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 conducted 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.

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3GPP RMa LOS path loss model:

- \[ PL_1 = 20 \log_{10} \left( 40\pi \cdot d_{3D} \cdot f_c / 3 \right) + \min(0.03h^{1.72}, 10) \log_{10}(d_{3D}) - \min(0.044h^{1.72}, 14.77) + 0.002 \log_{10}(h) \cdot d_{3D}; \sigma_{SF} = 4 \text{ dB} \]
- \[ PL_2 = PL_1(d_{BP}) + 40 \log_{10}(d_{3D}/d_{BP}); \sigma_{SF} = 6 \text{ dB} \]
  \[ d_{BP} = 2\pi \cdot h_{BS} \cdot h_{UT} \cdot f_c / c \]

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?

Applicability Ranges and Breakpoint Distance Concerns

RMa LOS 2D Breakpoint vs. Frequency

\[ d_{BP} > 10 \text{ km at } 9.1 \text{ GHz} \]

Frequency (GHz)

RMa LOS Breakpoint Beyond 10 km (Frequency [GHz] vs. \( h_{BS} \) [m])

<table>
<thead>
<tr>
<th>RMa LOS Default Values Applicability Range</th>
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<tbody>
<tr>
<td>( 10 \text{ m} &lt; d_{2D} &lt; d_{BP} ),</td>
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<td>( d_{BP} &lt; d_{2D} &lt; 10,000 \text{ m} ),</td>
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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.

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:**
  \[ \text{PL}^{\text{CI}}(f_c, d)[\text{dB}] = \text{FSPL}(f_c, d_0)[\text{dB}] + 10n \log_{10} \left( \frac{d}{d_0} \right) + \chi_\sigma; \]
  where \( d \geq d_0 \) and \( d_0 = 1 \text{ m} \)
  \[ = 32.4 + 10n \log_{10}(d) + 20 \log_{10}(f_c) + \chi_\sigma; \]

- **CIH Path Loss Model for Range of TX heights**
  \[ \text{PL}^{\text{CIH}}(f_c, d, h_{BS})[\text{dB}] = 32.4 + 20 \log_{10}(f_c) + 10n \left( 1 + b_{tx} \left( \frac{h_{BS} - h_{B0}}{h_{B0}} \right) \right) \log_{10}(d) + \chi_\sigma; \]
  where \( d \geq 1 \text{ m} \) and \( h_{B0} = \text{average BS height} \)

- **Effective PLE (PLE}_{\text{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.

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
- $d \geq 1\, \text{m}; \, h_{B0} = 35\, \text{m}$

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

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

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

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

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

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

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: -2°; height of 110 m above terrain
- TX and RX antennas: 27 dBi gain w/ 7° 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

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
- $2^\circ$ downtilt – avoids diffraction by mountain edge
- TX about 110 m above terrain
- Provided ~11 km measurement range
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

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.

Empirical CI and CIH Models

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

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

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

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

\[d \geq 1 \text{ m}; \quad h_{\text{BS}} = 35 \text{ m}; \quad 10 \text{ m} \leq h_{\text{BS}} \leq 150 \text{ m}\]
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 \(\sigma\) 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**

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**CI and CIH RMa Path Loss Model Parameters**

<table>
<thead>
<tr>
<th>Model</th>
<th>Data</th>
<th>Env.</th>
<th>Eq.</th>
<th>PLE</th>
<th>(\sigma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLCI-3GPP-LOS</td>
<td>Sim.</td>
<td>LOS</td>
<td>(9)</td>
<td>2.31</td>
<td>5.9 dB</td>
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<tr>
<td>PLCI-RMa-LOS</td>
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<td>LOS</td>
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<td>2.16</td>
<td>1.7 dB</td>
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<td>PLCI-3GPP-NLOS</td>
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<td>NLOS</td>
<td>(10)</td>
<td>3.04</td>
<td>8.2 dB</td>
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<tr>
<td>PLCI-RMa-NLOS</td>
<td>Meas.</td>
<td>NLOS</td>
<td>(14)</td>
<td>2.75</td>
<td>6.7 dB</td>
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</table>

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<tr>
<th>Model</th>
<th>Data</th>
<th>Env.</th>
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<th>(n)</th>
<th>(b_{tx})</th>
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<tr>
<td>PLCI-3GPP-LOS</td>
<td>Sim.</td>
<td>LOS</td>
<td>(11)</td>
<td>2.31</td>
<td>-0.006</td>
<td>5.6 dB</td>
</tr>
<tr>
<td>PLCI-RMa-LOS</td>
<td>Meas.</td>
<td>LOS</td>
<td>(15)</td>
<td>2.31</td>
<td>-0.03</td>
<td>1.7 dB</td>
</tr>
<tr>
<td>PLCI-3GPP-NLOS</td>
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<td>NLOS</td>
<td>(12)</td>
<td>3.07</td>
<td>-0.06</td>
<td>8.7 dB</td>
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<td>PLCI-RMa-NLOS</td>
<td>Meas.</td>
<td>NLOS</td>
<td>(16)</td>
<td>3.07</td>
<td>-0.049</td>
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</tbody>
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Acknowledgement to our NYU WIRELESS Industrial Affiliates and NSF:
References

References


Questions