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

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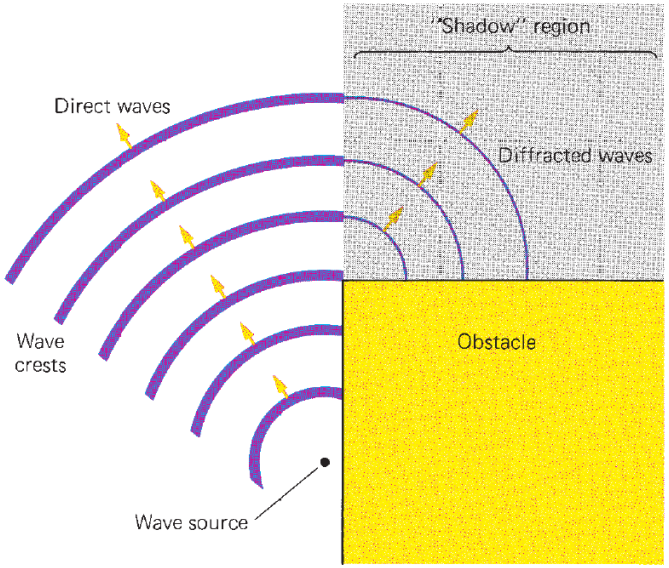
Agenda

- 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

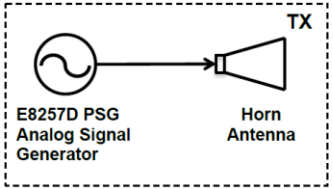
- Understand diffraction loss vs. frequency in indoor and outdoor environments
- Investigate effects of environment, material type and object shape
- Develop accurate and simple diffraction loss models

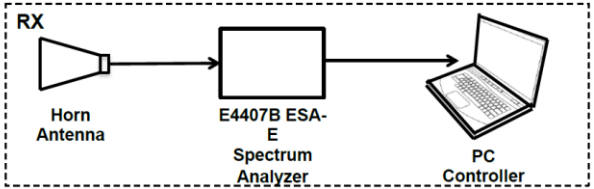


T. S. Rappaport, Wireless Communications: Principles and Practice, 2nd ed. Upper Saddle River, NJ: Prentice Hall, 2002.
K. B. Krauskopf, A. Beiser, The Physical Universe, McGraw Hill, 2002.

Measurement System Characteristics

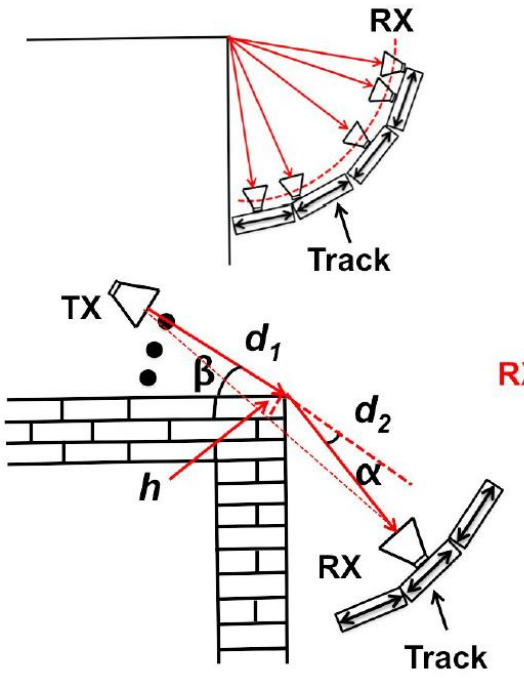
Carrier Frequency	10 GHz	20 GHz	26 GHz
Maximum TX Power	6 dBm		
TX/RX Antenna Azi./Elv. HPBW (Gain)	17°/ 17° (20 dBi)	17°/ 17° (20 dBi)	10.9°/ 8.6° (24.5 dBi)
TX Max. EIRP	26 dBm	26 dBm	30.5 dBm
Cross Polarization Discrimination (XPD)*	33.1 dB	32.1 dB	29.4 dB
TX-RX Polarization	V–V, H-V		
TX Antenna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

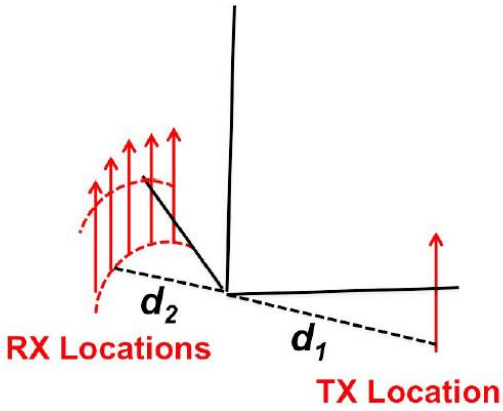


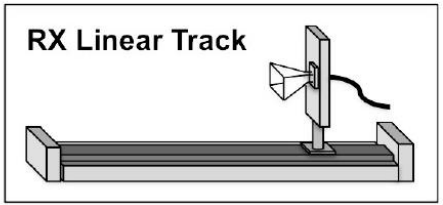


* XPD values were measured at 3 m free space distance.
* 2 m is in the far field of these antennas.

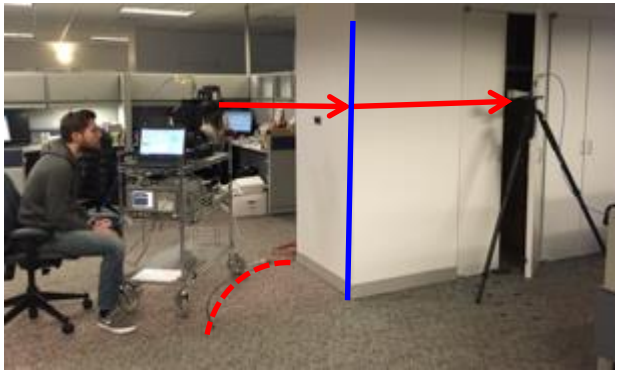
10, 20, and 26 GHz Measurements







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

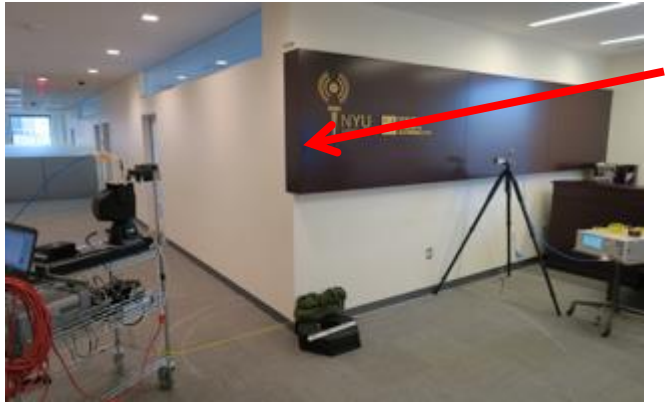


Indoor Diffraction Measurement Material

Three measurement materials: Drywall Corner, Plastic Board, and Wooden Corner

Plastic Board

Semi-transparent board with a thickness of 2 cm



Wooden Corner

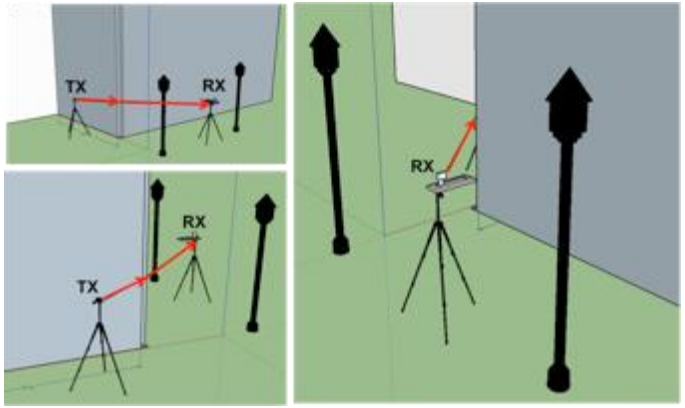
Drywall Corner

Vertical metal stud inside

Drywall Corner

Outdoor Diffraction Measurements

Two measurement locations: Marble Corner and Stone Pillar



Rough Surface with rounded corners

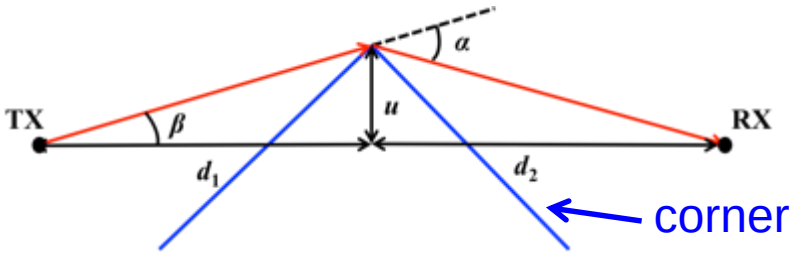
Knife Edge Diffraction Model

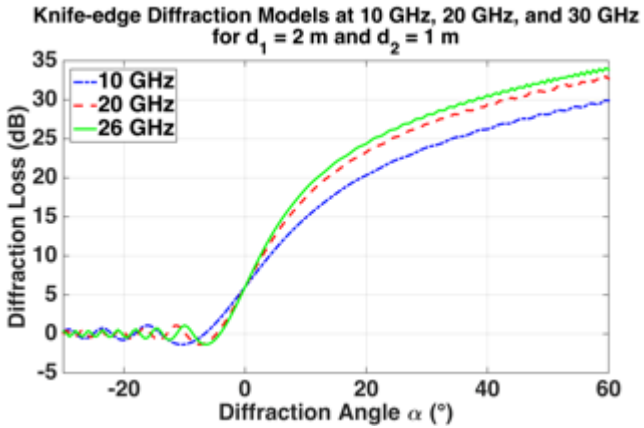
Knife Edge Diffraction Model (KED)

$$\frac{E_{\mathrm{KED}}}{E_0} = F(u) = \frac{1+j}{2} \times \int_u^{\infty} e^{-j(\pi/2)t^2}\, dt$$

$$u = u\sqrt{\frac{2(d_1+d_2)}{\lambda\, d_1 d_2}} = a\sqrt{\frac{2 d_1 d_2}{\lambda\,(d_1+d_2)}}$$

$$G(u)[\mathrm{dB}] = -P(u) = 20\log_{10}|F(u)|$$





A Function of Frequency and Diffraction Angle

T. S. Rappaport, Wireless Communications: Principles and Practice, 2nd ed. Upper Saddle River, NJ: Prentice Hall, 2002.

Creeping Wave Linear Model

Linear Model with fixed anchor point

$$E \sim E_i e^{-jk\alpha R_h} \cdot \frac{e^{-jkd_2}}{\sqrt{kd_2}} \sum_{p=1}^{\infty} D_p R_h \exp(-\Psi_p \alpha)$$

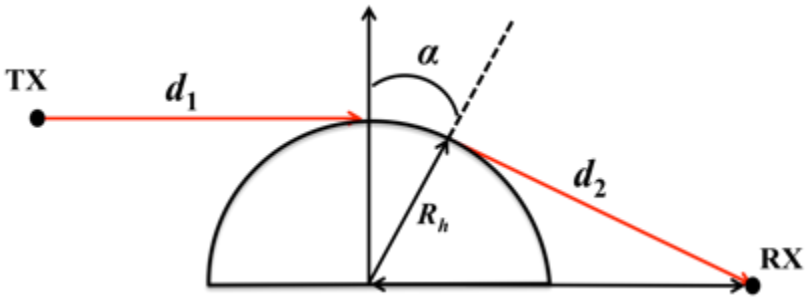
$$\frac{E}{E_i} \sim D_p R_h \exp(-\Psi \alpha)$$

$$D_p, \Psi_h \sim \left(\frac{kR_h}{2}\right)^{\frac{1}{3}}$$

$$G(\alpha)[\text{dB}] = -P(\alpha) = 20\log_{10} E = -A(R_h, f)\Psi_p \alpha + C(R_h, f)$$

$$P(\alpha) = n\alpha + c$$

A function of diffraction angle (α in degrees)
c = 6.03 dB



E_i **Incident field**

k **Wave number**

D_p **Excitation coefficient**

y_p **Attenuation constant**

L. Piazzi and H. L. Bertoni, “Effect of terrain on path loss in urban environments for wireless applications,” IEEE Transactions on Antennas and Propagation, vol. 46, no. 8, pp. 1138-1147, Aug. 1998.

Statistics Between Measurements And Prediction

Error between measurements and prediction

$$D(a_i)[\mathrm{dB}] = P_{meas}(a_i) - P_{pred}(a_i)$$

Mean Error

$$\mathrm{ME}[\mathrm{dB}] = \frac{1}{N}\sum_{i=1}^{N} D(a_i)$$

Indicator for the overall trend of the prediction

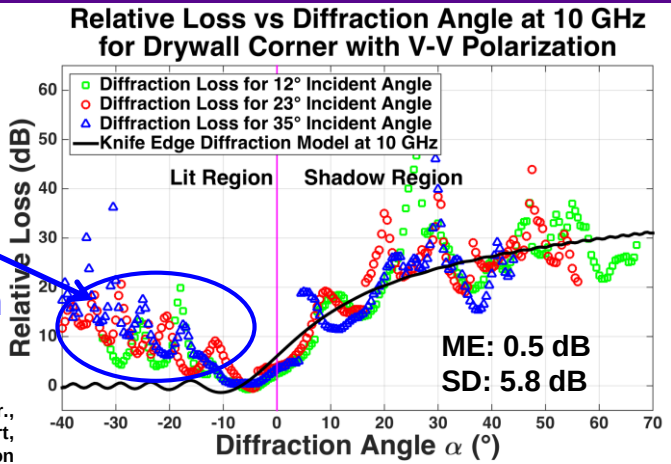
Sample Standard Deviation

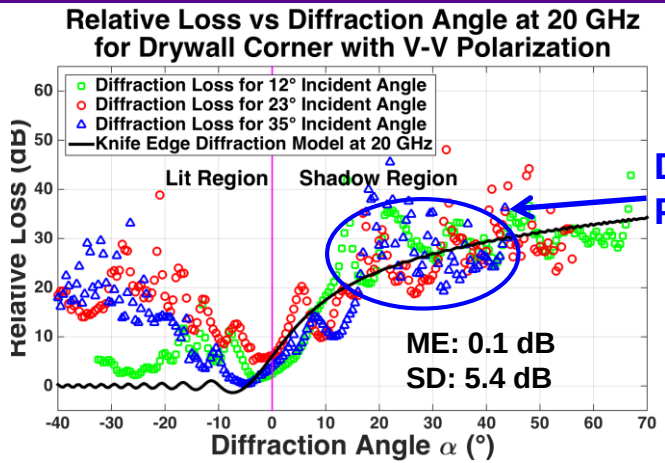
$$\mathrm{SD}[\mathrm{dB}] = \left[\frac{1}{N-1}\sum_{i=1}^{N}\left(D(a_i) - ME\right)^2\right]^{\frac{1}{2}}$$

T. Negishi, V. Picco, D. Spitzer, D. Erricolo, G. Carluccio, F. Puggelli, and M. Albani, ”Measurements to validate the UTD triple diffraction coefficient,” IEEE Transactions on Antennas and Propagation, vol. 62, no. 7, pp. 3723-3730, July 2014.

Drywall KED Measurements Results

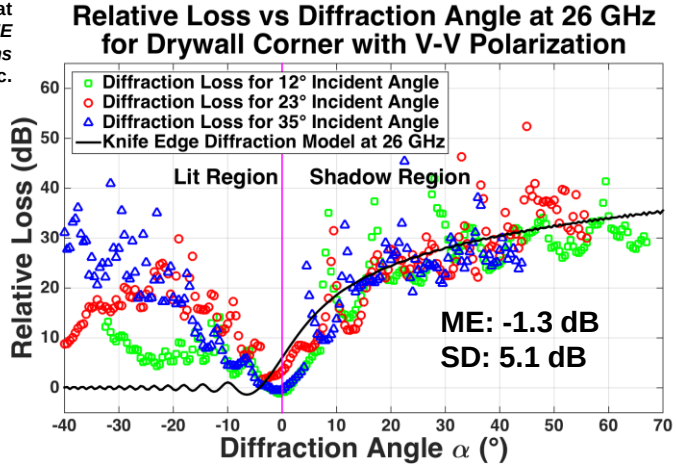
Free Space Transmission, Reflection, and Diffraction

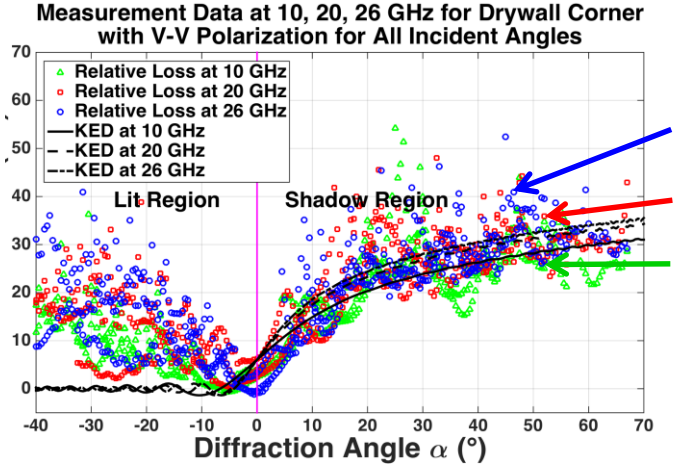




Diffraction and Penetration

S. Deng, G. R. MacCartney, Jr., and T. S. Rappaport, "Millimeter Wave Diffraction Measurements and Models at 10, 20, and 30 GHz," *2016 IEEE Global Communications Conference (GLOBECOM)*, Dec. 2016.



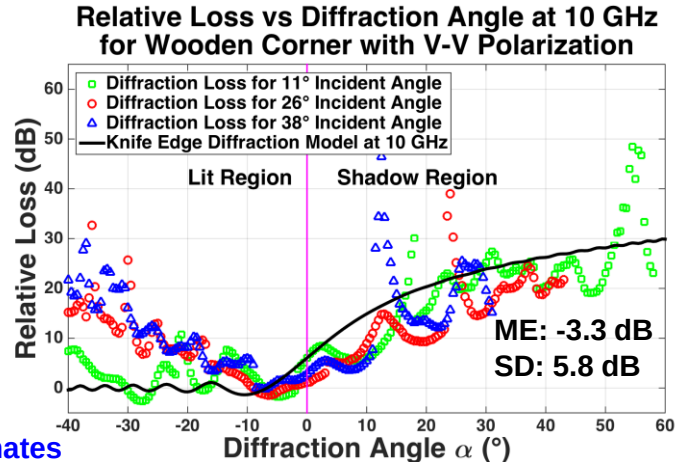


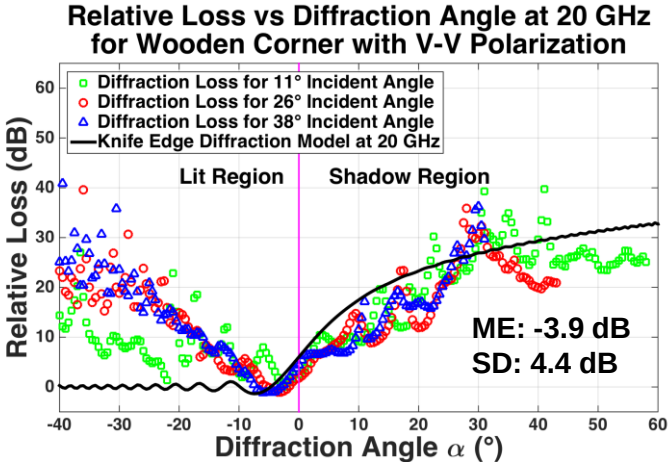
26 GHz

20 GHz

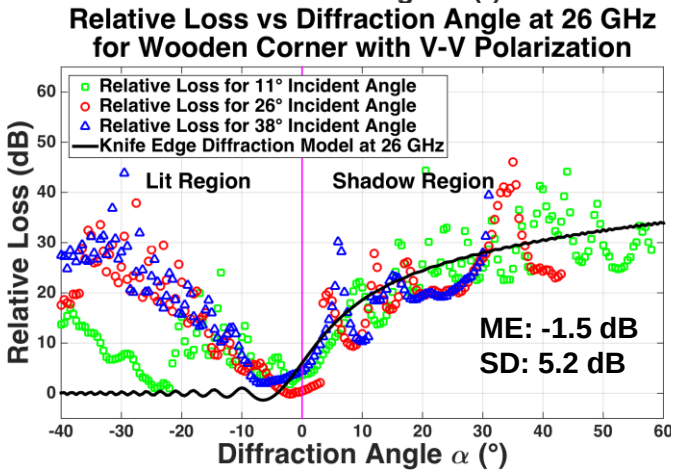
10 GHz

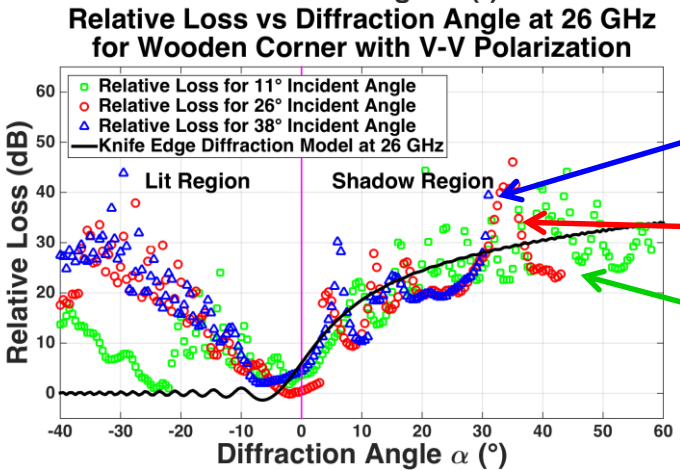
Wooden Corner KED Measurements Results





KED overestimates by 2 – 4 dB





26 GHz

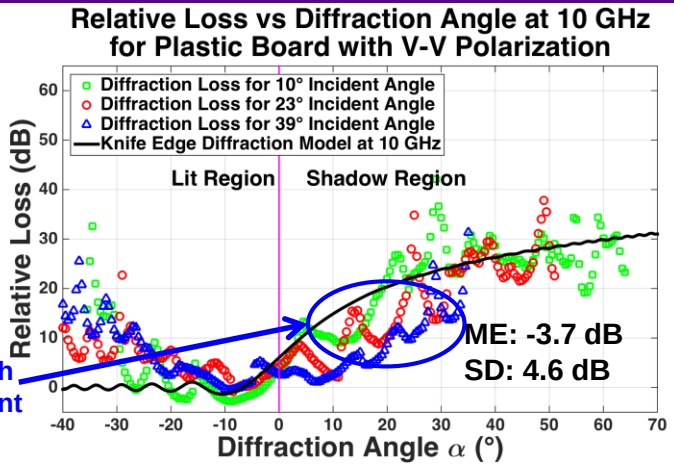
20 GHz

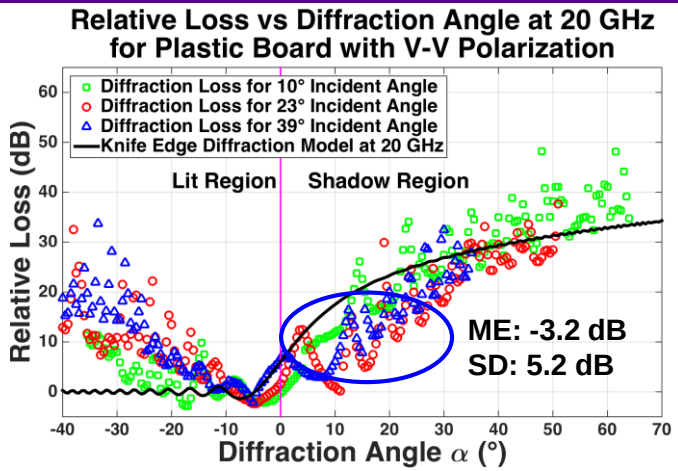
10 GHz

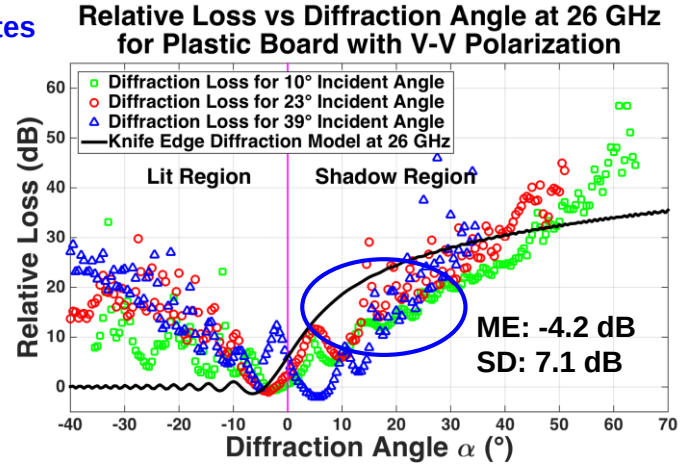
Plastic Board KED Measurements Results

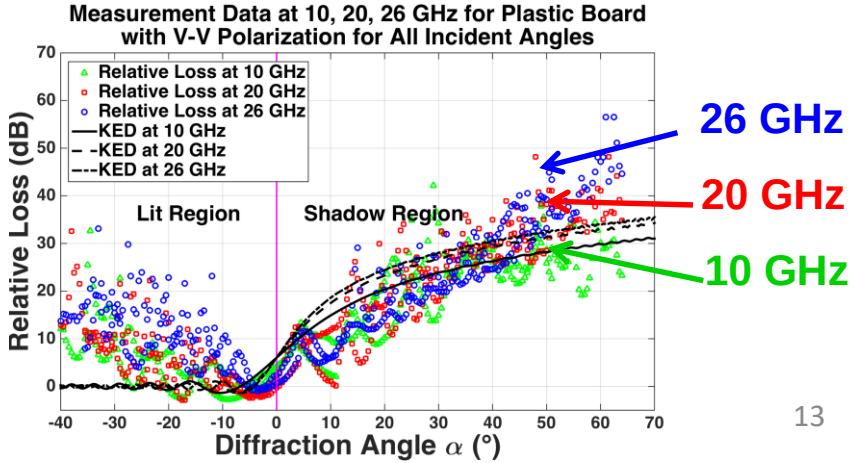
Penetration through the semi-transparent board

KED overestimates by 2 – 4 dB









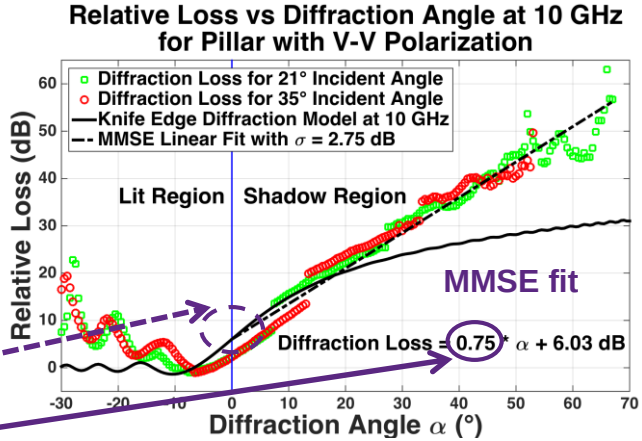
Stone Pillar Creeping Wave Measurements Results

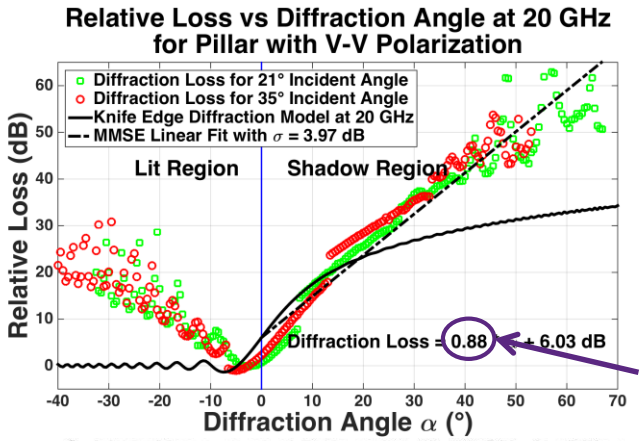
Linear Model
ME: 0.03 dB
SD: 2.8 dB

KED Model
ME: 6.8 dB
SD: 7.5 dB

Anchor point from KED model

n=0.75





Linear Model
ME: 0.45 dB
SD: 4.3 dB

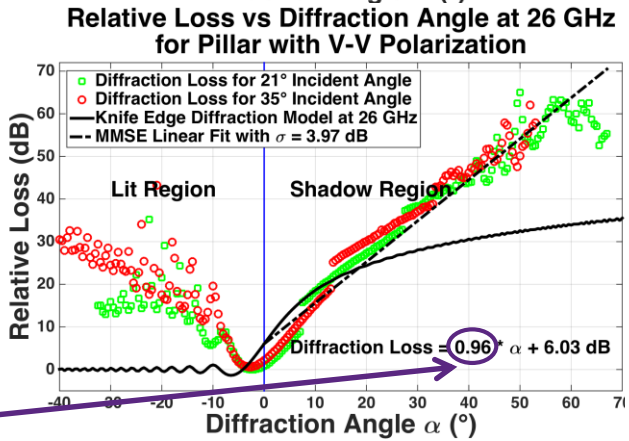
KED Model
ME: 8.5 dB
SD: 9.2 dB

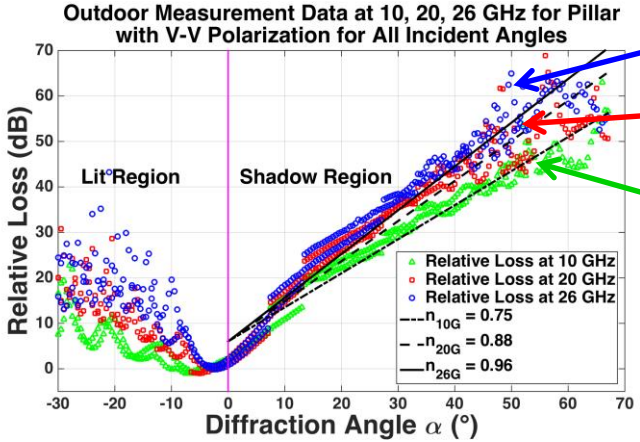
n=0.88

Linear Model
ME: 0.48 dB
SD: 4.0 dB

KED Model
ME: 9.9 dB
SD: 10.3 dB

n=0.96





26 GHz

20 GHz

10 GHz

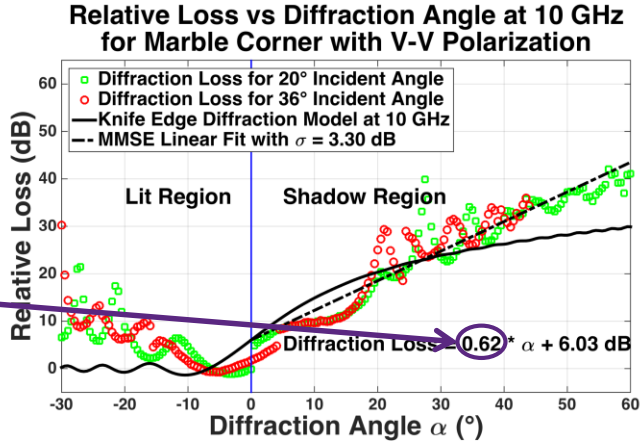
P. A. Tenerelli and C. W. Bostian, "Measurements of 28 GHz diffraction loss by building corners," *IEEE International Symposium on Personal, Indoor and Mobile Radio Communication*, vol.3, pp. 1166-1169, Sept. 1998

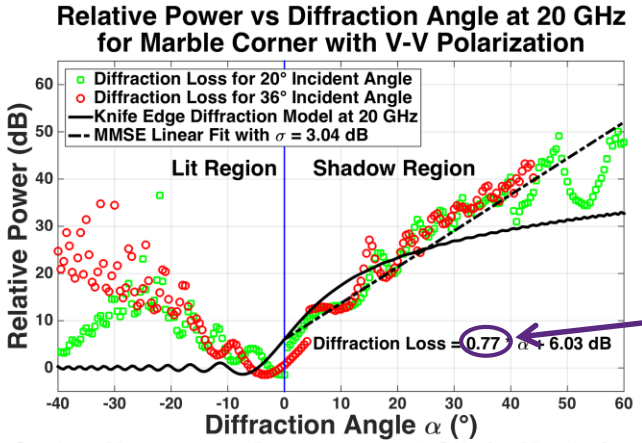
Marble Corner Creeping Wave Measurements Results

Linear Model
ME: -0.34 dB
SD: 3.3 dB

KED Model
ME: 1.3 dB
SD: 5.5 dB

n=0.62





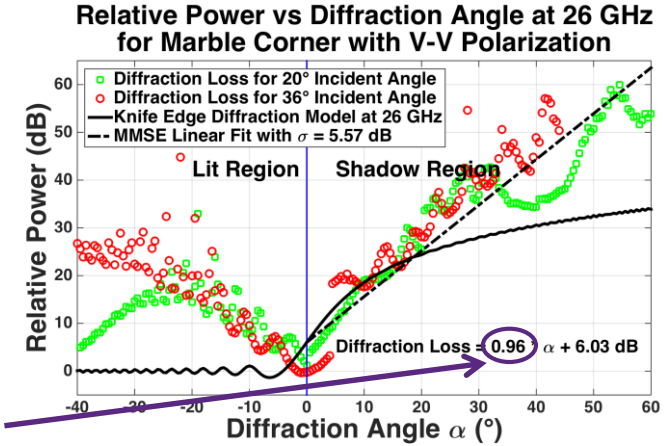
Linear Model
ME: 0.45 dB
SD: 4.3 dB

KED Model
ME: 3.3 dB
SD: 5.8 dB

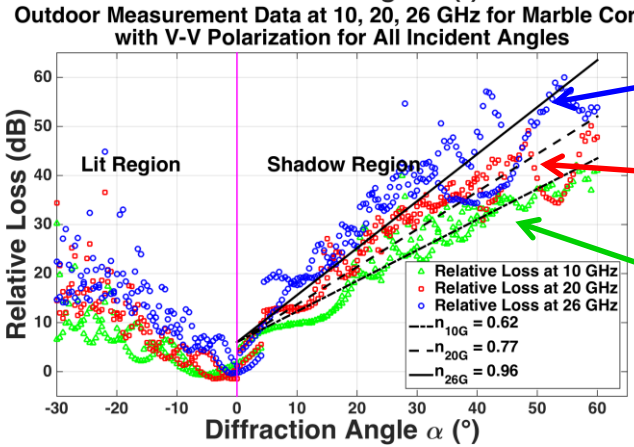
n=0.77

Linear Model
ME: 4.8 dB
SD: 5.0 dB

KED Model
ME: 7.8 dB
SD: 8.6 dB



n=0.96

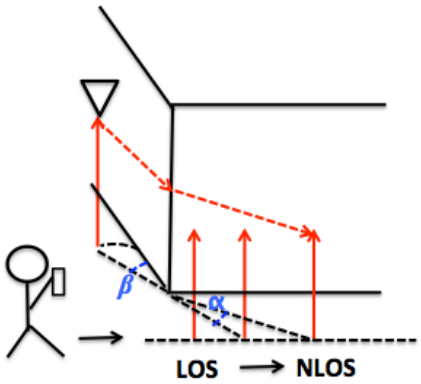


26 GHz

20 GHz

10 GHz

Indoor Examples



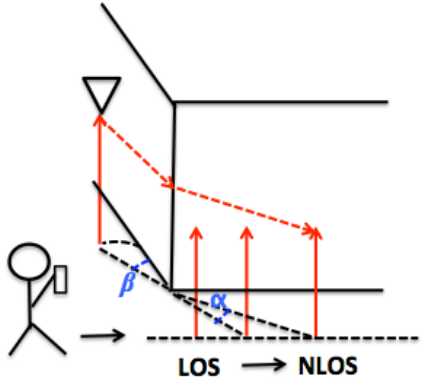
Indoor Environment

Diffraction angle **α** from 0º to **20º**
Diffraction Loss by the **KED Model**
10 GHz: **20.3 dB** (± 5 dB)
20 GHz: **23.3 dB** (± 5 dB)
26 GHz: **24.4 dB** (± 5 dB)

Diffraction angle **α** from 0º to **30º**
Diffraction Loss by the **KED Model**
10 GHz: **23.9 dB** (± 5 dB)
20 GHz: **26.9 dB** (± 5 dB)
26 GHz: **28.1 dB** (± 5 dB)

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

Outdoor Examples



Typical Slope Values

Frequency	Stone	Marble
10 GHz	0.76	0.63
20 GHz	0.90	0.78
26 GHz	0.98	0.98

Outdoor Environment

Diffraction angle **α** from 0º to **20º**

Diffraction Loss by the **Linear Model**

For the **stone** rounded surface
10 GHz: **21.0 dB** (± 4 dB)
20 GHz: **23.7 dB** (± 5 dB)
26 GHz: **25.3 dB** (± 5 dB)

For the **marble** surface
10 GHz: **18.5 dB** (± 4 dB)
20 GHz: **21.4 dB** (± 5 dB)
26 GHz: **25.2 dB** (± 5 dB)

Diffraction angle **α** from 0º to **30º**

Diffraction Loss by the **KED Model**

For the **stone** rounded surface
10 GHz: **28.5 dB** (± 4 dB)
20 GHz: **32.5 dB** (± 5 dB)
26 GHz: **34.9 dB** (± 5 dB)

For the **marble** surface
10 GHz: **24.8 dB** (± 4 dB)
20 GHz: **29.0 dB** (± 5 dB)
26 GHz: **34.8 dB** (± 5 dB)

If v = 1m/s, the received signal is dropping at a rate of about 30 dB/s

Conclusion

- 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.

Acknowledgment

Acknowledgement to our NYU WIRELESS Industrial Affiliates and NSF

Grants: 1320472, 1302336, and 1555332

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[9] T. S. Rappaport et al., “Wideband millimeter-wave propagation measurements and channel models for future wireless communication system design (invited paper),” IEEE Transactions on Communications, vol. 63, no. 9, pp. 3029–3056, Sept. 2015.
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Thank You!

Questions