Study on 3GPP Rural Macrocell Path Loss Models for Millimeter Wave Wireless Communications

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Agenda

- ☐ Background and Motivation
- ☐ 3GPP and ITU Standard RMa Path Loss Models
- ☐ Simplified RMa Path Loss Models with Monte Carlo Simulations
- ☐ 73 GHz RMa Measurement Campaign
- ☐ Empirically-Based CI and CIH Path Loss Models for RMa
- ☐ Conclusions and Noteworthy Observations

Background

- The world ignored mmWave for rural macrocells and said it wouldn’t work: **We conduced measurements that show that it does work!**

- 3GPP TR 38.900 V14.2.0 and ITU-R M.2135 completed RMa path loss models but did not verify with measurements!

- RMa path loss models originate from measurements below 2 GHz in downtown Tokyo!

- **No extensive validation for RMa path loss in the literature!**

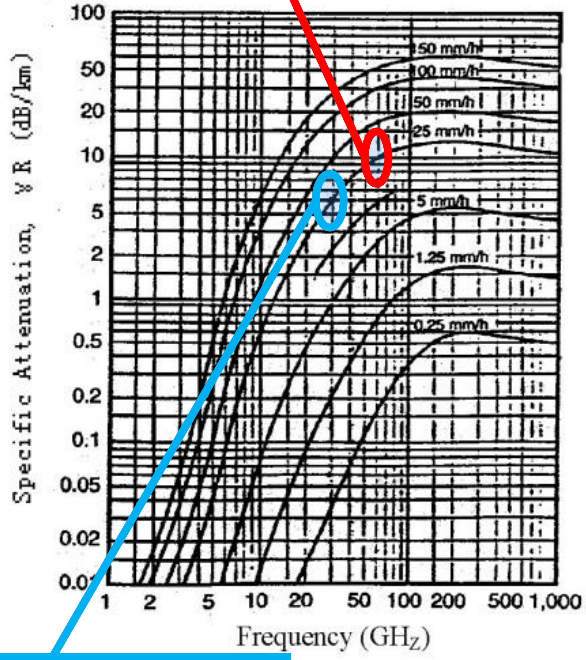
Motivation

Why look closer at 3GPP TR 38.900 RMa Path Loss Model?

- We conducted one of the first studies to show mmWave RMa works
- Are **numerous correction factors** actually needed?
  - Determine which physical parameters are important
- Use measurements to generate empirical models that are just as **accurate** but much **simpler** than 3GPP RMa path loss models
  - Why not use **similar CI-based** models that are in 3GPP TR 38.900
- Studies of mmWave for **RMa are lacking / more peer-reviewed work** is necessary to see future potentials in rural settings
- We developed new models that are simplified and just as accurate

Why do we need a rural path loss model?

- ❑ This work proves RMa works in clear weather
- ❑ FCC 16-89 offers up to **28 GHz** of new spectrum
- ❑ Rural backhaul becomes intriguing with multi-GHz bandwidth spectrum (**fiber replacement**)
- ❑ Rural Macrocells (towers taller than 35 m) already exist for cellular and are **easy to deploy on existing infrastructure** (boomer cells)
- ❑ Weather and rain pose issues, but **antenna gains and power can overcome**



Heavy Rainfall @ 73 GHz
10 dB attenuation @ 1km

Heavy Rainfall @ 28 GHz
6 dB attenuation @ 1km

[2] T. S. Rappaport et al. Millimeter Wave Mobile Communications for 5G Cellular: It Will Work! IEEE Access, vol. 1, pp. 335–349, May 2013.

[36] Federal Communications Commission, "Spectrum Frontiers R&O and FNPRM: FCC16-89," July. 2016. [Online]. Available: https://apps.fcc.gov/edocs public/attachmatch/FCC-16-89A1 Rcd.pdf

RMa Path Loss Models Adopted by 3GPP TR 38.900 for > 6 GHz

- 3GPP RMa LOS path loss model:
  - $$PL_1 = 20\log_{10}(40\pi \cdot d_{3D} \cdot f_c/3) + \min(0.03h^{1.72}, 10)\log_{10}(d_{3D}) - \min(0.044h^{1.72}, 14.77) + 0.002\log_{10}(h)\, d_{3D}\ ;\ \sigma_{SF} = 4\text{ dB}$$
  - $$PL_2 = PL_1(d_{BP}) + 40\log_{10}(d_{3D}/d_{BP})\ ;\ \sigma_{SF} = 6\text{ dB}$$
    - $d_{BP} = 2\pi \cdot h_{BS} \cdot h_{UT} \cdot f_c/c$
- 3GPP RMa NLOS path loss model:
  - $$PL = \max(PL_{RMa-LOS}, PL_{RMa-NLOS})$$
  - $$PL_{RMa-NLOS} = 161.04 - 7.1\log_{10}(W) + 7.5\log_{10}(h) - (24.37 - 3.7(h/h_{BS})^2)\log_{10}(h_{BS}) + (43.42 - 3.1\log_{10}(h_{BS}))(\log_{10}(d_{3D}) - 3) + 20\log_{10}(f_c) - (3.2(\log_{10}(11.75h_{UT}))^2 - 4.97)\ ;\ \sigma_{SF} = 8\text{ dB}$$

- Adopted from ITU-R M.2135
- Long & confusing equations!
- Not physically based
- Numerous parameters
- Confirmed by mmWave data?

[9] 3GPP, “Technical specification group radio access network; channel model for frequency spectrum above 6 GHz (Release 14),” 3rd Generation Partnership Project (3GPP), TR 38.900 V14.2.0, Dec. 2016. [Online]. Available: http://www.3gpp.org/DynaReport/38900.htm

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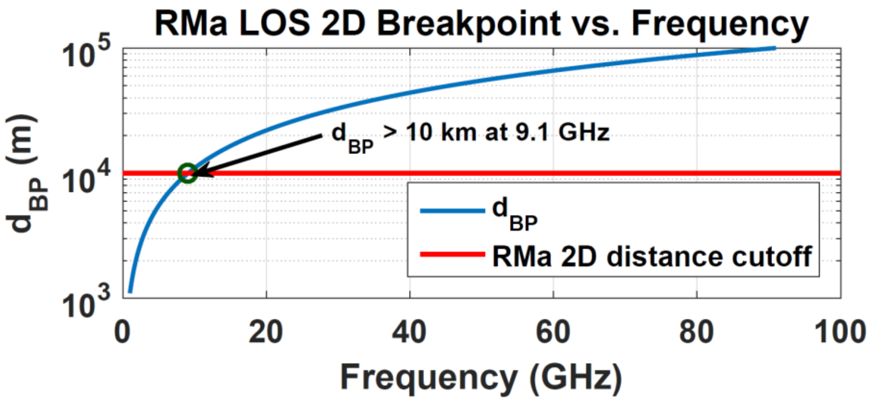
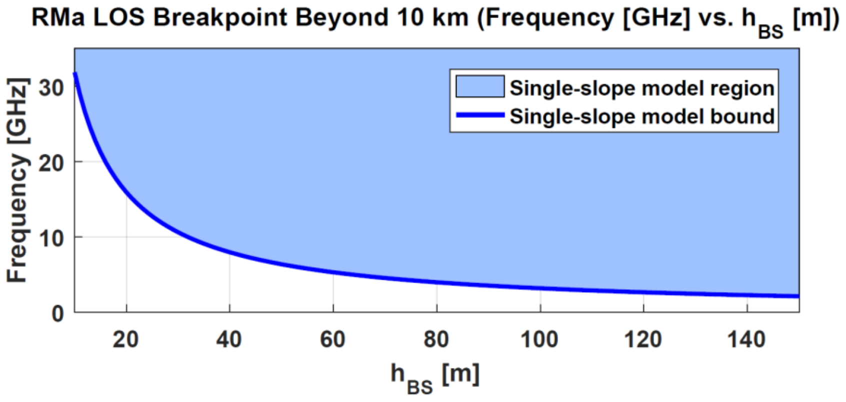
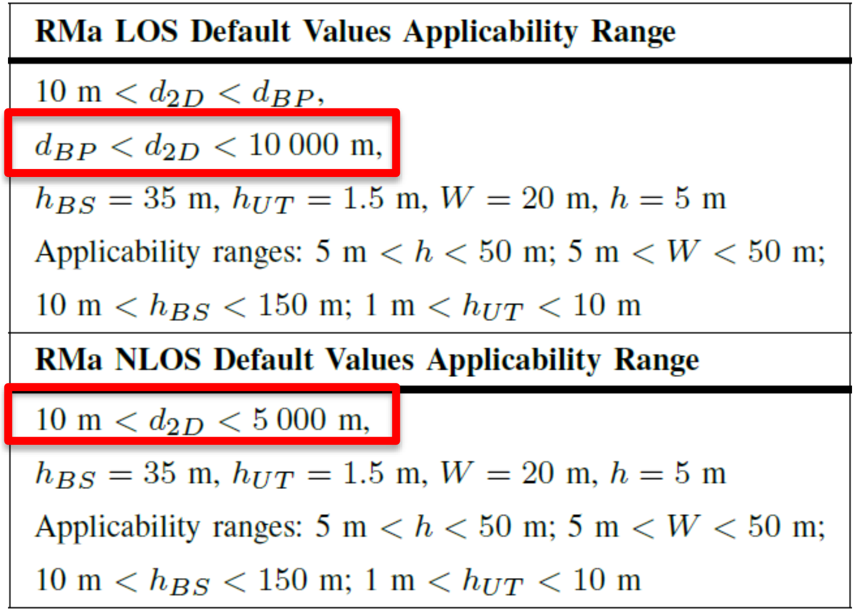
[35] G. R. MacCartney, Jr. and T. S. Rappaport, “Rural Macrocell Path Loss Models for Millimeter Wave Wireless Communications,” IEEE Journal on Selected Areas in Communications, July 2017.

Applicability Ranges and Breakpoint Distance Concerns







RMa LOS Default Values Applicability Range
$10 \text{ m} < d_{2D} < d_{BP}$,
$d_{BP} < d_{2D} < 10\,000 \text{ m}$,
$h_{BS} = 35 \text{ m}, h_{UT} = 1.5 \text{ m}, W = 20 \text{ m}, h = 5 \text{ m}$
Applicability ranges: $5 \text{ m} < h < 50 \text{ m}; 5 \text{ m} < W < 50 \text{ m};$
$10 \text{ m} < h_{BS} < 150 \text{ m}; 1 \text{ m} < h_{UT} < 10 \text{ m}$
RMa NLOS Default Values Applicability Range
$10 \text{ m} < d_{2D} < 5\,000 \text{ m}$,
$h_{BS} = 35 \text{ m}, h_{UT} = 1.5 \text{ m}, W = 20 \text{ m}, h = 5 \text{ m}$
Applicability ranges: $5 \text{ m} < h < 50 \text{ m}; 5 \text{ m} < W < 50 \text{ m};$
$10 \text{ m} < h_{BS} < 150 \text{ m}; 1 \text{ m} < h_{UT} < 10 \text{ m}$

RMa LOS in TR 38.900 is undefined and reverts to a single-slope model for frequencies above 9.1 GHz, since the breakpoint distance is larger than the defined distance range when using default model parameters! Very odd, and seemed to stem from UHF

[35] G. R. MacCartney, Jr. and T. S. Rappaport, "Rural Macrocell Path Loss Models for Millimeter Wave Wireless Communications," IEEE Journal on Selected Areas in Communications, July 2017.

Issues / Room for Improvement with Existing 3GPP RMa Path Loss Models

- Could find only **one report of measurements used to validate** 3GPP's TR 38.900 RMa model above 6 GHz; at 24 GHz but not peer reviewed, until this paper

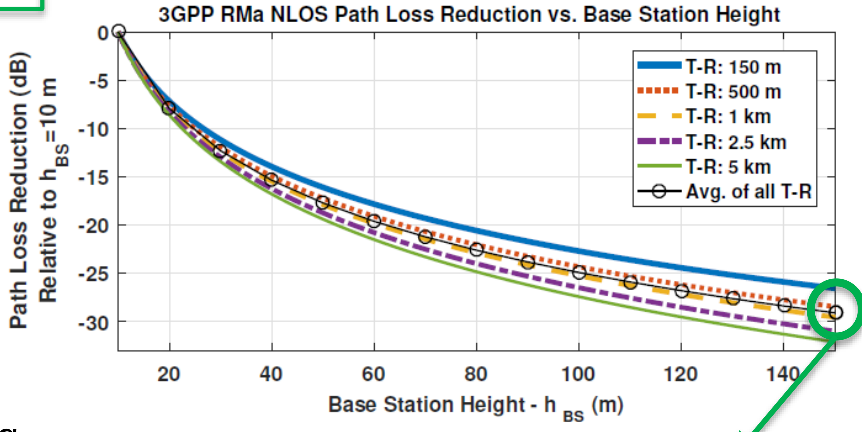
- 3GPP/ITU NLOS model based on 1980's work at 813 MHz and 1433 MHz UHF in downtown Tokyo (**not rural or mmWave!**) with an extension from 450 MHz to 2200 MHz

- Investigated **applicability of CI-based path loss model for RMa** and extending to 100 GHz like other 3GPP path loss models: UMa, UMi, and InH

- We carried out a **rural macrocell measurement and modeling campaign**

Newly Proposed RMa Path Loss Model Formulas

- CI Path Loss Model:
  - $$\mathrm{PL}^{\mathrm{CI}}(f_c,d)[\mathrm{dB}] = \mathrm{FSPL}(f_c,d_0)[\mathrm{dB}] + 10n\log_{10}\left(\frac{d}{d_0}\right) + \chi_\sigma;$$
    $$\text{where } d \geq d_0 \text{ and } d_0 = 1\ \mathrm{m}$$
    $$= 32.4 + 10n\log_{10}(d) + 20\log_{10}(f_c) + \chi_\sigma;$$
- CIH Path Loss Model for Range of TX heights
  - $$\mathrm{PL}^{\mathrm{CI}H}(f_c,d,h_{BS})[\mathrm{dB}] = 32.4 + 20\log_{10}(f_c) + 10n\left(1 + b_{tx}\left(\frac{h_{BS}-h_{B0}}{h_{B0}}\right)\right)\log_{10}(d) + \chi_\sigma;$$
    $$\text{where } d \geq= 1\ \mathrm{m}, \quad \text{and } h_{B0} = \text{average BS height}$$
  - Effective PLE (PLE_{eff}): $n \cdot \left(1 + b_{tx}\left(\frac{h_{BS}-h_{B0}}{h_{B0}}\right)\right)$
  - b_{tx} is a model parameter that is an optimized weighting factor that scales the parameter n as a function of the base station height relative to the average base station height h_{B0}.



Path loss reduced by 26 dB and 32 dB for T-R separation distances of 150 m and 5 km, respectively, w.r.t. to 10 m base station heights

[35] G. R. MacCartney, Jr. and T. S. Rappaport, "Rural Macrocell Path Loss Models for Millimeter Wave Wireless Communications," IEEE Journal on Selected Areas in Communications, July 2017.

Finding Equivalent but Simpler RMa Path Loss Models as Options for ITU / 3GPP RMa

- ☐ Re-create 3GPP/ITU path loss models with Monte Carlo simulations and derive a much simpler path loss model for frequencies from 0.5 GHz to 100 GHz
- ☐ Monte Carlo simulation #1 with default parameters: 500,000 million random samples
- ☐ Monte Carlo simulation #2 varying base station heights: 13 million random samples
- ☐ $d \geq 1$ m; $h_{B0} = 35$ m

$$\mathrm{PL}_{\mathrm{LOS}}^{\mathrm{CI-3GPP}}(f_c, d)[\mathrm{dB}] = 32.4 + \mathbf{23.1} \log_{10}(d) + 20 \log_{10}(f_c) + \chi_{\sigma_{\mathrm{LOS}}};\ \sigma_{\mathrm{LOS}} = 5.9 \text{ dB}$$

$$\mathrm{PL}_{\mathrm{NLOS}}^{\mathrm{CI-3GPP}}(f_c, d)[\mathrm{dB}] = 32.4 + \mathbf{30.4} \log_{10}(d) + 20 \log_{10}(f_c) + \chi_{\sigma_{\mathrm{NLOS}}};\ \sigma_{\mathrm{NLOS}} = 8.2 \text{ dB}$$

Comparable standard deviations to 3GPP:
3GPP LOS: 4-6 dB
3GPP NLOS: 8 dB

$$\mathrm{PL}_{\mathrm{LOS}}^{\mathrm{CIH-3GPP}}(f_c, d, h_{BS})[\mathrm{dB}] = 32.4 + 20 \log_{10}(f_c) + \mathbf{23.1}\left(1 - \mathbf{0.006}\left(\frac{h_{BS} - 35}{35}\right)\right) + \chi_{\sigma_{\mathrm{LOS}}};\ \sigma_{\mathrm{LOS}} = 5.6 \text{ dB}$$

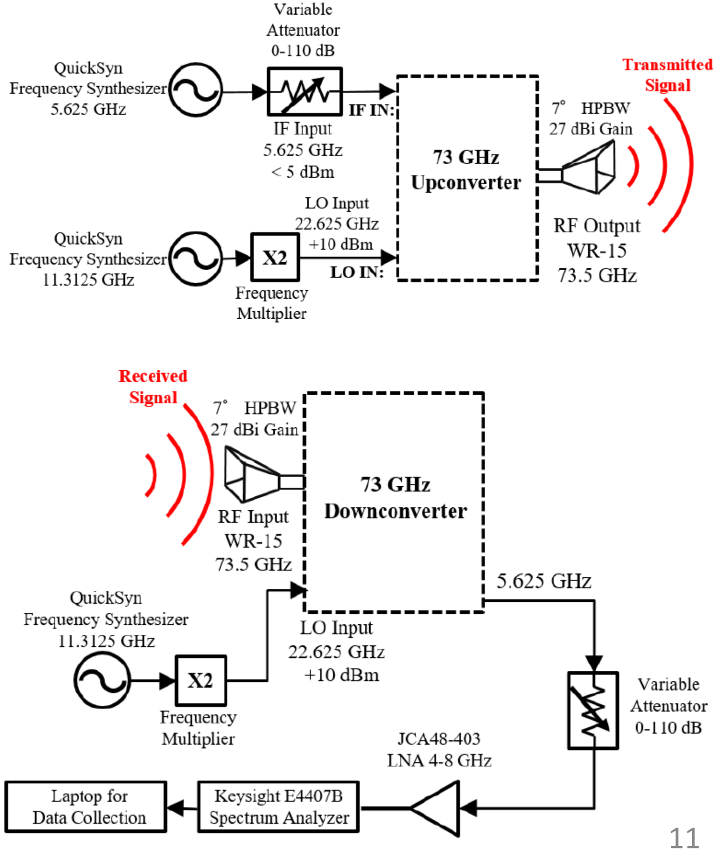
$$\mathrm{PL}_{\mathrm{NLOS}}^{\mathrm{CIH-3GPP}}(f_c, d, h_{BS})[\mathrm{dB}] = 32.4 + 20 \log_{10}(f_c) + \mathbf{30.7}\left(1 - \mathbf{0.06}\left(\frac{h_{BS} - 35}{35}\right)\right) + \chi_{\sigma_{\mathrm{NLOS}}};\ \sigma_{\mathrm{NLOS}} = 8.7 \text{ dB}$$

Simple form with 32.4 and $20 \log_{10}(f_c)$ representing FSPL at 1 m at 1 GHz.

[35] G. R. MacCartney, Jr. and T. S. Rappaport, "Rural Macrocell Path Loss Models for Millimeter Wave Wireless Communications," IEEE Journal on Selected Areas in Communications, July 2017.

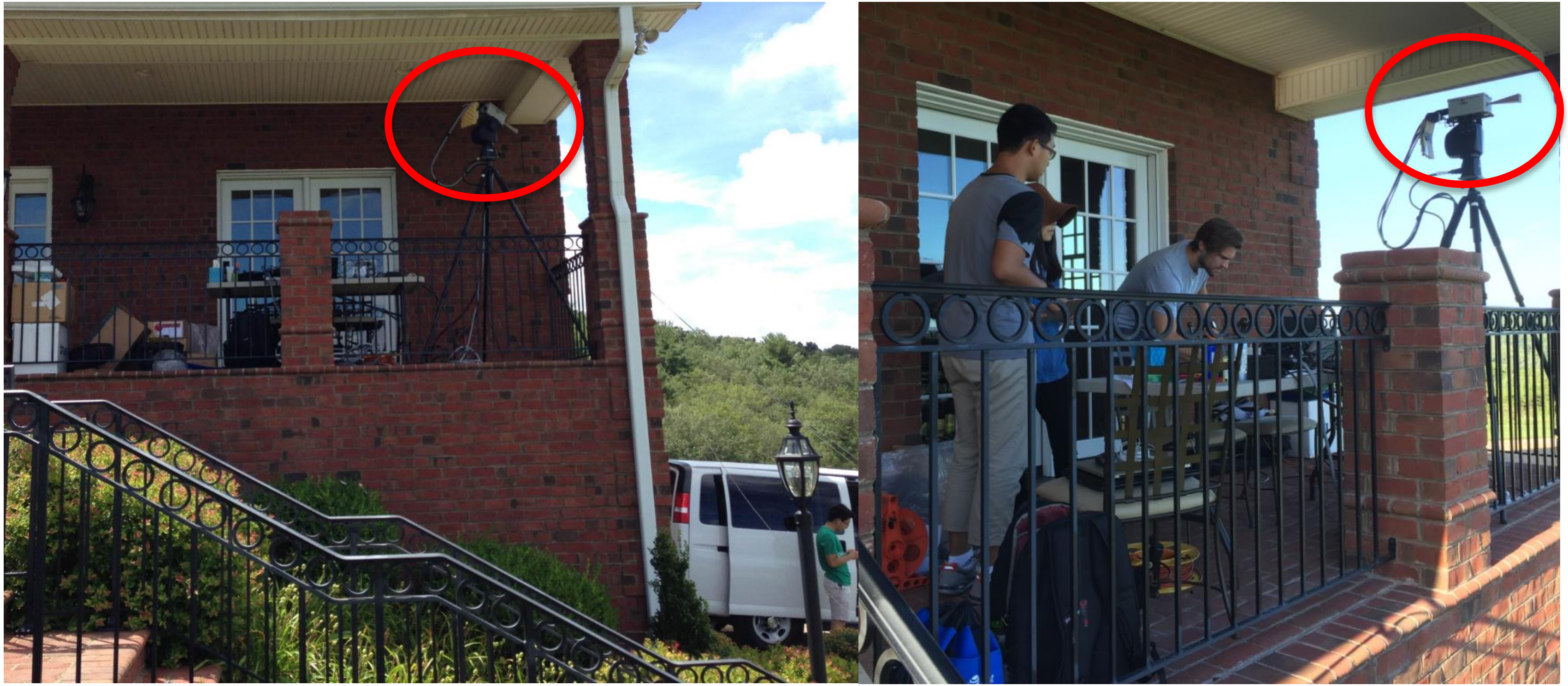
73 GHz Millimeter-Wave Measurements in an RMa Scenario

- Measurements in rural Riner, Virginia
- 73.5 GHz narrowband CW tone, 15 kHz RX bandwidth, TX power **14.7 dBm** (29 mW) with **190 dB of dynamic range**
- Equivalent to a **wideband channel sounder** with 800 MHz of BW and 190 dB of max measurable path loss (TX EIRP of 21.7 dBW)
- 14 LOS: 33 m to 10.8 km 2D T-R separation
- 17 NLOS: 3.4 km to 10.6 km 2D T-R separation (5 outages)
- TX antenna fixed downtilt: -2º; height of 110 m above terrain
- TX and RX antennas: 27 dBi gain w/ 7º Az./El. HPBW
- RX antenna: 1.6 to 2 meter height above ground
- The best TX antenna Az. angle and best RX antenna Az./El. angle were manually determined for each measurement



[1] G. R. MacCartney, Jr. et al., "Millimeter wave wireless communications: New results for rural connectivity," in Proceedings of the 5th Workshop on All Things Cellular: Operations, Applications and Challenges: in conjunction with MobiCom 2016, ser. ATC '16. New York, NY, USA: ACM, Oct. 2016, pp. 31–36.
[35] G. R. MacCartney, Jr. and T. S. Rappaport, "Rural Macrocell Path Loss Models for Millimeter Wave Wireless Communications," IEEE Journal on Selected Areas in Communications, July 2017.

73 GHz TX Equipment in Field



TX View of Horizon

View to the North from Transmitter.

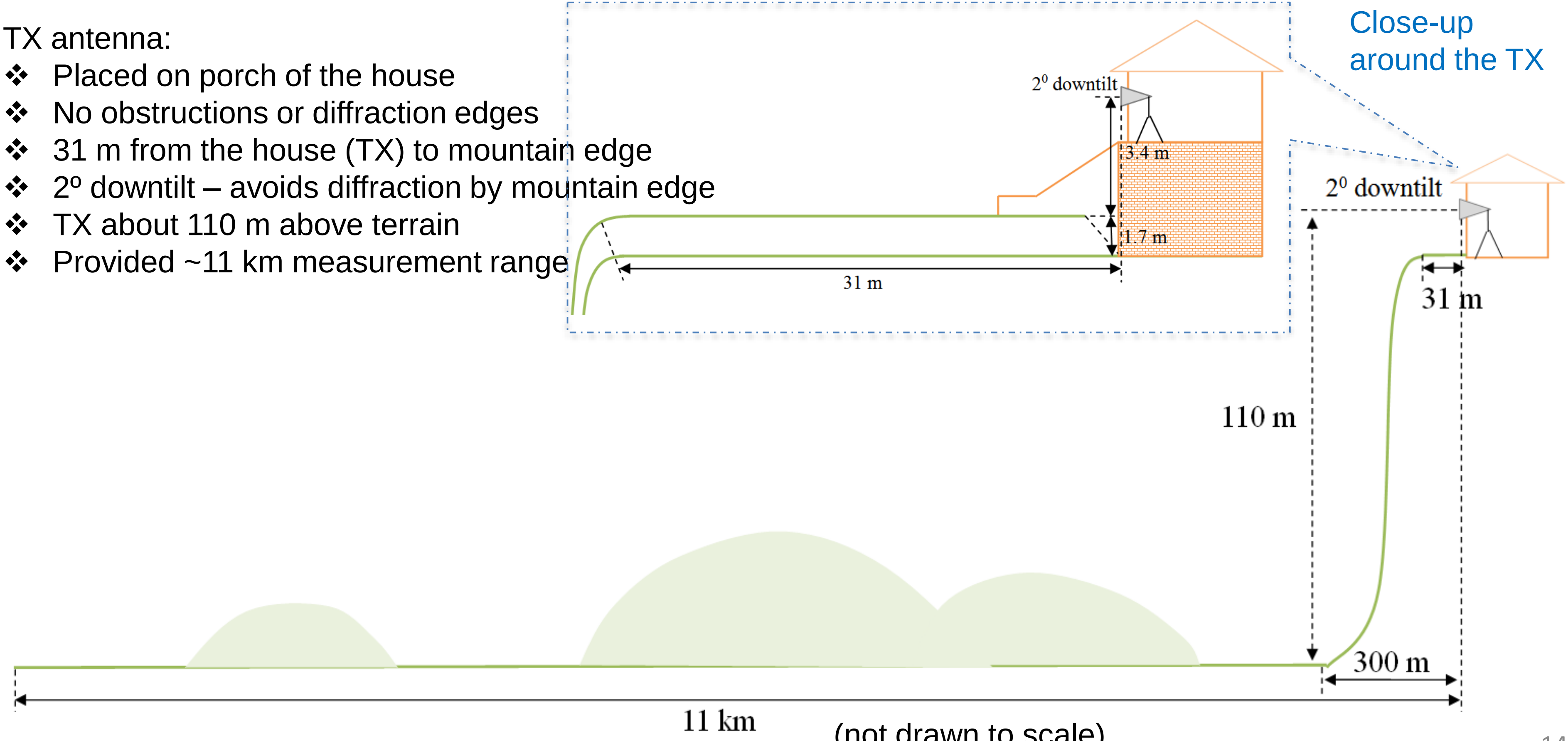
Note mountain on left edge, and the yard slopes up to right, creating a diffraction edge with TX antenna if TX points too far to the right.

TX beam headings and RX locations were confined to the center of the photo to avoid both the mountain and the right diffraction edge

Schematic of TX Location and Surroundings

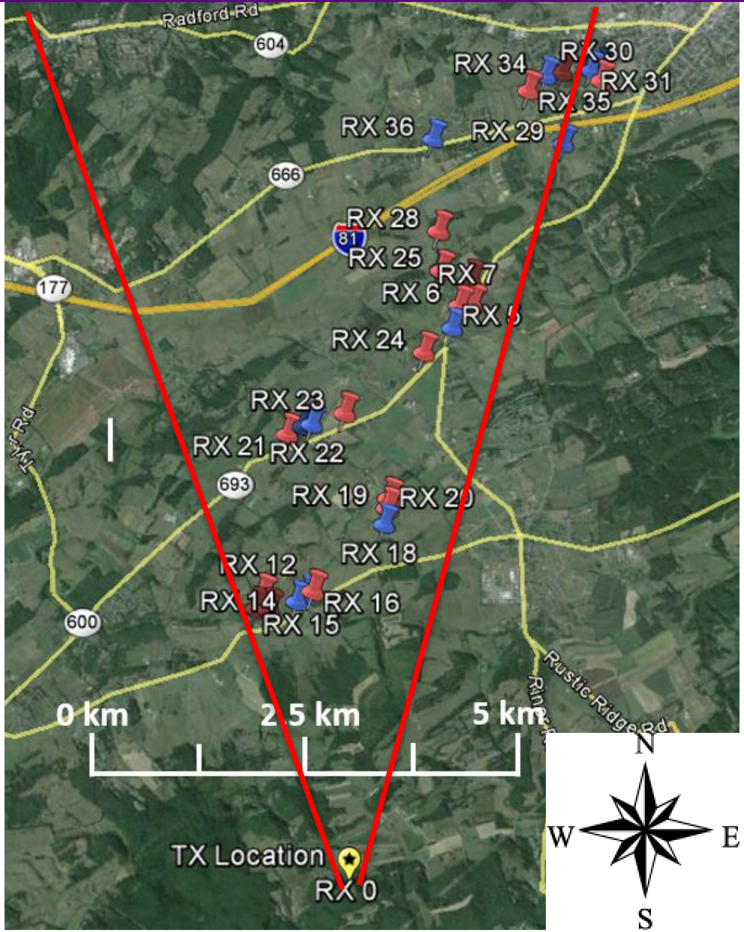
TX antenna:

- Placed on porch of the house
- No obstructions or diffraction edges
- 31 m from the house (TX) to mountain edge
- 2º downtilt – avoids diffraction by mountain edge
- TX about 110 m above terrain
- Provided ~11 km measurement range



(not drawn to scale)

Map of Locations



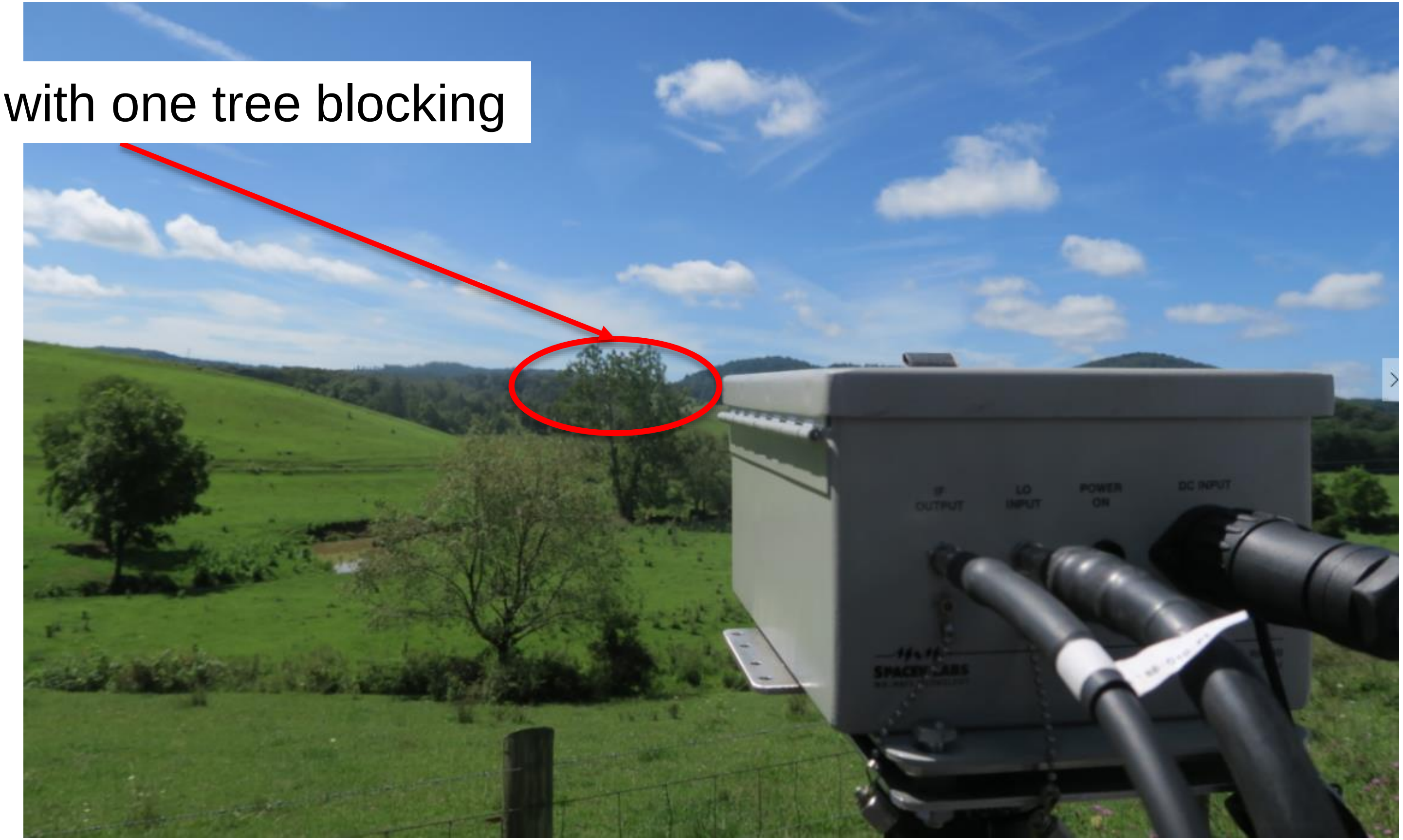
TX Location

LOS Scenario

NLOS Scenario

TX Azimuth Angle of View (+/- 10º of North) to avoid diffraction from mountain on left and yard slope on right

RX 15 LOS Location: 3.44 km

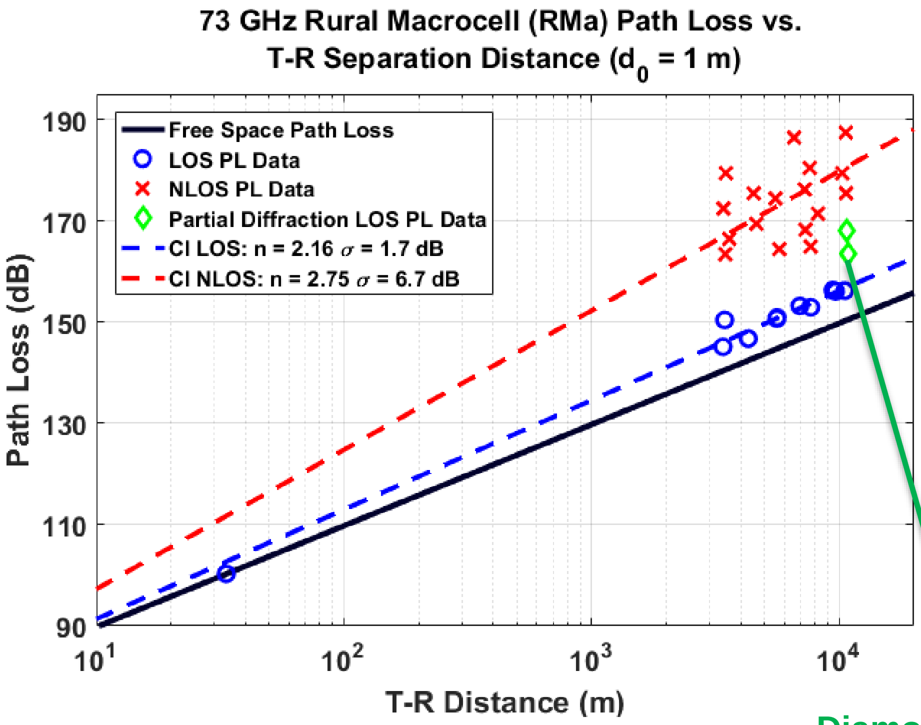


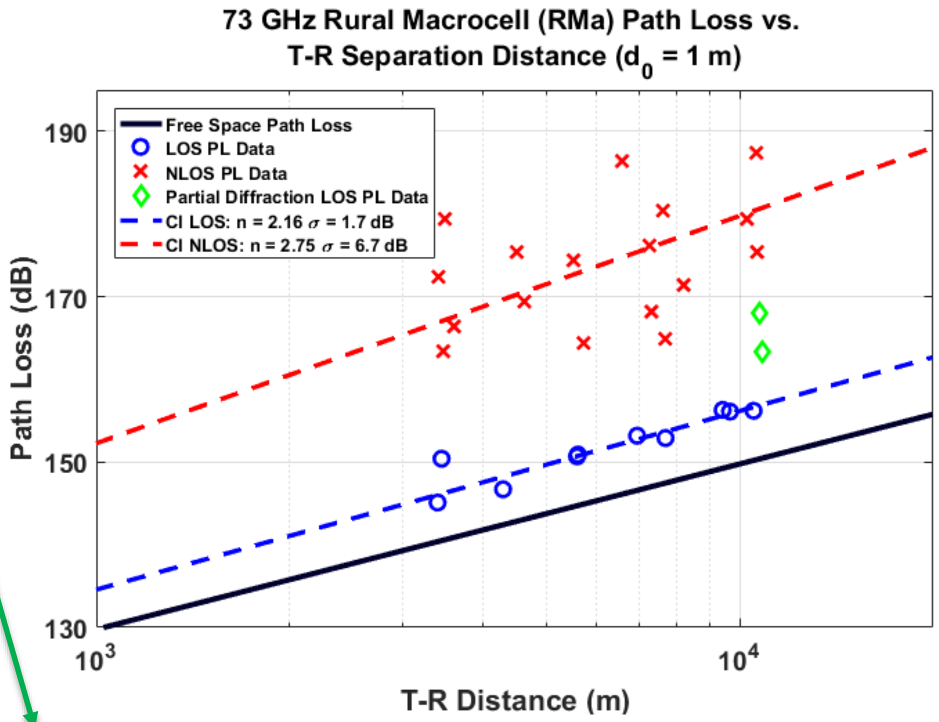
LOS with one tree blocking

RX 26 LOS Location: 7.67 km

TX location at house – LOS location

73 GHz RMa Path Loss Data and Models


73 GHz Rural Macrocell (RMa) Path Loss vs. T-R Separation Distance (d_0 = 1 m)


73 GHz Rural Macrocell (RMa) Path Loss vs. T-R Separation Distance (d_0 = 1 m)

Diamonds are LOS locations with partial diffraction from TX azimuth departure angle from close-in mountain edge on the right, causing diffraction loss on top of free space

[1] G. R. MacCartney, Jr. et al., “Millimeter wave wireless communications: New results for rural connectivity,” in Proceedings of the 5th Workshop on All Things Cellular: Operations, Applications and Challenges: in conjunction with MobiCom 2016, ser. ATC ’16. New York, NY, USA: ACM, Oct. 2016, pp. 31–36.

Empirical CI and CIH Models

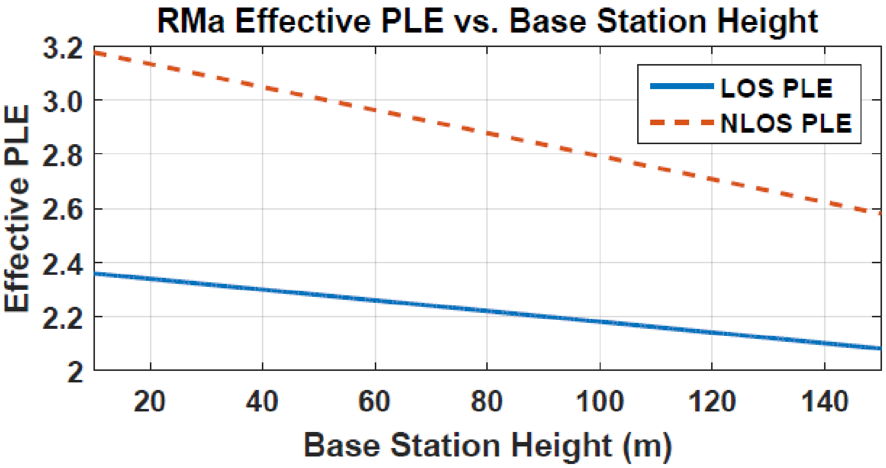
$$\mathrm{PL}_{\mathrm{LOS}}^{\mathrm{CI-RMa}}(f_c,d)[\mathrm{dB}] = 32.4 + \mathbf{21.6}\log_{10}(d) + 20\log_{10}(f_c) + \chi_{\sigma_{\mathrm{LOS}}};\ \sigma_{\mathrm{LOS}} = 1.7\ \mathrm{dB}$$

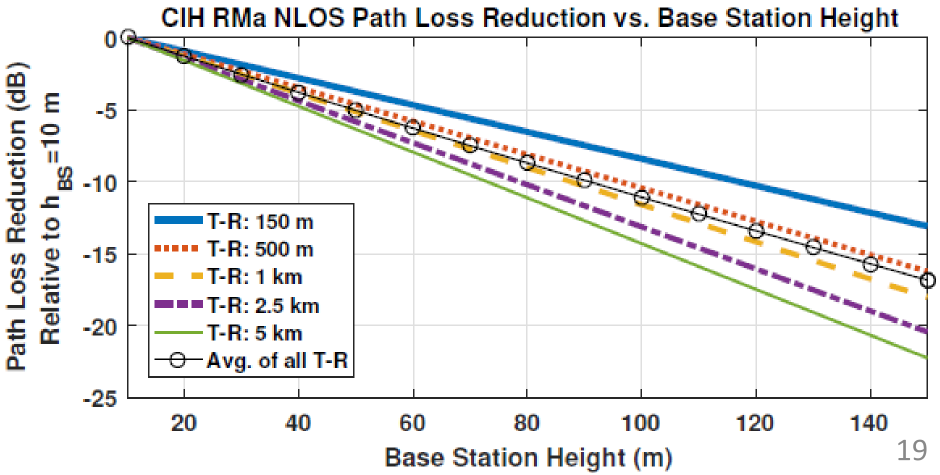
$$\mathrm{PL}_{\mathrm{NLOS}}^{\mathrm{CI-RMa}}(f_c,d)[\mathrm{dB}] = 32.4 + \mathbf{27.5}\log_{10}(d) + 20\log_{10}(f_c) + \chi_{\sigma_{\mathrm{NLOS}}};\ \sigma_{\mathrm{NLOS}} = 6.7\ \mathrm{dB}$$

$d \geq 1$ m; h_{B0} = 35 m; 10 m $\leq h_{BS} \leq$ 150 m

$$\mathrm{PL}_{\mathrm{LOS}}^{\mathrm{CIH-RMa}}(f_c,d,h_{BS})[\mathrm{dB}] = 32.4 + 20\log_{10}(f_c) + \mathbf{23.1}\left(1-\mathbf{0.03}\left(\frac{h_{BS}-35}{35}\right)\right) + \chi_{\sigma_{\mathrm{LOS}}};\ \sigma_{\mathrm{LOS}} = 1.7\ \mathrm{dB},$$

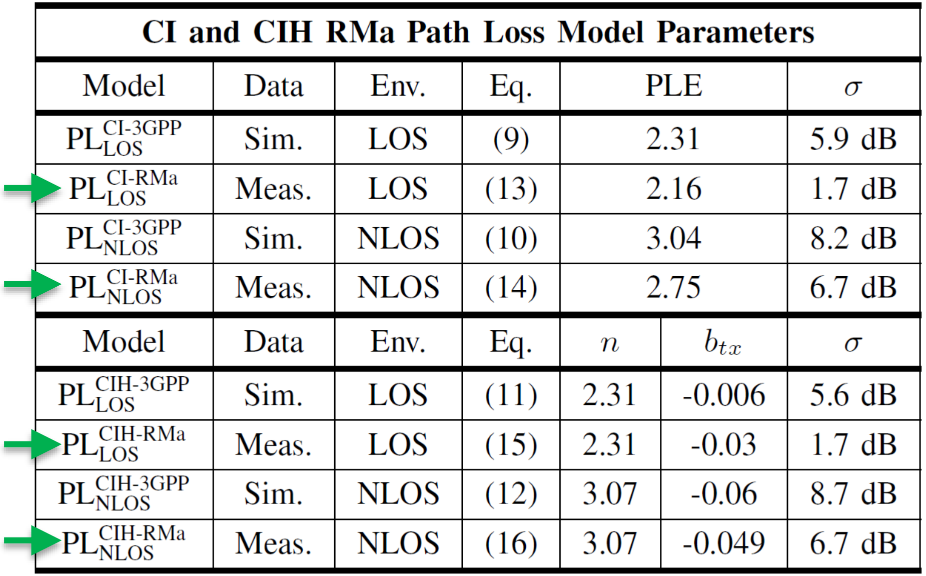
$$\mathrm{PLN}_{\mathrm{NLOS}}^{\mathrm{CIH-RMa}}(f_c,d,h_{BS})[\mathrm{dB}] = 32.4 + 20\log_{10}(f_c) + \mathbf{30.7}\left(1-\mathbf{0.049}\left(\frac{h_{BS}-35}{35}\right)\right) + \chi_{\sigma_{\mathrm{NLOS}}};\ \sigma_{\mathrm{NLOS}} = 6.7\ \mathrm{dB},$$





Conclusions and Observations

- mmWave links are **possible** in rural settings **> 10 km**
- Literature and standards show that RMa models **NOT verified** for all distances/frequencies
  - Based on measurements below **2 GHz in Tokyo**
  - LOS model **breakpoint distance is undefined >9 GHz**
- **CI models** result in **nearly identical accuracy**, are grounded in the true physics of free space, use **much fewer terms** (one – PLE), and are **simpler** to understand
- **New CIH model** is **accurate and stable** and effectively **scales the PLE** as a function of the TX height
- **Proposal**: Use empirical CI and CIH RMa path loss models as optional for 3GPP/ITU-R (use σ of 4 dB to 6 dB and 8 dB in LOS and NLOS, respectively)
  - **Valid from 0.5 GHz to 100 GHz and frequency independent beyond the first meter of propagation**



CI and CIH RMa Path Loss Model Parameters

Model	Data	Env.	Eq.	PLE		σ
$PL^{CI\text{-}3GPP}_{LOS}$	Sim.	LOS	(9)	2.31		5.9 dB
$PL^{CI\text{-}RMa}_{LOS}$	Meas.	LOS	(13)	2.16		1.7 dB
$PL^{CI\text{-}3GPP}_{NLOS}$	Sim.	NLOS	(10)	3.04		8.2 dB
$PL^{CI\text{-}RMa}_{NLOS}$	Meas.	NLOS	(14)	2.75		6.7 dB
Model	Data	Env.	Eq.	n	b_{tx}	σ
$PL^{CIH\text{-}3GPP}_{LOS}$	Sim.	LOS	(11)	2.31	-0.006	5.6 dB
$PL^{CIH\text{-}RMa}_{LOS}$	Meas.	LOS	(15)	2.31	-0.03	1.7 dB
$PL^{CIH\text{-}3GPP}_{NLOS}$	Sim.	NLOS	(12)	3.07	-0.06	8.7 dB
$PL^{CIH\text{-}RMa}_{NLOS}$	Meas.	NLOS	(16)	3.07	-0.049	6.7 dB

[35] G. R. MacCartney, Jr. and T. S. Rappaport, "Rural Macrocell Path Loss Models for Millimeter Wave Wireless Communications," IEEE Journal on Selected Areas in Communications, 2017, July 2017.

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Thank You!

Questions