Millimeter Wave Wireless Communications: New Results for Rural Connectivity

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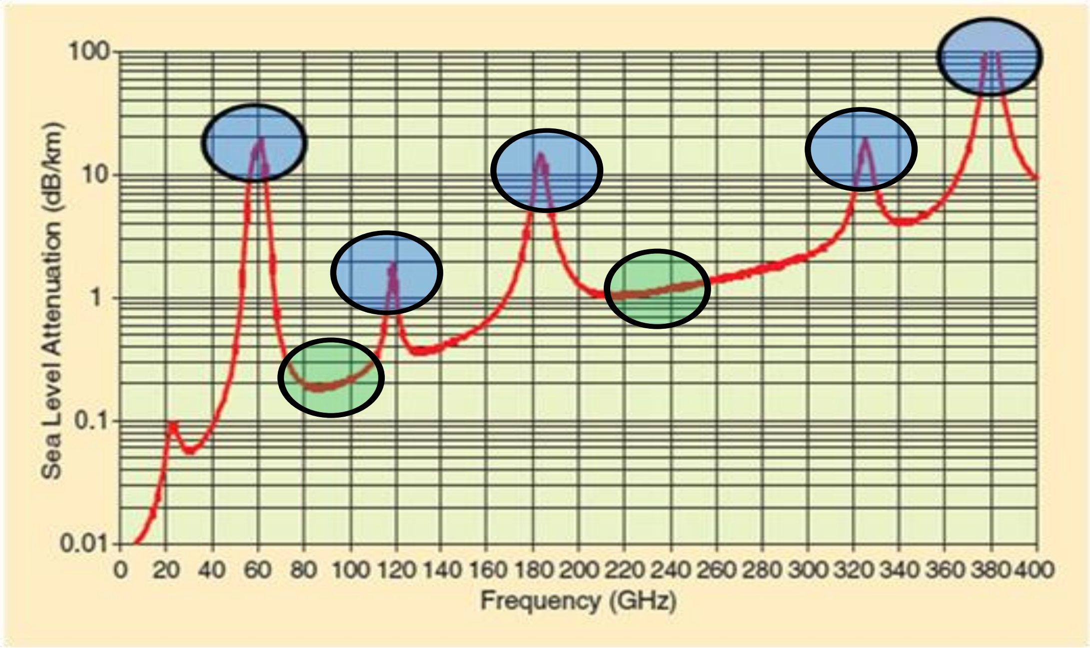
G. R. MacCartney, S. Sun, and T. S. Rappaport, Y. Xing, H. Yan, J. Koka, R. Wang, and D. Yu, “Millimeter Wave Wireless Communications: New Results for Rural Connectivity,” *All Things Cellular'16: 5th Workshop on All Things Cellular Proceedings,* in conjunction with ACM MobiCom, Oct. 7, 2016.

Agenda

A Rural Macrocell (RMa) Path Loss Model for Frequencies Above 6 GHz in the 3GPP Channel Model Standard

- Motivation for path loss model in rural areas
- Existing RMa path loss models adopted in 3GPP TR 38.900
- Problems with the existing RMa path loss models
- Proposal of a close-in reference distance (CI) RMa path loss model
- New 73 GHz measurement campaign for RMa path loss models

Millimeter Wave Promise



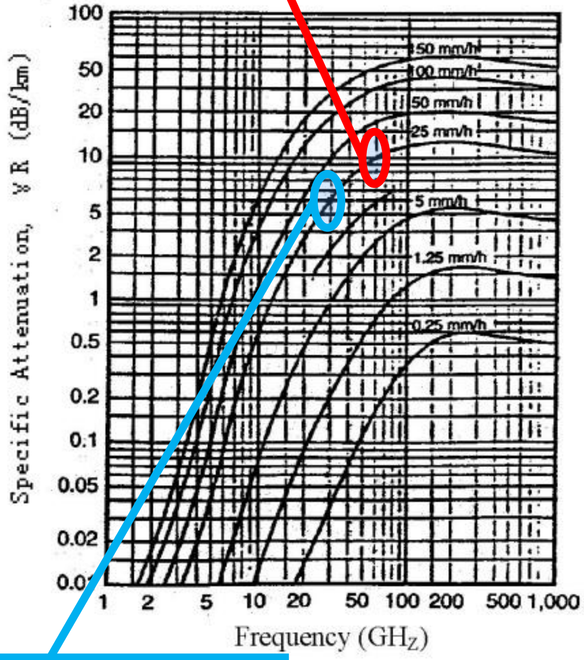
T. S. Rappaport, et. al., *Millimeter Wave Wireless Communications*, Prentice-Hall c. 2015.

- **60 GHz, 183 GHz, 325 GHz, and 380 GHz for short-range apps.**
- **Other frequencies have little air loss compared to < 6 GHz**
- **Worldwide agreement on 60 GHz!**

Why do we need a rural path loss model?

- FCC 16-89 offers up to 28 GHz of new spectrum
- Rural backhaul becomes interesting 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

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

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

Path Loss vs. Distance

- Propagation is based on physics, good models should comply with physics
- Cellular and WiFi design and deployment need path loss models for analysis,simulation
- Friis' equation describes radio propagation in free space, proven to be a vital close-in reference
- UHF/VHF (below 3 GHz) was found to have a ground bounce (break point) in urban microcells

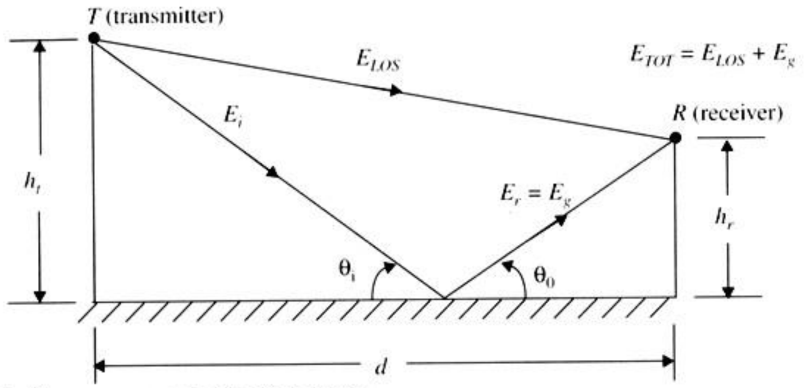


Figure 4.7 Two-ray ground reflection model.

S. Sun *et al*., "Investigation of Prediction Accuracy, Sensitivity, and Parameter Stability of Large-Scale Propagation Path Loss Models for 5G Wireless Communications," in *IEEE Transactions on Vehicular Technology*, vol. 65, no. 5, pp. 2843-2860, May 2016.

T. S. Rappaport, Wireless Communications, Principles and Practice, 2nd ed. Prentice Hall, 2002.

K. L. Blackard, et. al., "Path loss and delay spread models as functions of antenna height for microcellular system design," *IEEE 42nd Vehicular Technology Conference*, Denver, CO, 1992, vol. 1, pp. 333-337.

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

- **3GPP RMa LOS path loss model (how to predict signal over distance)**

$$PL_1 = 20\log(40\pi \cdot d_{3D} \cdot f_c/3) + \min(0.03h^{1.72}, 10)\log_{10}(d_{3D})$$
$$- \min(0.044h^{1.72}, 14.77) + 0.002\log_{10}(h)d_{3D}$$

$$PL_2 = PL_1(d_{BP}) + 40\log_{10}(d_{3D}/d_{BP})$$

$$d_{BP} = 2\pi \cdot h_{BS} \cdot h_{UT} \cdot f_c/c$$

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

- **3GPP RMa NLOS path loss model**

$$PL = \max(PL_{RMa-LOS}, PL_{RMa-NLOS})$$

$$PL_{RMa-NLOS} = 161.04 - 7.1\log_{10}(W) + 7.5\log_{10}(h)$$
$$- (24.37 - 3.7(h/h_{BS})^2)\log_{10}(h_{BS})$$
$$+ (43.42 - 3.1\log_{10}(h_{BS}))(\log_{10}(d_{3D}) - 3)$$
$$+ 20\log_{10}(f_c) - (3.2(\log_{10}(11.75h_{UT}))^2 - 4.97)$$

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 V14.0.0, June. 2016. [Online]. Available: http://www.3gpp.org/DynaReport/38900.htm

International Telecommunications Union, "Guidelines for evaluation of radio interface technologies for IMT-Advanced," Geneva, Switzerland, REP. ITU-R M.2135-1, Dec. 2009.

Existing RMa path loss models adopted in 3GPP TR 38.900

3GPP TR 38.900 Release 14 LOS and NLOS RMa path loss model default antenna height values and applicability ranges

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

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 V14.0.0, June. 2016. [Online]. Available: http://www.3gpp.org/DynaReport/38900.htm

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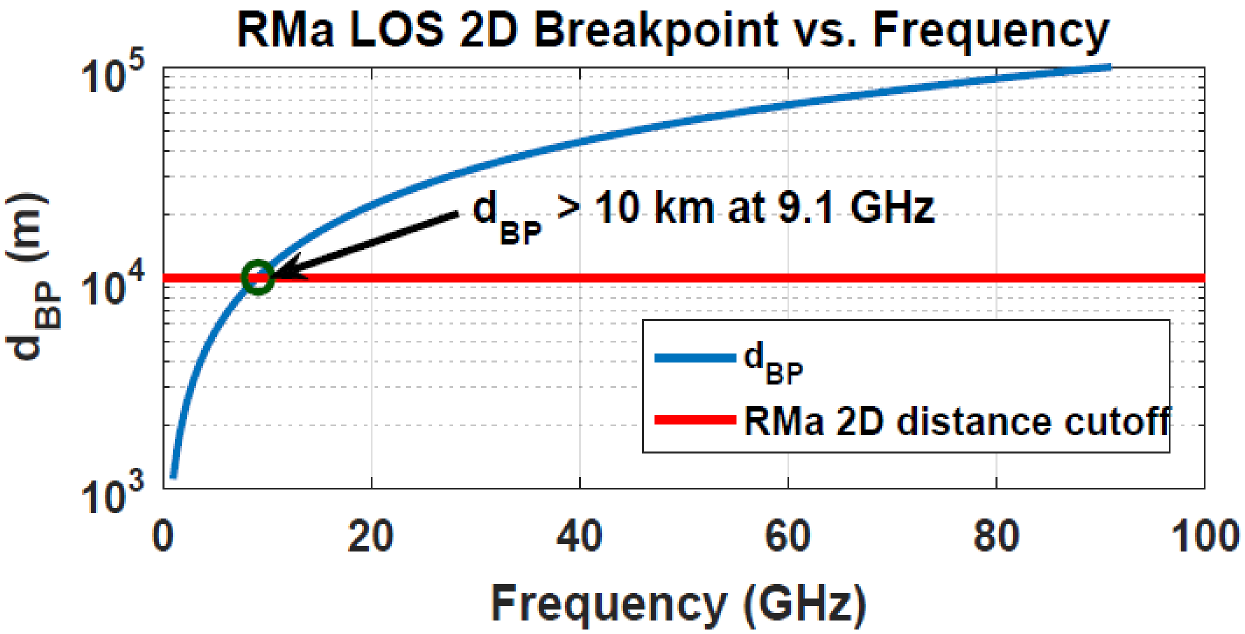
Problems with the Existing RMa Path Loss Models

$$d_{BP} = 2\pi \cdot h_{BS} \cdot h_{UT} \cdot f_c / c$$



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

Problems with the Existing 3GPP RMa Path Loss Models

- We could find only one report of measurements at 24 GHz to validate 3GPP's TR 38.900 RMa model using very few measurements, not peer reviewed, no distinction LOS/NLOS.
- In the single 24 GHz study, 2D T-R separation ranged from 200 m to 500 m, but the RMa model in 3GPP TR 38.900 is specified out to 10 km in LOS and 5 km in NLOS. Model has not been verified over specified distance range!
- There was no best-fit indicator (e.g., RMSE) given between measured data and model
- Further investigation shows the 3GPP/ITU model appears to be based on 1980's work at 1.4 – 2.6 GHz in downtown Tokyo (not rural or mmWave!)
- We decided to carry out a rural macrocell measurement and modeling campaign

3GPP, "New measurements at 24 GHz in a rural macro environment," Telstra, Ericsson, Tech. Rep. TDOC R1-164975, May 2016.

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Proposed new RMa Path Loss Model

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- **Close-in Free Space Reference Distance (CI) Path Loss Model**

$$\mathrm{PL}^{\mathrm{CI}}(f_c, d)[\mathrm{dB}] = \mathrm{FSPL}(f_c, d_0)[\mathrm{dB}] + 10n\log_{10}\left(\frac{d}{d_0}\right) + \chi_\sigma^{\mathrm{CI}}, \text{ where } d \geq d_0$$

$$\text{For } d_0 = 1 \text{ m: } \mathrm{FSPL}(f_c, d_0)[\mathrm{dB}] = 20\log_{10}\left(\frac{4\pi f_c d_0 \times 10^9}{c}\right) = 32.4 \text{ dB} + 20\log_{10}(f_c)$$

➢ f_c is the carrier frequency in GHz, d_0 is the close-in free space reference distance set at 1 m, n is path loss exponent (PLE) and χ_σ denotes a zero-mean Gaussian random variable with standard deviation σ in dB.

- **3GPP Optional CI Model Form with d_0 = 1 m:**

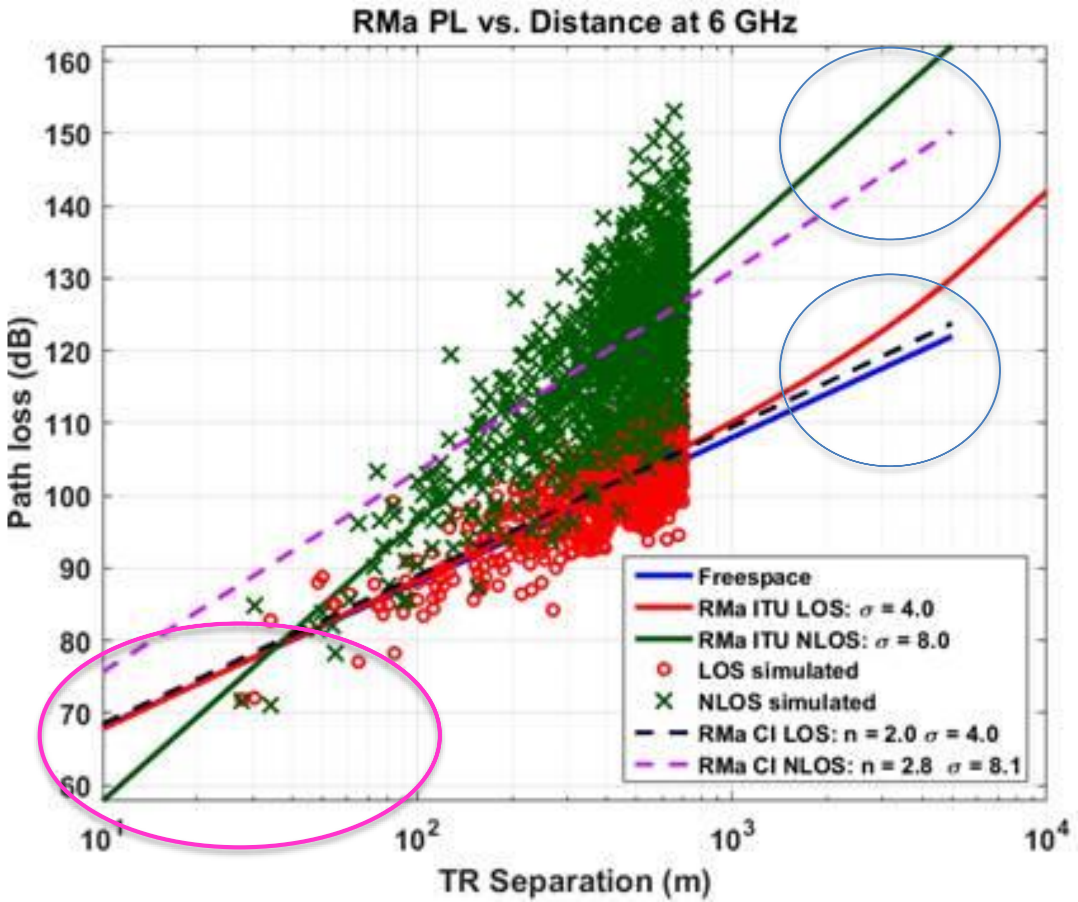
$$\mathrm{PL}^{\mathrm{CI}}(f_c[\mathrm{GHz}], d)[\mathrm{dB}] = 32.4 + 10n\log_{10}(d) + 20\log_{10}(f_c[\mathrm{GHz}]) + \chi_\sigma^{\mathrm{CI}}, \text{ where } d \geq 1 \text{ m}$$

$$\mathrm{FSPL}(1 \text{ GHz}, 1 \text{ m}) = 32.4 \text{ dB}$$

S. Sun *et al*., "Investigation of Prediction Accuracy, Sensitivity, and Parameter Stability of Large-Scale Propagation Path Loss Models for 5G Wireless Communications," in *IEEE Transactions on Vehicular Technology*, vol. 65, no. 5, pp. 2843-2860, May 2016.

T. A. Thomas et al., "A Prediction Study of Path Loss Models from 2-73.5 GHz in an Urban-Macro Environment," 2016 IEEE 83rd Vehicular Technology Conference (VTC Spring), Nanjing, 2016, pp. 1-5.

Path Loss Models for RMa Scenario



EXAMPLE: We ran current ITU/3GPP path loss model using Monte Carlo simulations (before the breakpoint). Example: 6 GHz.

KEY OBSERVATION: Existing 3GPP RMa NLOS path loss model underestimates path loss well below free space value at close-in distances within 50 m, and has obvious errors (NLOS should be much lossier than free space) in first 500 meters.

For 6 GHz, CI model using n=2 (LOS) and n=2.8 (NLOS) predicts much more accurately for first several hundred meters at 6 GHz with same std. dev. and improved stability as shown for CI models, see: http://ieeexplore.ieee.org/document/7434656/

Finding an Equivalent but Simpler RMa Path Loss Model
An option for ITU / 3GPP TR 38.900 Model RMa

- Monte Carlo simulations were performed using 3GPP TR 38.900/ITU-R M.2135
- Simulations used LOS and NLOS RMa models at: 1, 2, 6, 15, 28, 38, 60, 73, and 100 GHz
- Each frequency simulated 50,000 times for T-R distances up to 10 km (LOS) and 5 km (NLOS)
- Resulting CI models are simpler models with virtually identical predictive results as ITU-R M.2135 and TR 38.900 but with fewer parameters and no break point problem.
- Presented these models to NTIA, ITU, FCC in June 2016 – these eqns. improve accuracy when compared to the RMa 3GPP/ITU-R M.2135 model for all frequencies from 500 MHz to 100 GHz (rain and oxygen effects are easily added):

$$\mathrm{PL}^{\text{CI-3GPP}}_{\text{RMa-LOS}}(f_c, d_{3D})[\text{dB}] = 32.4 + 23.1\log_{10}\left(\frac{d_{3D}}{d_0}\right) + 20\log_{10}(f_c) + \chi_{\sigma_{\text{LOS}}};\ \text{where } \sigma_{\text{LOS}} = 5.9 \text{ dB, and } d_{3D} \geq 1 \text{ m}$$

$$\mathrm{PL}^{\text{CI-3GPP}}_{\text{RMa-NLOS}}(f_c, d_{3D})[\text{dB}] = 32.4 + 30.4\log_{10}\left(\frac{d_{3D}}{d_0}\right) + 20\log_{10}(f_c) + \chi_{\sigma_{\text{NLOS}}};\ \text{where } \sigma_{\text{NLOS}} = 8.3 \text{ dB, and } d_{3D} \geq 1 \text{ m}$$

- f_c in GHz

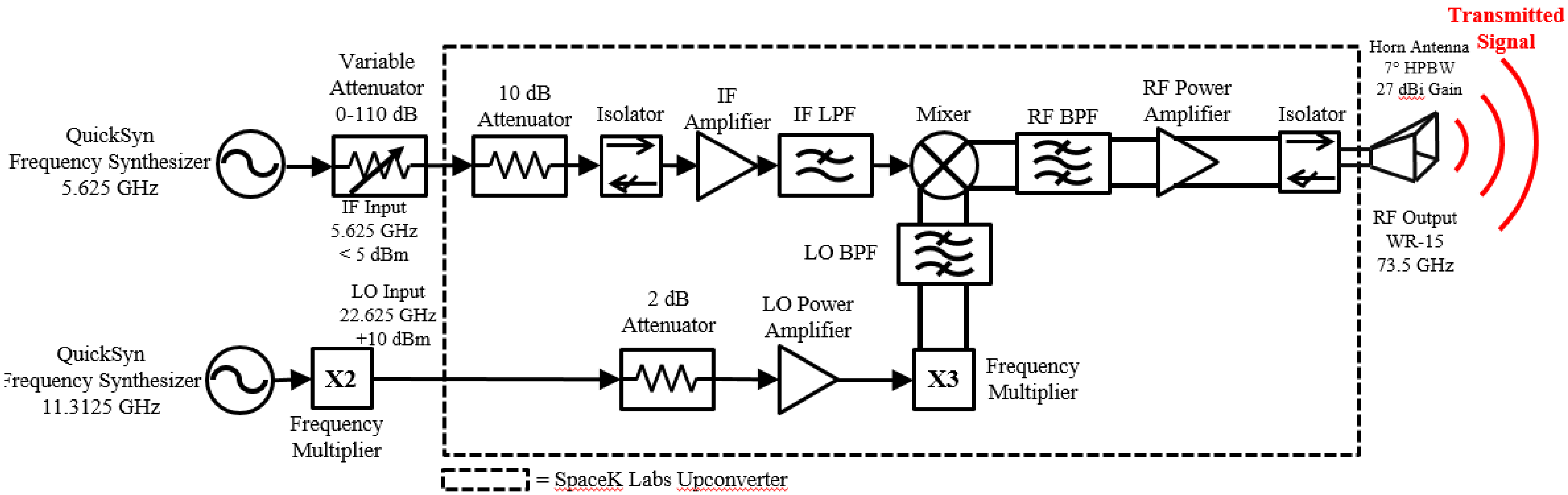
See: http://wireless.engineering.nyu.edu/presentations/NTIA-propagation-presentation-JUNE-15-2016_v1%203.pdf see slides 25-30

New Measurement Campaign at 73 GHz for RMa Path Loss Models Above 6 GHz

- Measurements were conducted in a **rural** setting in Riner, Virginia with 190 dB range
- Motivation: To validate the CI RMA model well beyond 1 km in the field
- Transmitted 73.5 GHz CW tone, 15 kHz RX bandwidth, TX power 14.7 dBm (29 mW)
- 14 LOS locations, 17 NLOS locations, 5 outages
- Local time averaging used to obtain RX power at each location
- 2D T-R separation ranged from:
  - 33 m to 10.8 km for LOS scenarios
  - 3.4 km to 10.6 km for NLOS scenarios
- TX location: top of mountain ridge (altitude above sea level: 763 m, ~110m above terrain).
- RX locations: average altitude of 650 m above sea level on undulating terrain.
- TX and RX antennas: 27 dBi of gain and 7º azimuth and elevation half-power beamwidth.
- TX antenna: fixed downtilt of 2º
- RX antenna: 1.6 to 2 meter height above ground, on average
- For each measurement location, the best TX antenna azimuth angle and best RX antenna azimuth and elevation angle were manually determined

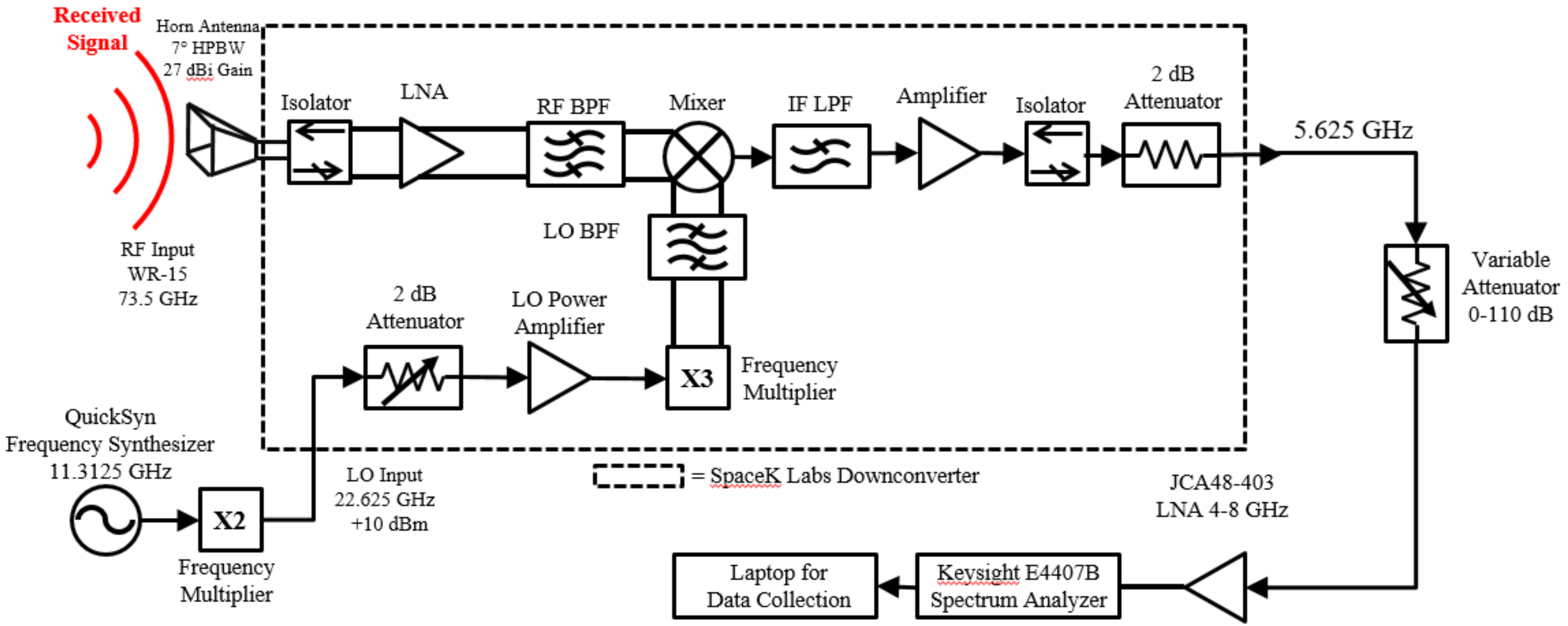
73 GHz Transmitter Equipment

- Max transmit power: 14.71 dBm (29 milliwatts)
- With horn antenna, equivalent to 14.8 W EIRP



73 GHz Receiver Equipment

- Downconverter gain of 30 dB
- RX JCA LNA gain of 35 dB
- Max measurable path loss of 190 dB
- RX height of ~ 1.6 - 2 meters on average



73 GHz TX Equipment in Field

TX View of Horizon

View to the North from Transmitter.

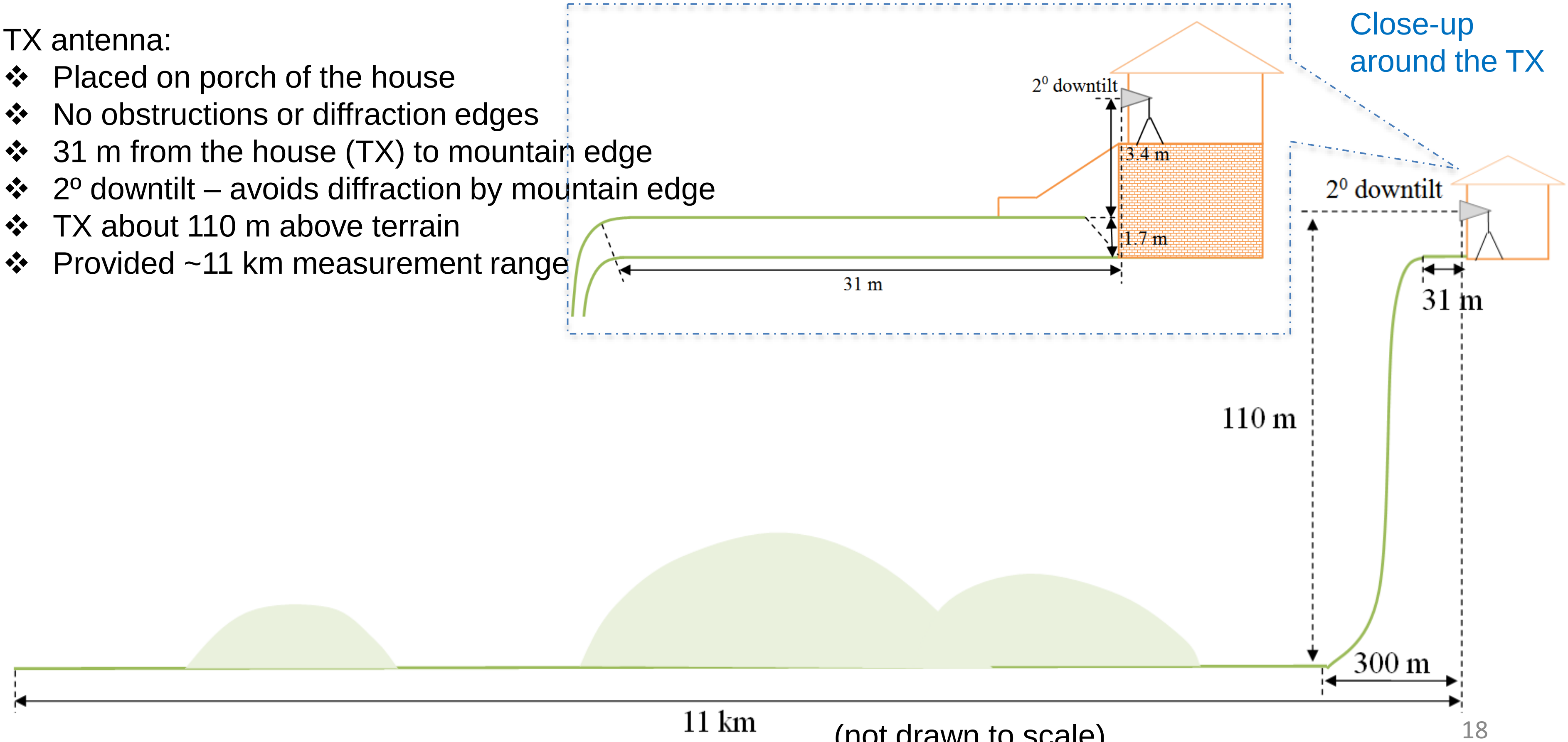
Note mountain on left edge, and the yard slopes up to right, creating a diffraction edge with TX antenna if TX points too far to the right.

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

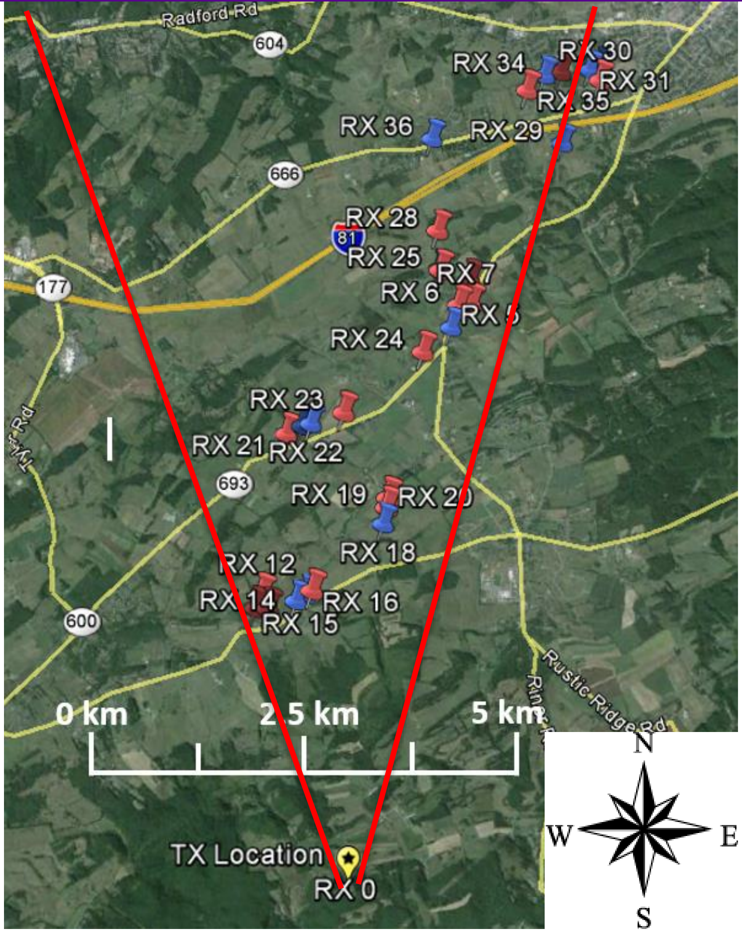
TX antenna:

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



(not drawn to scale)

Map of Locations



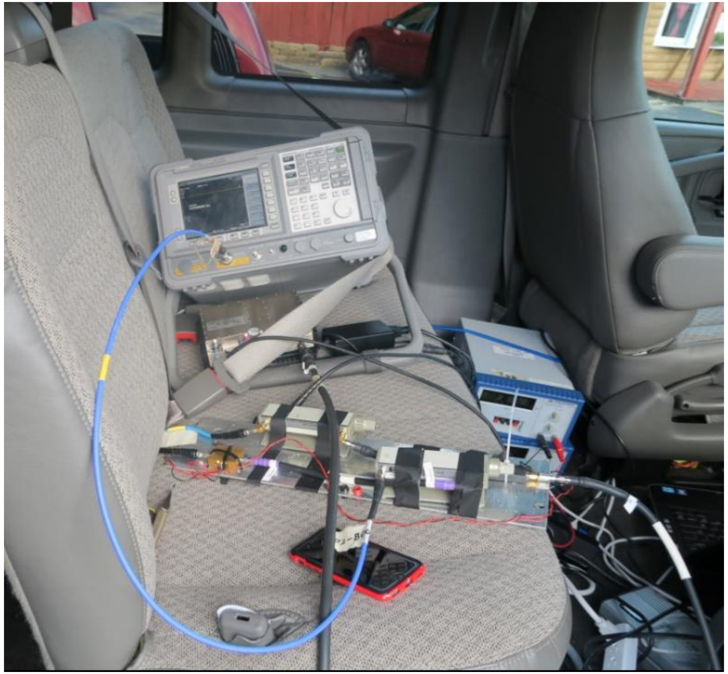
TX Location

LOS Scenario

NLOS Scenario

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

73 GHz RX Equipment in Field

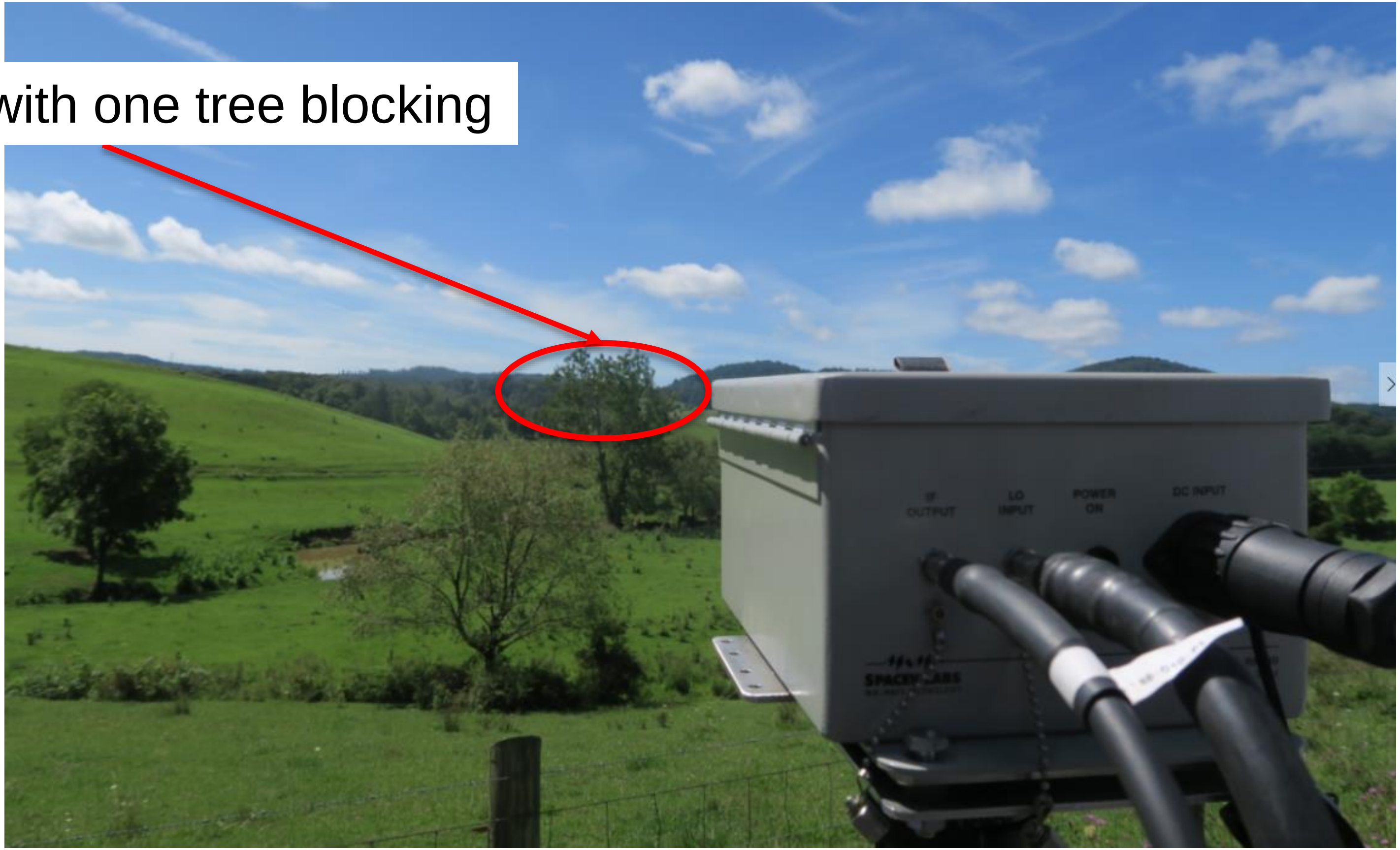


RX 5 LOS Location: 6.93 km

LOS with one tree blocking

RX 15 LOS Location: 3.44 km

LOS with one tree blocking



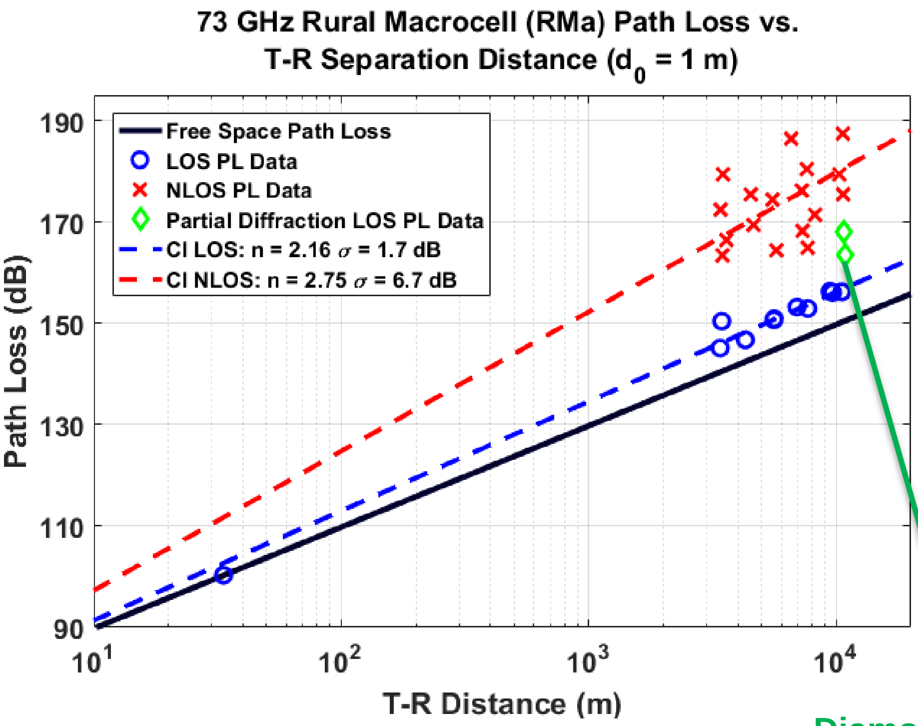
RX 23 NLOS Location: 5.72 km

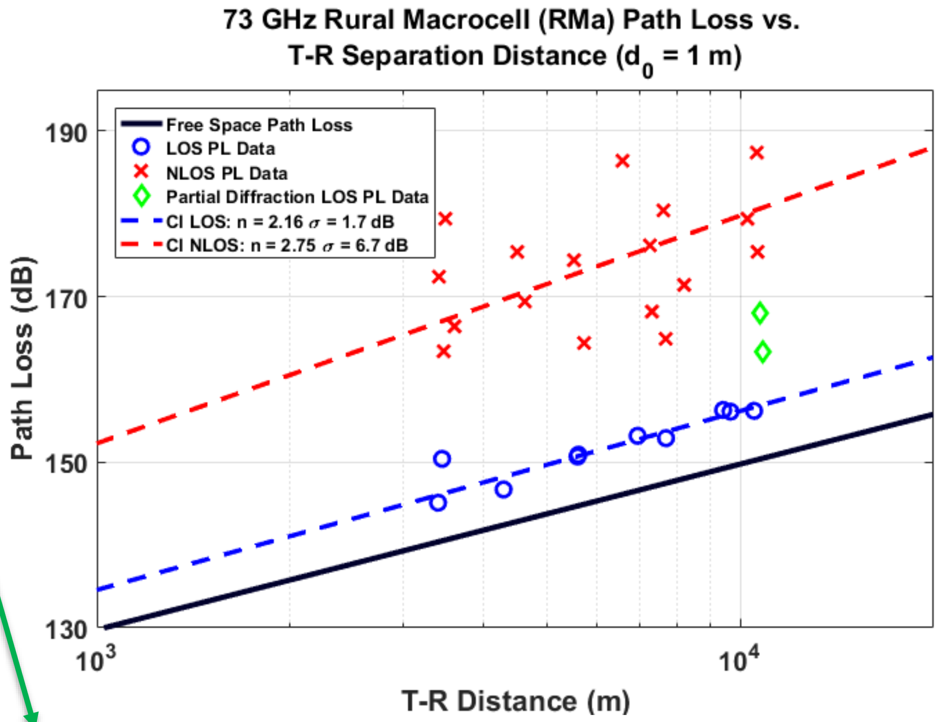
Hills and foliage
create NLOS scenario

RX 26 LOS Location: 7.67 km

TX location at house – LOS location

73 GHz RMa Path Loss Data and Models





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

Proposed RMa Path Loss Models For Frequencies Above 6 GHz

- Earlier RMa CI model based on simulations using 3GPP model and default parms. to 5/10 km

$$\mathrm{PL}^{\text{CI-3GPP}}_{\text{RMa-LOS}}(f_c, d_{3D})[\text{dB}] = 32.4 + 23.1\log_{10}\left(\frac{d_{3D}}{d_0}\right) + 20\log_{10}(f_c) + \chi_{\sigma_{\text{LOS}}};\ \text{ where } \sigma_{\text{LOS}} = 5.9\text{ dB, and } d_{3D} \geq 1\text{ m}$$

$$\mathrm{PL}^{\text{CI-3GPP}}_{\text{RMa-NLOS}}(f_c, d_{3D})[\text{dB}] = 32.4 + 30.4\log_{10}\left(\frac{d_{3D}}{d_0}\right) + 20\log_{10}(f_c) + \chi_{\sigma_{\text{NLOS}}};\ \text{ where } \sigma_{\text{NLOS}} = 8.3\text{ dB, and } d_{3D} \geq 1\text{ m}$$

- Based on New RMa Measurements at 73 GHz to 11 km distance, we found best-fit RMa model:

$$\mathrm{PL}^{\text{CI}}_{\text{RMa-LOS}}(f_c, d_{3D})[\text{dB}] = 32.4 + 21.6\log_{10}(d_{3D}) + 20\log_{10}(f_c) + \chi_{\sigma_{\text{LOS}}};\ \text{ where } \sigma_{\text{LOS}} = 1.7\text{ dB, and } d_{3D} \geq 1\text{ m}$$

$$\mathrm{PL}^{\text{CI}}_{\text{RMa-NLOS}}(f_c, d_{3D})[\text{dB}] = 32.4 + 27.5\log_{10}(d_{3D}) + 20\log_{10}(f_c) + \chi_{\sigma_{\text{NLOS}}};\ \text{ where } \sigma_{\text{NLOS}} = 6.7\text{ dB, and } d_{3D} \geq 1\text{ m}$$

http://wireless.engineering.nyu.edu/presentations/NTIA-propagation-presentation-JUNE-15-2016_v1%203.pdf see slides 25-30

Conclusions

- mmWave communication links will be useful to rural distances > 10 km (RMa).

- Existing 3GPP LOS RMa path loss models are not proven, and revert to a single slope model above 9.1 GHz due to the breakpoint. CI path loss model is simple, accurate, verified. Further work is including a factor in the PLE for TX height.

- **Proposal**: Replace 3GPP and ITU RMa models, or make the CI RMa path loss models *optional*. They are based on measurements, applicable from 1 m to 12 km and frequencies of 500 MHz to 100 GHz, may wish to increase σ to 4 or 8 dB (LOS/NLOS) to match current TR 38.900 3GPP RMa σ.

$$\mathrm{PL}^{\mathrm{CI}}_{\text{RMa-LOS}}(f_c, d_{3D})[\mathrm{dB}] = 32.4 + 21.6\log_{10}(d_{3D}) + 20\log_{10}(f_c) + \chi_{\sigma_{\mathrm{LOS}}};\ \text{where } \sigma_{\mathrm{LOS}} = 1.7\text{ dB, and } d_{3D} \geq 1\text{ m}$$

or 4.0 dB

$$\mathrm{PL}^{\mathrm{CI}}_{\text{RMa-NLOS}}(f_c, d_{3D})[\mathrm{dB}] = 32.4 + 27.5\log_{10}(d_{3D}) + 20\log_{10}(f_c) + \chi_{\sigma_{\mathrm{NLOS}}};\ \text{where } \sigma_{\mathrm{NLOS}} = 6.7\text{ dB, and } d_{3D} \geq 1\text{ m}$$

or 8.0 dB

G. R. MacCartney, S. Sun, and T. S. Rappaport, "Millimeter Wave Wireless Communications: New Results for Rural Connectivity," *All Things Cellular'16, 5th Workshop on All Things Cellular Proceedings, in conjunction with ACM MobiCom* , Oct. 7, 2016.

Acknowledgment

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References

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Thank You

Questions