Indoor and Outdoor 5G Diffraction Measurements and Models at 10, 20, and 26 GHz

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Agenda

- Millimeter Wave Diffraction Measurements at 10, 20, and 26 GHz
- Diffraction Measurement System and Procedures
- Indoor and Outdoor Measurement Environment and Measured Materials
- Diffraction Models: KED Model and Creeping Wave Linear Model
- Indoor and Outdoor Measurement Results and Fit to Models
- Impact of Diffraction in practical cm/mmWave systems
- Conclusion
Millimeter Wave Diffraction Measurements at 10, 20, and 26 GHz

- Understand diffraction loss vs. frequency in indoor and outdoor environments
- Investigate effects of environment, material type and object shape
- Develop accurate and simple diffraction loss models

# Measurement System Characteristics

<table>
<thead>
<tr>
<th>Carrier Frequency</th>
<th>10 GHz</th>
<th>20 GHz</th>
<th>26 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum TX Power</td>
<td>6 dBm</td>
<td>6 dBm</td>
<td>10.9°/8.6° (24.5 dBi)</td>
</tr>
<tr>
<td>TX/RX Antenna Azi./Elv. HPBW (Gain)</td>
<td>17°/17° (20 dBi)</td>
<td>17°/17° (20 dBi)</td>
<td>10.9°/8.6° (24.5 dBi)</td>
</tr>
<tr>
<td>TX Max. EIRP</td>
<td>26 dBm</td>
<td>26 dBm</td>
<td>30.5 dBm</td>
</tr>
<tr>
<td>Cross Polarization Discrimination (XPD)*</td>
<td>33.1 dB</td>
<td>32.1 dB</td>
<td>29.4 dB</td>
</tr>
<tr>
<td>TX-RX Polarization</td>
<td>V-V, H-V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TX Antenna Height (h_{TX})</td>
<td>1.4 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RX Antenna Height (h_{RX})</td>
<td>1.4 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TX to Corner *</td>
<td>2 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RX to Corner</td>
<td>1 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td># of TX Incident Angle</td>
<td>3 (Indoor), 2 (Outdoor)</td>
<td></td>
<td></td>
</tr>
<tr>
<td># of RX Track Locations</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Track Length</td>
<td>35.3 cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Track Increment</td>
<td>0.875 cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td># of Power Measurements per TX Incident Angle</td>
<td>200</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* XPD values were measured at 3 m free space distance.
* 2 m is in the far field of these antennas.
10, 20, and 26 GHz Measurements

• At 10, 20, and 26 GHz:
  • **Three** TX incidence angles per material (indoor)
    • Indoor $\beta$ Range: 10° to 39°
    • Outdoor $\beta$ Range: 20° to 36°
  • **Two** TX incidence angles per material (outdoor)
  • **Five** RX track locations, RX antenna moves in 8.75 mm increments (corresponding to 0.5° increments) from NLOS to LOS environment
  • **40** Measurements per track, **200** total data points for each TX incident angle

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![Diagram of TX and RX locations with track](image)
Three measurement materials: Drywall Corner, Plastic Board, and Wooden Corner

- **Plastic Board**: Semi-transparent board with a thickness of 2 cm
- **Drywall Corner**: Vertical metal stud inside
- **Wooden Corner**
Two measurement locations: Marble Corner and Stone Pillar

Rough Surface with rounded corners
Knife Edge Diffraction Model (KED)

\[
\frac{E_{\text{KED}}}{E_0} = F(u) = \frac{1 + j}{2} \times e^{j(\pi/2)^2 d}
\]

\[
= u \sqrt{\frac{2(d_1 + d_2)}{d_1 d_2}} = \sqrt{\frac{2d_1 d_2}{(d_1 + d_2)}}
\]

\[
G(\alpha)[\text{dB}] = P(\alpha) = 20 \log_{10}|F(u)|
\]

A Function of Frequency and Diffraction Angle

A function of diffraction angle ($\alpha$ in degrees)

$$c = 6.03 \text{ dB}$$

Error between measurements and prediction

\[ (i)_{\text{[dB]}} = P_{\text{meas}}(i) - P_{\text{pred}}(i) \]

Mean Error

\[ \text{ME[dB]} = \frac{1}{N} \sum_{i=1}^{N} (i) \]

Sample Standard Deviation

\[ \text{SD[dB]} = \left[ \frac{1}{N} \sum_{i=1}^{N} \left( (i) - \text{ME} \right)^2 \right]^{\frac{1}{2}} \]

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Wooden Corner KED Measurements Results

KED overestimates by 2 – 4 dB
Plastic Board KED Measurements Results

Penetration through the semi-transparent board

KED overestimates by 2 – 4 dB
Marble Corner Creeping Wave Measurements

Results

**Linear Model**
- ME: $-0.34$ dB
- SD: $3.3$ dB

**KED Model**
- ME: $1.3$ dB
- SD: $5.5$ dB

$n=0.62$

**Linear Model**
- ME: $0.45$ dB
- SD: $4.3$ dB

**KED Model**
- ME: $3.3$ dB
- SD: $5.8$ dB

$n=0.77$

$n=0.96$

26 GHz

20 GHz

10 GHz
Indoor Environment
Diffraction angle $\alpha$ from $0^\circ$ to $20^\circ$
Diffraction Loss by the KED Model
10 GHz: 20.3 dB ($\pm$ 5 dB)
20 GHz: 23.3 dB ($\pm$ 5 dB)
26 GHz: 24.4 dB ($\pm$ 5 dB)

Diffraction angle $\alpha$ from $0^\circ$ to $30^\circ$
Diffraction Loss by the KED Model
10 GHz: 23.9 dB ($\pm$ 5 dB)
20 GHz: 26.9 dB ($\pm$ 5 dB)
26 GHz: 28.1 dB ($\pm$ 5 dB)

If $v = 1$ m/s, the received signal is dropping at a rate of about 25 dB/s
Outdoor Examples

Outdoor Environment
Diffraction angle $\alpha$ from $0^\circ$ to $20^\circ$
Diffraction Loss by the Linear Model
For the stone rounded surface
10 GHz: $21.0 \text{ dB} \ (\pm \ 4 \text{ dB})$
20 GHz: $23.7 \text{ dB} \ (\pm \ 5 \text{ dB})$
26 GHz: $25.3 \text{ dB} \ (\pm \ 5 \text{ dB})$

Diffraction angle $\alpha$ from $0^\circ$ to $30^\circ$
Diffraction Loss by the KED Model
For the marble surface
10 GHz: $18.5 \text{ dB} \ (\pm \ 4 \text{ dB})$
20 GHz: $21.4 \text{ dB} \ (\pm \ 5 \text{ dB})$
26 GHz: $25.2 \text{ dB} \ (\pm \ 5 \text{ dB})$

Typical Slope Values

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Stone</th>
<th>Marble</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 GHz</td>
<td>0.76</td>
<td>0.63</td>
</tr>
<tr>
<td>20 GHz</td>
<td>0.90</td>
<td>0.78</td>
</tr>
<tr>
<td>26 GHz</td>
<td>0.98</td>
<td>0.98</td>
</tr>
</tbody>
</table>

If $v = 1\text{ m/s}$, the received signal is dropping at a rate of about 30 dB/s
The KED model can be used in ray tracing tools to calculate diffraction loss in the indoor environment, with about 5 dB standard deviation (due to the reflective indoor environment and penetration through the corner). The KED model underestimates diffraction loss of outdoor measurements for V-V antenna polarizations, especially in the deep shadow region. The diffraction loss for an outdoor building corner with a smooth or rounded edge can be better predicted by a simple linear creeping wave model. The diffraction loss as a function of diffraction angle clearly increased with frequency for identical outdoor measurement locations. Typical slope values found in the the linear creeping wave model increased from 0.62 to 0.96 from 10 to 26 GHz for outdoor buildings. At walking speeds around a corner, diffraction loss is 25-30 dB in a second.
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Questions