geq 1\ \mathrm{m} \quad (3)$$

$$PL_{\mathrm{NLOS,Close-In}}[\mathrm{dB}](d) = 20\log_{10}\left(\frac{4\pi}{\lambda}\right) + 10\overline{n}_{\mathrm{NLOS}}\log_{10}(d) + X_{\sigma,\mathrm{NLOS}}, \qquad d \geq 1\ \mathrm{m} \quad (4)$$

$$PL_{\mathrm{NLOS,Floating}}[\mathrm{dB}](d) = \alpha + 10\beta\log_{10}(d) + X_{\sigma,\mathrm{NLOS}} \qquad 30\ \mathrm{m} < d < 200\ \mathrm{m} \quad (5)$$

$$\boxed{\mathrm{PL}_{\mathrm{Prob}}[\mathrm{dB}](d) = P_{\mathrm{LOS}}(d) \times \mathrm{PL}_{\mathrm{LOS}}(d) + (1 - P_{\mathrm{LOS}}(d)) \times \mathrm{PL}_{\mathrm{NLOS}}(d) \quad (6)}$$

Measurements Parameters

PROBABILISTIC MODEL

It is clear that any other distance-dependent path loss model or other propagation models, could be used here .Eq. (6) can be rewritten as

$$\mathrm{PL}_{\mathrm{Prob}}[\mathrm{dB}](d) = \overline{PL}_{\mathrm{Prob}}(d) + X_\sigma(d) \qquad (7)$$

$$\overline{PL}_{\mathrm{Prob}}(d) = P_{\mathrm{LOS}}(d)\overline{PL}_{\mathrm{LOS}}(d) + P_{\mathrm{NLOS}}(d)\overline{PL}_{\mathrm{NLOS}}(d) \qquad (8)$$

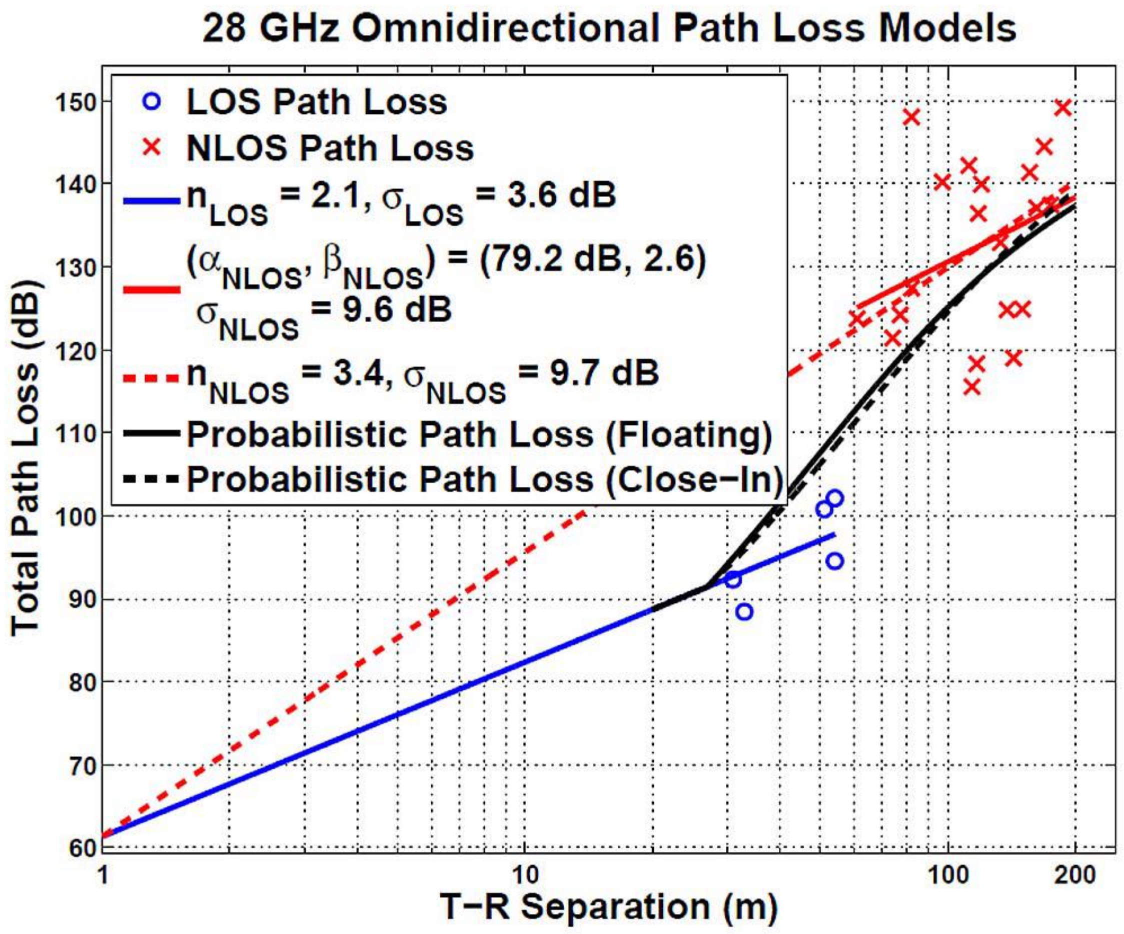
$$X_\sigma(d) = P_{\mathrm{LOS}}(d)X_{\sigma,\mathrm{LOS}} + P_{\mathrm{NLOS}}(d)X_{\sigma,\mathrm{NLOS}} \qquad (9)$$

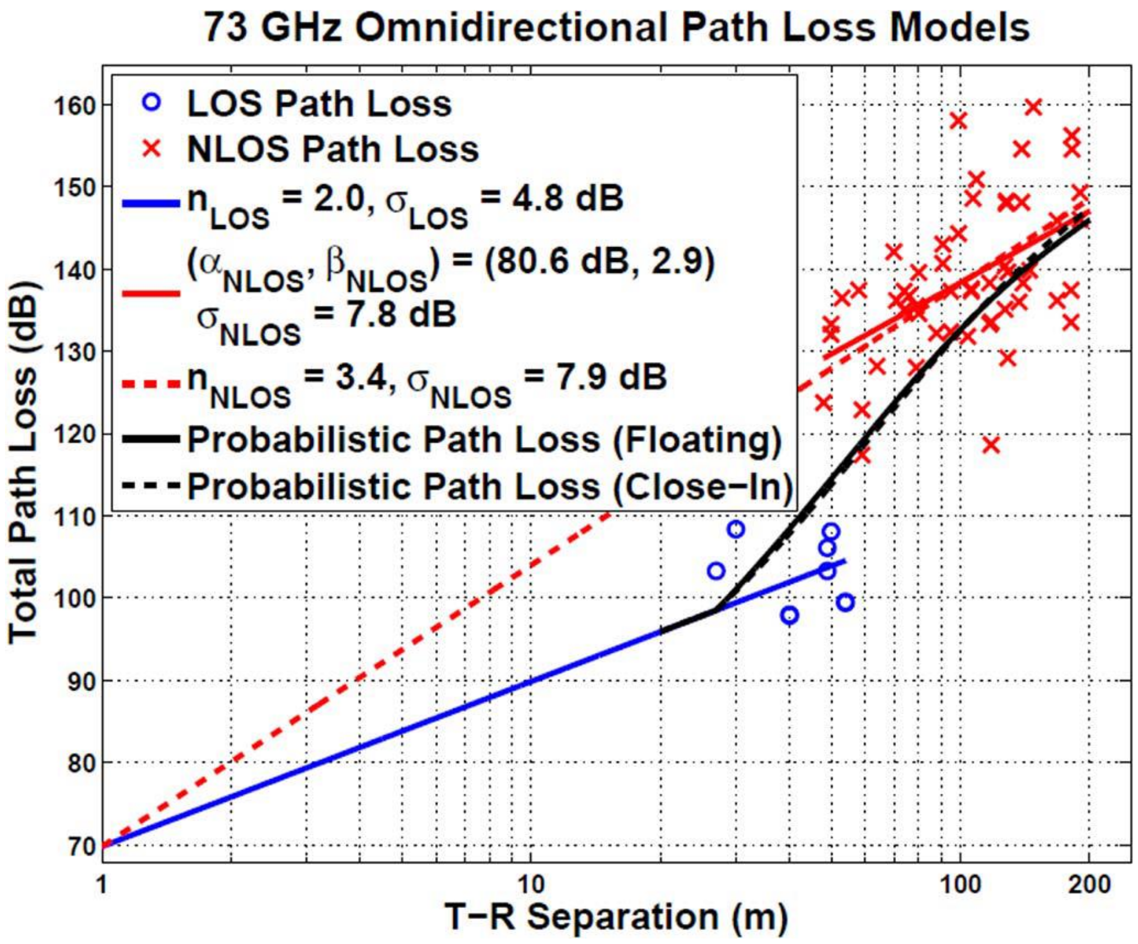
- $\overline{\mathrm{PL}}_{\mathrm{LOS}}(d)$, and $\overline{\mathrm{PL}}_{\mathrm{NLOS}}(d)$ are the mean LOS and NLOS distance-dependent path loss equations from Eqs. (3), and (4) or (5)
- ***$X_\sigma(d)$*** is the sum of two independent ***0 dB*** mean lognormal random variables, also with ***0 dB*** mean
- Distance-dependent standard deviation, i.e., shadow factor, (in **dB**)

$$\sigma(d) = \sqrt{P_{\mathrm{LOS}}^2(d)\sigma_{LOS}^2 + (1 - P_{\mathrm{LOS}}(d))^2\,\sigma_{NLOS}^2}$$

Measurements Parameters

PROBABILISTIC MODEL





Measurements Parameters

PROBABILISTIC MODEL

- The probabilistic omnidirectional path loss model shown in (6), and plotted in Figs. 3 and 4,
- Fig. 3 shows virtually no difference between the two probabilistic curves, indicating little difference between using the NLOS 1 m close-in free space reference or floating-intercept path loss models.
- In Figs. 3 and 4, the mean probabilistic path loss equation line is plotted, but the standard deviations σ_{LOS} and σ_{NLOS} from the lognormal distributions as shown in Eq. (9) must also be taken into account when performing system-wide simulations to model large-scale shadowing. The mean of the probabilistic path loss equation (Eq. (6)) is always found between the LOS and NLOS models. Thus, as the T-R separation increases from ***10 m to 27 m***, the LOS probability remains ***100%***, and the probabilistic path loss line follows the LOS measured path loss data. Similarly, as the T-R separation increases from ***27 m to 200 m***, the LOS probability falls from ***100%*** to ***4%,*** respectively.

Probabilistic path loss models

- Based on LOS and NLOS omnidirectional propagation path loss data
- Using a probability distribution for LOS obtained from a 3-D site-specific database in New York city.
- Estimate signal coverage, interference, and outage as a function of distance
- Provide a convenient way to model path loss for future **mmwave systems**, where highly directional antennas and the smaller wavelengths will be more sensitive to whether LOS conditions exist or not.

THANK YOU

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