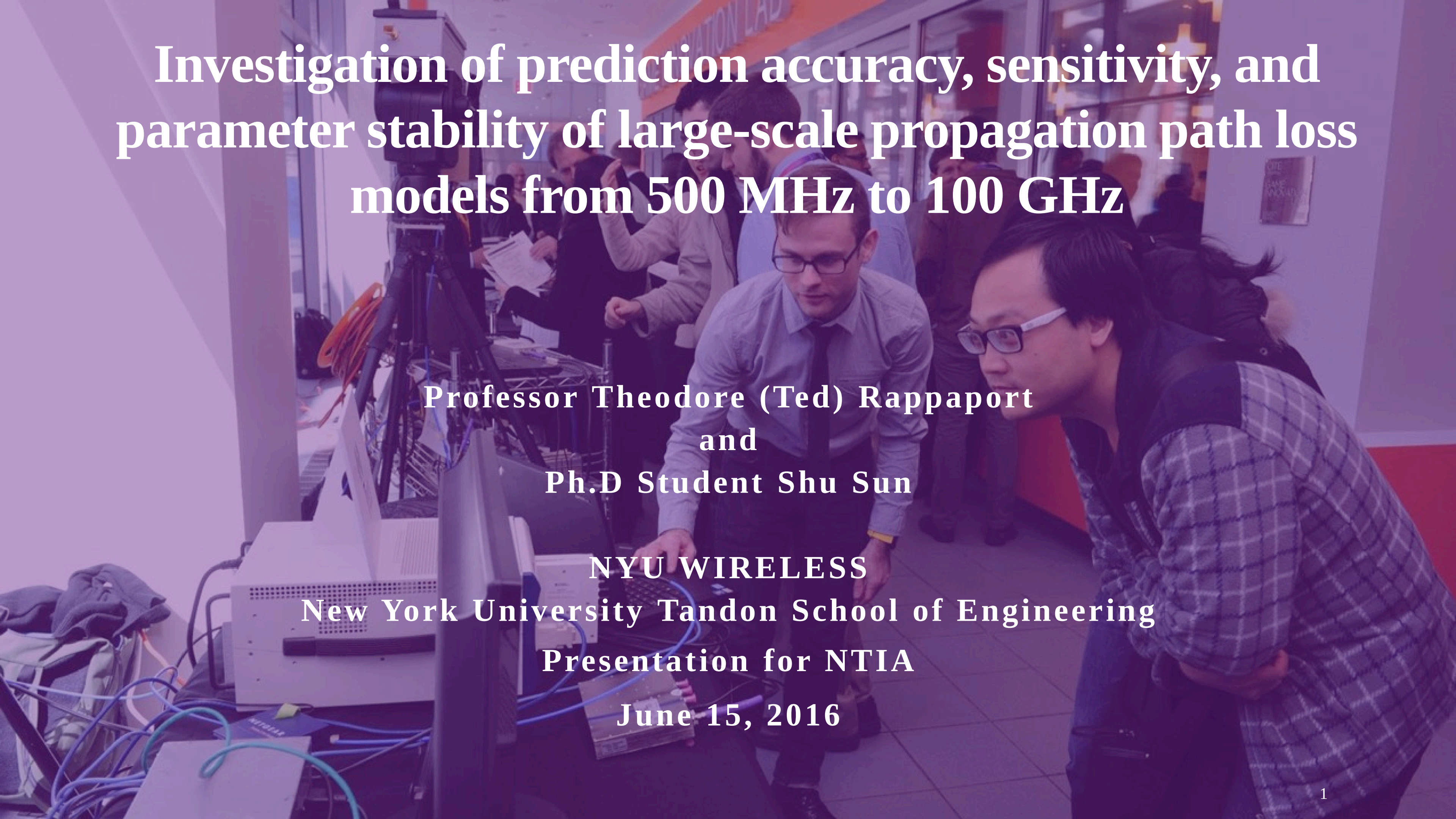


Investigation of prediction accuracy, sensitivity, and parameter stability of large-scale propagation path loss models from 500 MHz to 100 GHz

Professor Theodore (Ted) Rappaport
and
Ph.D Student Shu Sun

NYU WIRELESS
New York University Tandon School of Engineering

Presentation for NTIA

June 15, 2016

Challenges > 6 GHz: Range/Capacity/Cost

Friis' Law: $\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi r}\right)^2$

- Free-space channel gain $\propto \lambda^2$, but antenna gains $\propto 1/\lambda^2$
- Upshot: For fixed physical size antennas in free space, *frequency does not matter*!
- Path loss can be overcome with antenna beamforming, *independent of frequency*!

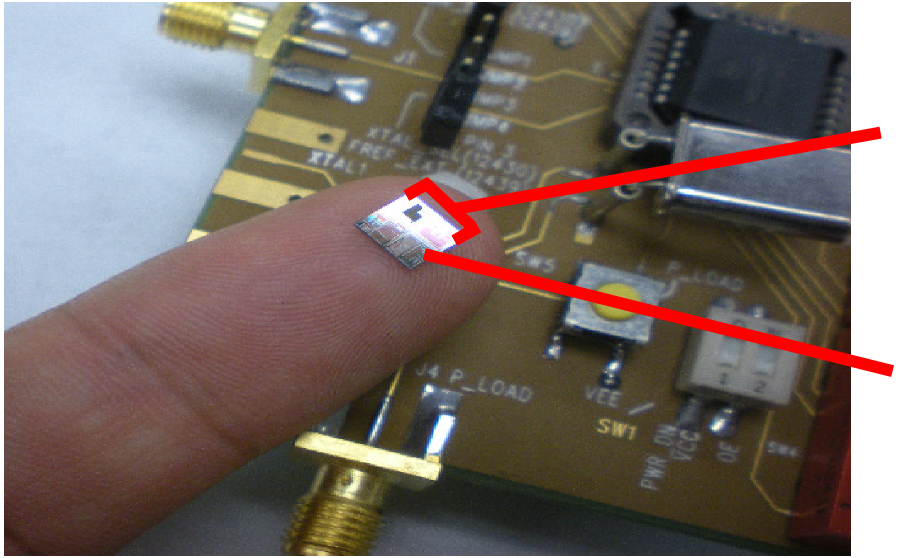
Shadowing: Significant transmission losses will occur:

- Brick, concrete > 35 dB
- Human body: Up to 35 dB
- But channel is rich in scattering and reflection, even from people! Enabler for propagation!

Millimeter wave works! NLOS propagation uses reflections and scattering

- Rappaport, et. al, "Millimeter wave mobile communications for 5G cellular: It will work!" IEEE Access, May 2013

mmWave Wavelength Visualization – 60 GHz



5 millimeters
16 antennas

Integrated Circuit

Source: F. Gutierrez, S. Agarwal, K. Parrish, and T.S. Rappaport, “On-Chip Integrated Antenna Structures in CMOS for 60 GHz WPAN Systems,” IEEE Journal on Selected Areas in Communications, vol. 27, no. 8, October 2009, pp. 1367 – 1377.

Early Work in Directional Channels

Overview of spatial channel models for antenna array communication systems

R.B. Ertel, et. al., IEEE PERSONAL COMMUNICATIONS, Vol. 5, No. 1, **February 1998**

Smart Antennas for Wireless Communications (book by Prentice-Hall)

J. C. Liberti, T.S. Rappaport, **c. 1999**

Application of narrow-beam antennas and fractional loading factor in cellular communication systems

Cardieri, et. al., IEEE TRANS. ON VEHICULAR TECHNOLOGY, Vol. 50, No. 3, **March 2001**

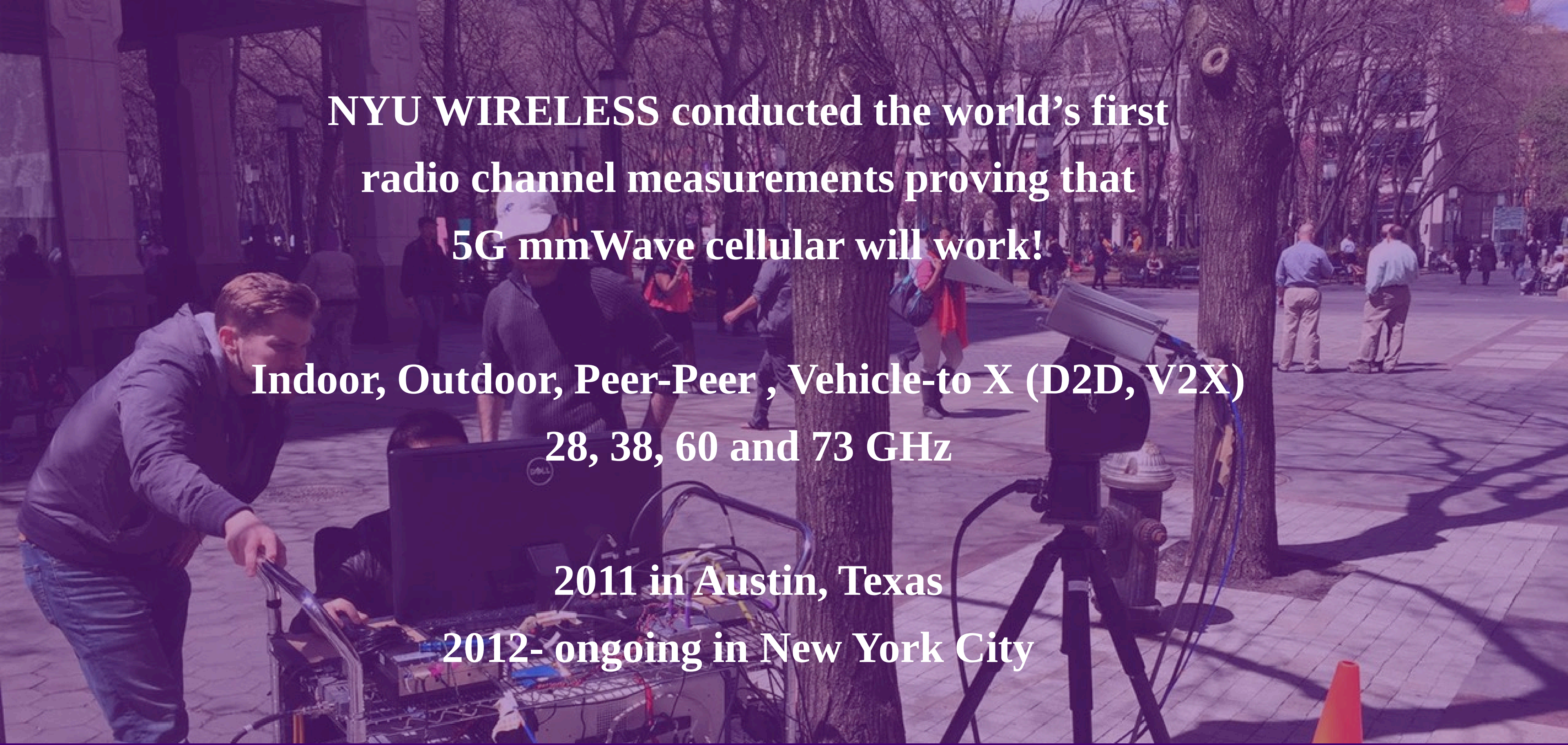
Spatial and temporal characteristics of 60-GHz indoor channels

Xu, et. al., IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, VOL.. 20, NO. 3, **April 2002**

Wideband Measurement of Angle and Delay Dispersion for Outdoor/Indoor/ Peer-to-Peer Channels @ 1920 MHz

Durgin, et. al., IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. 51, NO. 5, **May 2003**

1. **Multipath Shape Factor Theory** found new parameters to describe **directional channels**
2. **RMS delay spreads, interference, and Doppler effects all shrink dramatically** for small cell **directional antennas.**
3. **Multipath power is arriving from several discrete directions in azimuth (lobes)** instead of across a smooth continuum of azimuthal angles in NLOS channels.



NYU WIRELESS conducted the world's first radio channel measurements proving that 5G mmWave cellular will work!

Indoor, Outdoor, Peer-Peer , Vehicle-to X (D2D, V2X)

28, 38, 60 and 73 GHz

2011 in Austin, Texas

2012- ongoing in New York City

T. S. Rappaport, et. al, "Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!," IEE Access, No. 1, May 2013.

T.S. Rappaport, et. al., "Broadband Millimeter-Wave Propagation Measurements and Models Using Adaptive-Beam Antennas for Outdoor Urban Cellular Communications," IEEE Trans. Ant. Prop., Vo 61, No. 4, April 2013.

T. S. Rappaport, et. al, "Wideband Millimeter-Wave Propagation Measurements and Channel Models for Future Wireless Communication System Design," IEEE Trans. Comm., Vol. 63, No. 9, Sept .2015.

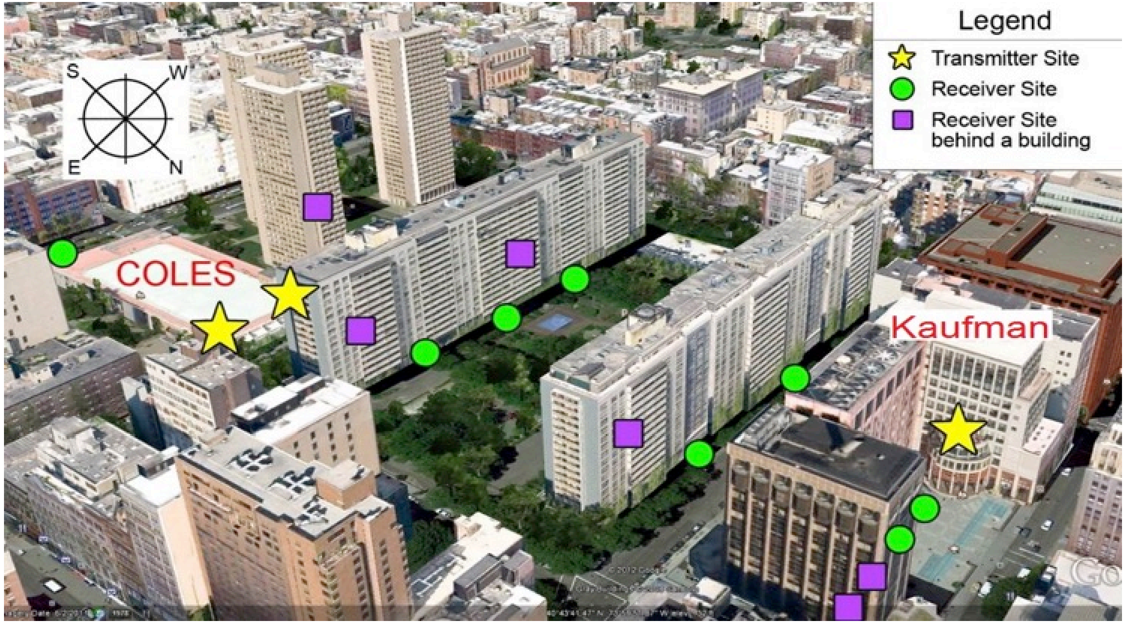
28 GHz Measurements in 2012 Dense, Urban NYC

- 4 TX sites
- 33 RX sites (35 w/ LOS)

- Pedestrian and vehicular traffic
- High-rise buildings, trees, shrubs

- TX sites:
  - TX-COL1 – 7 m
  - TX-COL2 – 7 m
  - TX-KAU – 17 m
  - TX-ROG – 40 m

- RX sites:
  - Randomly selected near AC outlets
  - Located outdoors in walkways



Rappaport, T.S.; Shu Sun; Mayzus, R.; Hang Zhao; Azar, Y.; Wang, K.; Wong, G.N.; Schulz, J.K.; Samimi, M.; Gutierrez, F., "Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!," IEEE *Access*, no. 1, pp.335-349, May 2013.

28 GHz Channel Sounder

TX Hardware

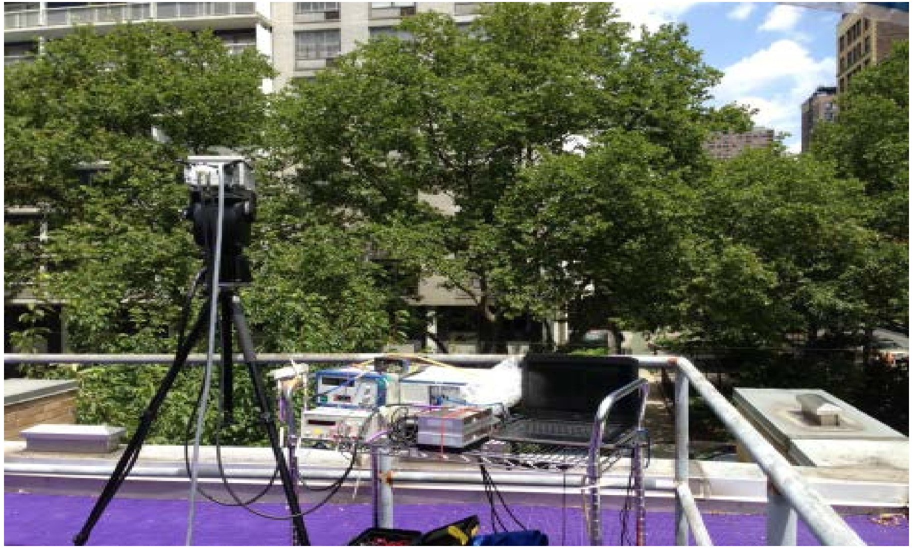
RX Hardware

Y. Azar, G. N. Wong, K. Wang, R. Mayzus, J. K. Schulz, H. Zhao, F. Gutierrez, D. Hwang, T. S. Rappaport, “28 GHz Propagation Measurements for Outdoor Cellular Communications Using Steerable Beam Antennas in New York City,” *2013 IEEE International Conference on Communications (ICC)*, June 9-13, 2013.

T.S. Rappaport,et. al.,”Wideband Millimeter Wave Propagation Measurements and Channel Models for Future Wireless Communication System Design”, IEEE Trans. Comm., Vol. 63, No. 9. Sept. 2015.

G.MacCartney, et. al., “Indoor Office Wideband Millimeter Wave Propagation Measurements and Channel Models at 28 and 73 GHz for ultra-dense 5G Wireless networks,” IEEE Access, Vol. 3. November 2015.

73 GHz Channel Sounder



TX Hardware

T.S. Rappaport,et. al.,"Wideband Millimeter Wave Propagation Measurements and Channel Models for Future Wireless Communication System Design, IEEE Trans. Comm., Vol. 63, No. 9. Sept. 2015.

G.MacCartney, et. al., "Indoor Office Wideband Millimeter Wave Propagation Measurements and Channel Models at 28 and 73 GHz for ultra-dense 5G Wireless networks," IEEE Access, Vol. 3. November 2015.

RX Hardware

Key Concepts and Lessons Learned

- **Measurements are very time consuming when using directional antennas. Accurate timing synch and automation is required**

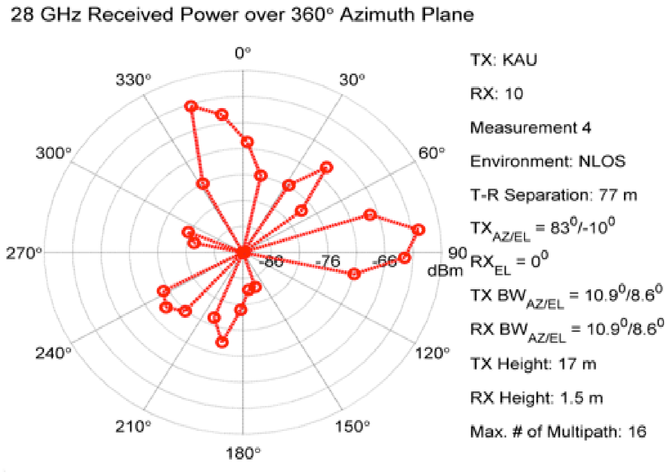
- **Omnidirectional antenna powers are accurately found by superposition of adjacent directional antennas (Globecom'15 http://arxiv.org/pdf/1511.07271v3.pdf)**

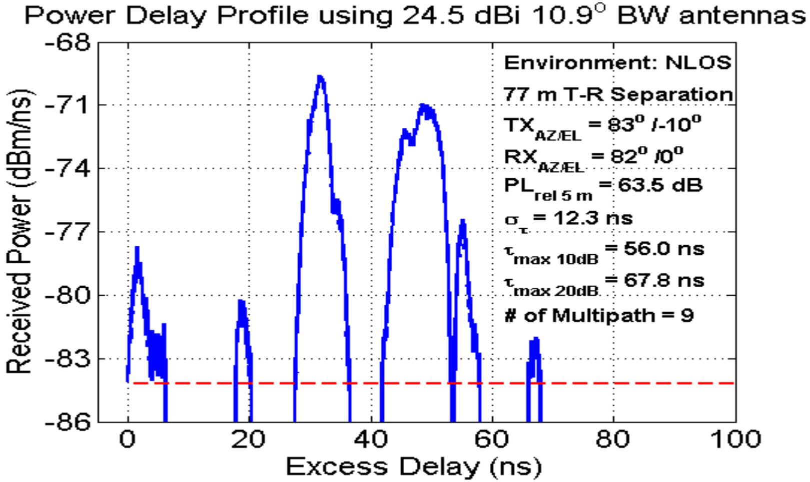
- **Beamforming offers great range extension/capacity at mmWave**
  (http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=6979962)
  (http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7109864)

- **Confusion/ no standard use of "path loss exponent" with "exponent for power gain/loss with distance"- dangerous repercussions**

S. Sun *et al.*, "Investigation of prediction accuracy, sensitivity, and parameter stability of large-scale propagation path loss models for 5G wireless communications," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 5, pp. 2843-2860, May 2016. http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7434656

Measurements show Millimeter Wave is Revolutionary!



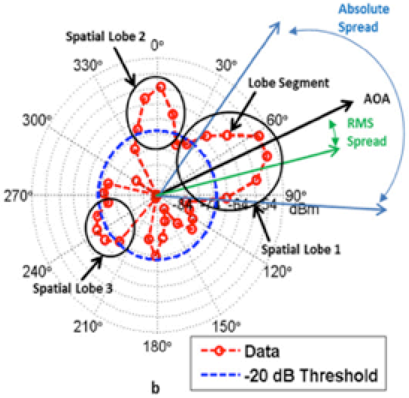


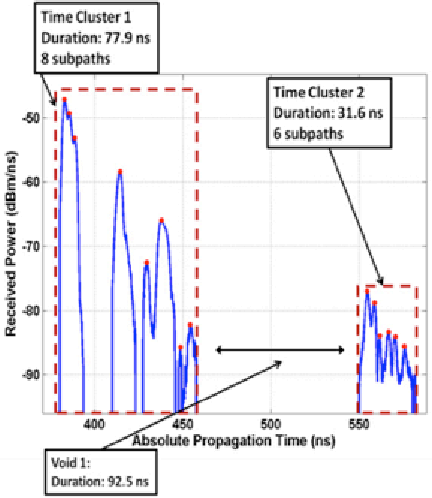
Signals arrive within 1 to 6 “lobes” in NYC over many azimuth angles in Non Line of Sight (NLOS) (See Samimi, IEEE T-MTT July 2016)

Rappaport, T.S.; Shu Sun; Mayzus, R.; Hang Zhao; Azar, Y.; Wang, K.; Wong, G.N.; Schulz, J.K.; Samimi, M.; Gutierrez, F., "Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!," *Access, IEEE* , vol.1, no., pp.335,349, 2013

NYU WIRELESS provides Open-source Simulation Framework and Modeling Software Suite For Global Development of 5G Millimeter Wave Wireless Networks (See: Samimi, IEEE MT-T July 2016)

Downloads include real world data from 28 GHz and 73 GHz, and many resources





Publically Available:

http://nyuwireless.com/5g-millimeter-wave-channel-modeling-software/

or

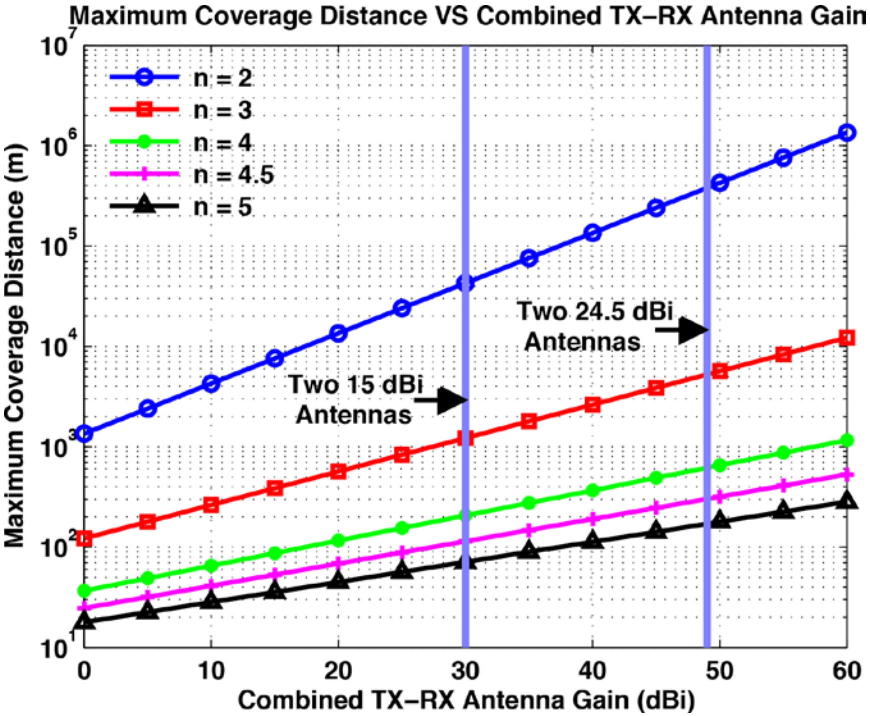
http://bit.ly/1WNPpDX

M. Samimi, et. al., "3-D Statistical Channel Model for Millimeter-Wave," IEEE International Conf. on Communications (ICC), May 2015.

M. Samimi, et. al, "Statistical Channel Model with Multi-Frequency and Arbitrary Antenna Beamwidth for Millimeter-Wave Outdoor Communications, IEEE Global Communication Conf. (Globecom), Dec. 2015

M. Samimi, et. al, "Local Multipath Model Parameters for Generating 5G Millimeter-Wave 3GPP-like Channel Impulse Response," 2016 EuCap, April 2016.

Propagation Path Loss Exponent (PLE)



NYU proposed a global standard for channel modeling: a 1 meter "free space" close-in reference distance to properly account for frequency-dependent path loss from 500 MHz to 100 GHz and beyond (> 2 OOM)

T. S. Rappaport, et. al., "Wideband Millimeter-Wave Propagation Measurements and Channel Models for Future Wireless Communication System Design," in *IEEE Transactions on Communications*, vol. 63, no. 9, pp. 3029-3056, Sept. 2015.

Large Scale Propagation Path Loss Models

- **Path Loss models used to predict coverage/capacity/interference**
- **Candidate 3GPP Large-Scale Propagation Path Loss Models**
    - **Alpha-Beta-Gamma (ABG) Model (Used in ITU/3GPP today)**
    - **Close-in Free Space Reference Distance (CI) Model**
- **Stability/Accuracy problems with 3GPP/ITU ABG path loss models!**

S. Sun *et al.*, "Investigation of prediction accuracy, sensitivity, and parameter stability of large-scale propagation path loss models for 5G wireless communications," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 5, pp. 2843-2860, May 2016. http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7434656

Sensitivity Analysis: ABG vs CI Path Loss Models

- **Path Loss Data Sources (30 measurement campaigns over 5 years):**
    - UMa: Aalborg University/Nokia (measured at 2, 10, 18, 28 GHz), NYU/UTA(measured at 38 GHz)
    - UMi: NYU (measured at 28, 73 GHz)
    - InH: Qualcomm (2, 28, 60 GHz), NYU (28, 73 GHz)

We asked: Can we use simple, physics-based models instead of current 3GPP ABG model, and how well do they work when applied at different distances/frequencies than measured?

- **All of the scattered path loss data samples were locally averaged over 2 m distance bins**
    - To remove the small-scale fading effect and to reduce the difference in the number of data points across measurement campaigns

- **All path loss values were upper-bounded to FSPL at 1 m plus 100 dB**
    - Based on the reasonable assumption that loss may increase with frequency, this frequency dependent threshold assured similar number of measurements at all frequencies.

Large-Scale Propagation Path Loss Models for UMi and UMa scenarios

- **Alpha-Beta-Gamma (ABG) Model used today in 3GPP/ITU**

$$\mathrm{PL}^{\mathrm{ABG}}(f,d)[\mathrm{dB}] = 10\alpha\log_{10}\left(\frac{d}{d_0}\right) + \beta + 10\gamma\log_{10}\left(\frac{f}{1\ \mathrm{GHz}}\right) + X_\sigma^{\mathrm{ABG}} \quad \text{for } \ d \geq d_0, \text{ where } d_0 = 1\ \mathrm{m}$$

- **Close-In Free Space Reference Distance (CI) Model: 1 m FSPL reference**

$$\mathrm{PL}^{\mathrm{CI}}(f,d)[\mathrm{dB}] = \mathrm{FSPL}(f,d_0) + 10n\log_{10}\left(\frac{d}{d_0}\right) + X_\sigma^{\mathrm{CI}} \quad \text{for } \ d \geq d_0, \text{ where } d_0 = 1\ \mathrm{m}$$

$$\mathrm{FSPL}(f, 1\ m)[dB] = 20\log_{10}\left(\frac{4\pi f}{c}\right)$$

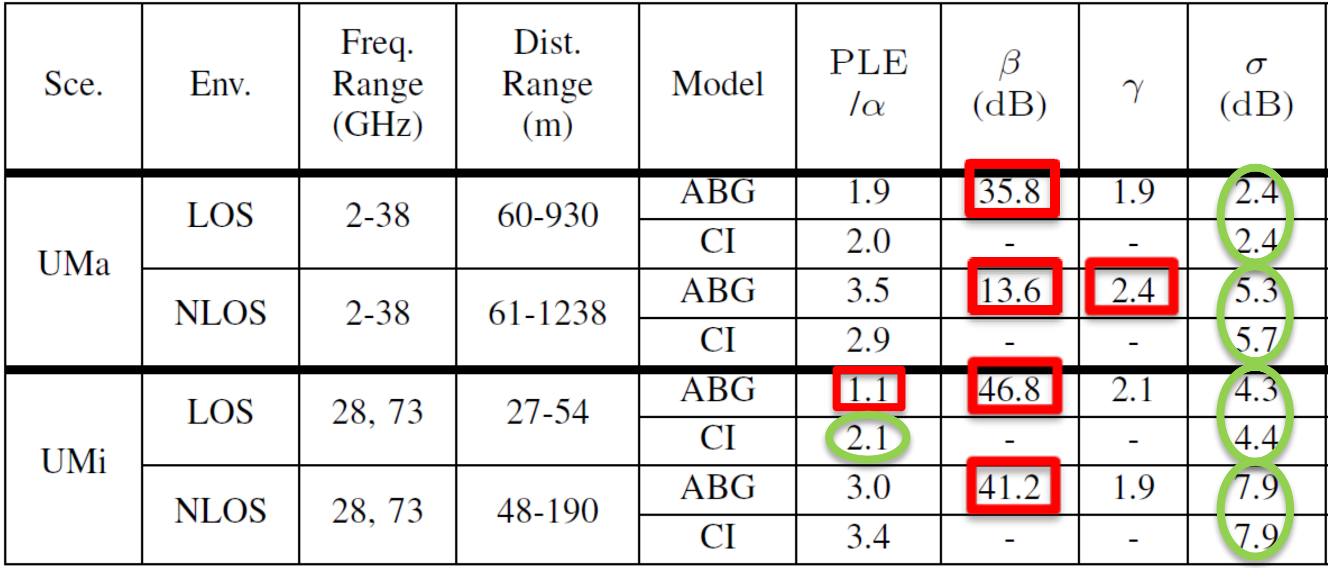
- MMSE method is used to minimize shadow fading standard deviation σ
- **ABG** model:
  - Only valid over the distance range of d and frequency range of f
  - Three parameters (α, β, and γ) need to be optimized
- **CI** model
  - n is the path loss exponent (PLE)
  - Only **one** parameter (n, or PLE) needs to be optimized

S. Sun *et al.*, "Investigation of prediction accuracy, sensitivity, and parameter stability of large-scale propagation path loss models for 5G wireless communications," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 5, pp. 2843-2860, May 2016. http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7434656

Modeling Performance of ABG and CI Models

- Fit to Measured Data: the single-parameter CI model provides reasonable parameter (PLE) values, while the three-parameter ABG model can yield unreasonable parameter values

- The shadow fading standard deviations are close or identical between the two models



Sce.	Env.	Freq. Range (GHz)	Dist. Range (m)	Model	PLE $/\alpha$	β (dB)	γ	σ (dB)
UMa	LOS	2-38	60-930	ABG	1.9	35.8	1.9	2.4
				CI	2.0	-	-	2.4
	NLOS	2-38	61-1238	ABG	3.5	13.6	2.4	5.3
				CI	2.9	-	-	5.7
UMi	LOS	28, 73	27-54	ABG	1.1	46.8	2.1	4.3
				CI	2.1	-	-	4.4
	NLOS	28, 73	48-190	ABG	3.0	41.2	1.9	7.9
				CI	3.4	-	-	7.9

ABG and CI modeling parameters in the UMa and UMi scenarios across different frequencies and distances in the NLOS environment

3GPP/ITU PATH LOSS MODELS > 6 GHz

UMa LOS Scenario:
CLOSE-IN REF. MODEL: (CI): $\mathrm{PL}(f,d) = 32.4 + 20log_{10}(d) + 20log_{10}(f),\ \sigma = 4.1\ \mathrm{dB}$

UMa NLOS Scenario:
ABG: $\mathrm{PL}(f,d) = 19.2 + 34log_{10}(d) + 23log_{10}(f),\ \sigma = 6.5\ \mathrm{dB}$
CI: $\mathrm{PL}(f,d) = 32.4 + 30log_{10}(d) + 20log_{10}(f),\ \sigma = 6.8\ \mathrm{dB}$

UMi SC LOS Scenario:
CI: $\mathrm{PL}(f,d) = 32.4 + 21log_{10}(d) + 20log_{10}(f),\ \sigma = 3.8\ \mathrm{dB}$

UMi SC NLOS Scenario:
ABG: $\mathrm{PL}(f,d) = 22.4 + 35log_{10}(d) + 21log_{10}(f),\ \sigma = 7.8\ \mathrm{dB}$
CI: $\mathrm{PL}(f,d) = 32.4 + 32log_{10}(d) + 20log_{10}(f),\ \sigma = 8.1\ \mathrm{dB}$

UMi OS LOS Scenario:
CI: $\mathrm{PL}(f,d) = 32.4 + 19log_{10}(d) + 20log_{10}(f),\ \sigma = 4.2\ \mathrm{dB}$

UMi OS NLOS Scenario:
ABG: $\mathrm{PL}(f,d) = 3.7 + 41log_{10}(d) + 24log_{10}(f),\ \sigma = 7.0\ \mathrm{dB}$
CI: $\mathrm{PL}(f,d) = 32.4 + 29log_{10}(d) + 20log_{10}(f),\ \sigma = 7.1\ \mathrm{dB}$

Note: f is in GHz and d is in meters. These equations are in 3GPP/ITU format.

3GPP RAN IS NOW DEBATING IN RAN#1 WHETHER TO USE THE LEGACY ABG OR NEW CI MODELS – VERY IMPORTANT FOR SIMULATION!

K. Haneda *et al*., “5G 3GPP-like channel models for outdoor urban microcellular and macrocellular environments,” *2016 IEEE 83rd Vehicular Technology Conference (VTC Spring)*, May 2016. [Online]. Available: http://arxiv.org/abs/1602.07533.
K. Haneda *et al*., “Indoor 5G 3GPP-like channel models for office and shopping mall environments,” 2016 IEEE International Conference on Communications Workshops (ICCW), May 2016. [Online]. Available: http://arxiv.org/abs/1603.04079

Example of model inaccuracies using Results from Industry White Paper

much lower loss than free space when close to TX

UMa LOS Scenario:
CI: $\mathrm{PL}(f,d) = 20\log_{10}(d) + 32.4 + 20\log_{10}(f),\ \sigma = 4.1\ \mathrm{dB}$

UMa NLOS Scenario:
ABG: $\mathrm{PL}(f,d) = 34\log_{10}(d) + \boxed{19.2} + \boxed{23}\log_{10}(f),\ \sigma = 6.5\ \mathrm{dB}$
CI: $\mathrm{PL}(f,d) = 30\log_{10}(d) + 32.4 + 20\log_{10}(f),\ \sigma = 6.8\ \mathrm{dB}$

UMi SC LOS Scenario:
CI: $\mathrm{PL}(f,d) = 21\log_{10}(d) + 32.4 + 20\log_{10}(f),\ \sigma = 3.8\ \mathrm{dB}$

UMi SC NLOS Scenario:
ABG: $\mathrm{PL}(f,d) = 35\log_{10}(d) + \boxed{22.4} + 21\log_{10}(f),\ \sigma = 7.8\ \mathrm{dB}$
CI: $\mathrm{PL}(f,d) = 32\log_{10}(d) + 32.4 + 20\log_{10}(f),\ \sigma = 8.1\ \mathrm{dB}$

UMi OS LOS Scenario:
CI: $\mathrm{PL}(f,d) = 19\log_{10}(d) + 32.4 + 20\log_{10}(f),\ \sigma = 4.2\ \mathrm{dB}$

UMi OS NLOS Scenario:
ABG: $\mathrm{PL}(f,d) = 41\log_{10}(d) + \boxed{3.7} + \boxed{24}\log_{10}(f),\ \sigma = 7.0\ \mathrm{dB}$
CI: $\mathrm{PL}(f,d) = 29\log_{10}(d) + 32.4 + 20\log_{10}(f),\ \sigma = 7.1\ \mathrm{dB}$

much higher than free space loss with frequency

Note: *f* is in GHz and *d* is in meters.
These forms are in 3GPP/ITU style.

K. Haneda *et al*., "5G 3GPP-like channel models for outdoor urban microcellular and macrocellular environments," *2016 IEEE 83rd Vehicular Technology Conference (VTC Spring)*, May 2016. [Online]. Available: http://arxiv.org/abs/1602.07533.
K. Haneda *et al*., "Indoor 5G 3GPP-like channel models for office and shopping mall environments," 2016 IEEE International Conference on Communications Workshops (ICCW), May 2016. [Online]. Available: http://arxiv.org/abs/1603.04079

Example of model inaccuracies using Results from Industry White Paper

InH Office LOS Scenario:
CI: $\mathrm{PL}(f,d) = 17\log_{10}(d) + 32.4 + 20\log_{10}(f),\ \sigma = 3.0\ \mathrm{dB}$

InH Office NLOS Scenario:
Single-Slope Models:

much lower loss than free space when close to TX

ABG: $\mathrm{PL}(f,d) = 38\log_{10}(d) + \boxed{17.3} + \boxed{25}\log_{10}(f),\ \sigma = 8.0\ \mathrm{dB}$
CIF: $\mathrm{PL}(f,d) = 32 * (1 + 0.06 * (f - 24.2)/24.2) * \log_{10}(d) + 32.4 + 20\log_{10}(f),\ \sigma = 8.3\ \mathrm{dB}$

much higher than free space loss with frequency

InH Office NLOS Scenario:
Dual-Slope Models:

ABG: $\mathrm{PL}(f,d) = \begin{cases} 17\log_{10}(d) + 33.0 + \boxed{25}\log_{10}(f),\ 1\ \mathrm{m} < d < 6.9\ \mathrm{m} \\ 17\log_{10}(6.9) + 33.0 + 25\log_{10}(f) + 42\log_{10}(d/6.9),\ \ d > 6.9\ \mathrm{m} \end{cases}\quad \sigma = 7.8\ \mathrm{dB}$

CIF:

$$\mathrm{PL}(f,d) = \begin{cases} 25 * (1 + 0.12 * (f - 24.1)/24.1) * \log_{10}(d) + 32.4 + 20\log_{10}(f),\ 1\ \mathrm{m} < d < 7.8\ \mathrm{m} \\ 25 * (1 + 0.12 * (f - 24.1)/24.1) * \log_{10}(7.8) + 32.4 + 20\log_{10}(f) + 43 * (1 + 0.04 * (f - 24.1)/24.1) * \log_{10}(d/7.8),\ d > 7.8\ \mathrm{m} \end{cases}\quad \sigma = 7.7\ \mathrm{dB}$$

Note: *f* is in GHz and *d* is in meters. These forms are in 3GPP/ITU style.

K. Haneda *et al.*, "5G 3GPP-like channel models for outdoor urban microcellular and macrocellular environments," *2016 IEEE 83rd Vehicular Technology Conference (VTC Spring)*, May 2016. [Online]. Available: http://arxiv.org/abs/1602.07533.
K. Haneda *et al.*, "Indoor 5G 3GPP-like channel models for office and shopping mall environments," 2016 IEEE International Conference on Communications Workshops (ICCW), May 2016. [Online]. Available: http://arxiv.org/abs/1603.04079
See: http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7434656

Example of model inaccuracies Using Results from Industry White Paper

InH Shopping Mall LOS Scenario:
CI: $\mathrm{PL}(f,d) = 17\log_{10}(d) + 32.4 + 20\log_{10}(f),\ \sigma = 2.0\ \mathrm{dB}$

much lower loss than free space when close to TX

InH Shopping Mall NLOS Scenario:
Single-Slope Models:
ABG: $\mathrm{PL}(f,d) = 32\log_{10}(d) + \boxed{18.1} + 22\log_{10}(f),\ \sigma = 7.0\ \mathrm{dB}$
CIF: $\mathrm{PL}(f,d) = 26 * (1 + 0.01 * (f - 39.5)/39.5) * \log_{10}(d) + 32.4 + 20\log_{10}(f),\ \sigma = 7.4\ \mathrm{dB}$

InH Shopping Mall NLOS Scenario:
Dual-Slope Models:

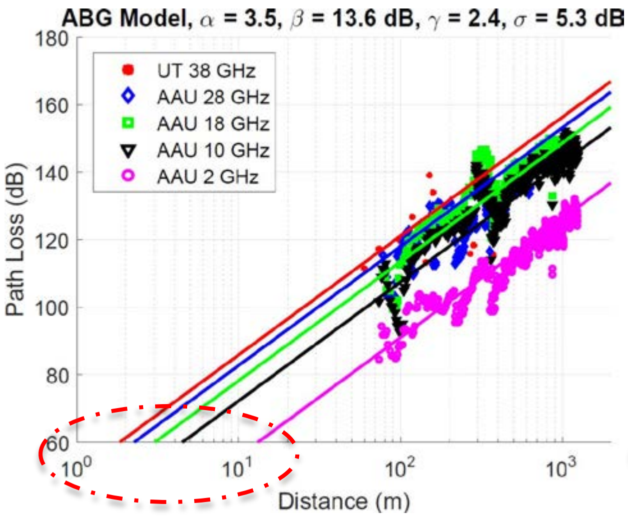
ABG: $$\mathrm{PL}(f,d) = \begin{cases} 29\log_{10}(d) + \boxed{22.2} + 22\log_{10}(f),\ 1\ \mathrm{m} < d < 147.0\ \mathrm{m} \\ 29\log_{10}(147.0) + 22.2 + 22\log_{10}(f) + 115\log_{10}(d/147.0), d > 147.0\mathrm{m} \end{cases} \quad \sigma = 6.4\ \mathrm{dB}$$

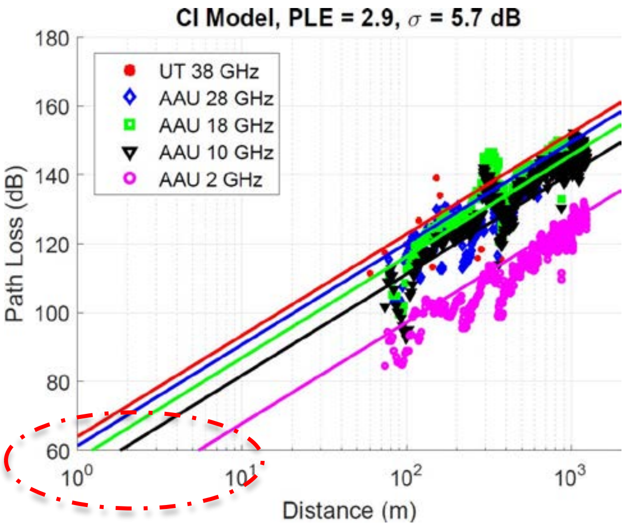
CIF:
$$\mathrm{PL}(f,d) = \begin{cases} 24 * (1 - 0.01 * (f - 39.5)/39.5) * \log_{10}(d) + 32.4 + 20\log_{10}(f),\ 1\ \mathrm{m} < d < 110\ \mathrm{m} \\ 24 * (1 - 0.01 * (f - 39.5)/39.5) * \log_{10}(110) + 32.4 + 20\log_{10}(f) + 84 * (1 + 0.39 * (f - 39.5)/39.5) * \log_{10}(d/110),\ d > 110\ \mathrm{m} \end{cases} \quad \sigma = 6.3\ \mathrm{dB}$$

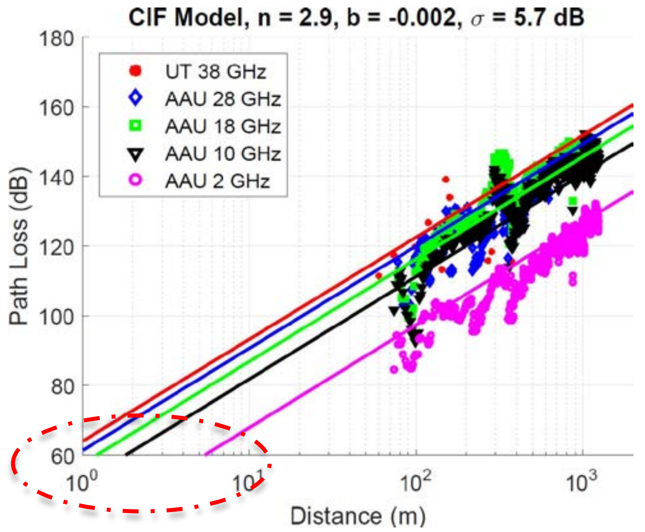
Note: *f* is in GHz and *d* is in meters. These forms are in 3GPP/ITU style.

K. Haneda *et al.*, “5G 3GPP-like channel models for outdoor urban microcellular and macrocellular environments,” *2016 IEEE 83rd Vehicular Technology Conference (VTC Spring)*, May 2016. [Online]. Available: http://arxiv.org/abs/1602.07533.
K. Haneda *et al.*, “Indoor 5G 3GPP-like channel models for office and shopping mall environments,” 2016 IEEE International Conference on Communications Workshops (ICCW), May 2016. [Online]. Available: http://arxiv.org/abs/1603.04079
See: http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7434656

Example of model inaccuracies


ABG Model, α = 3.5, β = 13.6 dB, γ = 2.4, σ = 5.3 dB

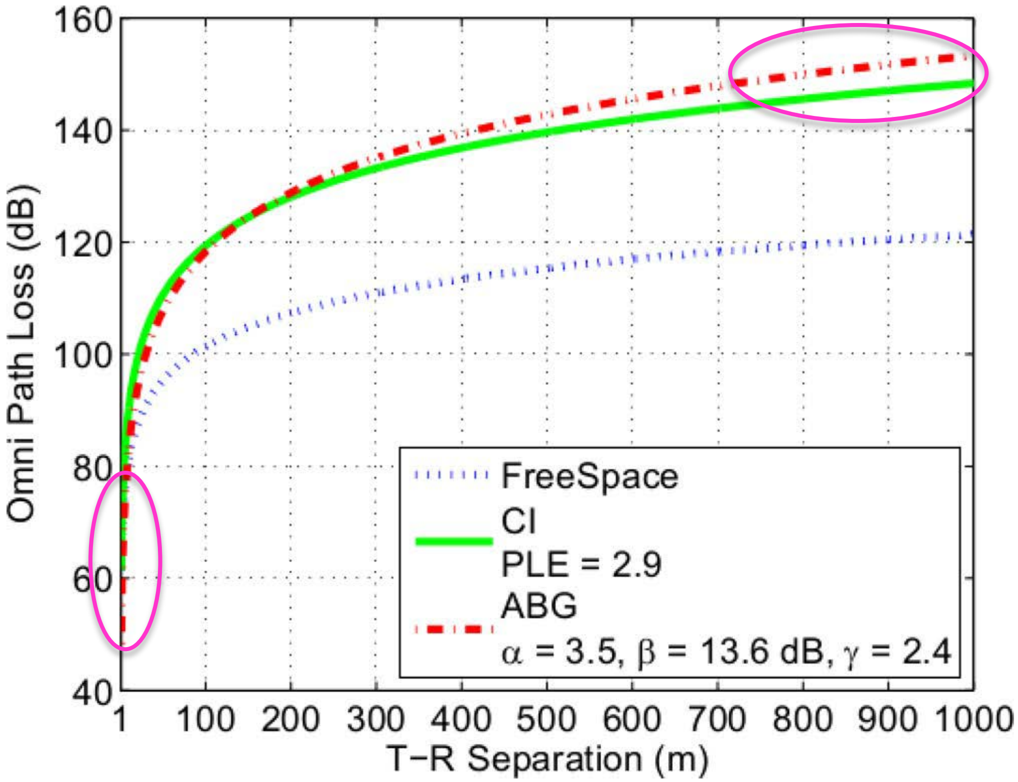

CI Model, PLE = 2.9, σ = 5.7 dB


CIF Model, n = 2.9, b = -0.002, σ = 5.7 dB

The currently approved 3GPP model (ABG) has noticeable errors at close-in distances, i.e., it predicts much less path loss compared with free space. Optional close-in (CI) ref. distance does not have this issue

S. Sun *et al.*, "Investigation of prediction accuracy, sensitivity, and parameter stability of large-scale propagation path loss models for 5G wireless communications," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 5, pp. 2843-2860, May 2016. http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7434656

Example of model inaccuracies

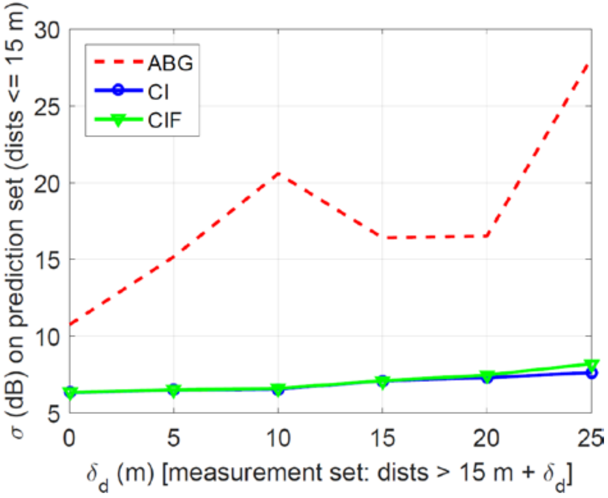


The ABG model underestimates path loss at short distances, while overestimating path loss (i.e., underestimates interference) at large distances (e.g. 800 m) compared with the CI model

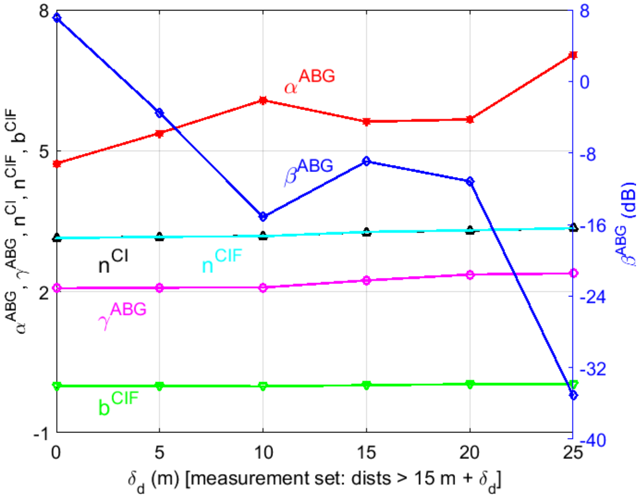
The CI/CIF model is more conservative when analyzing interference-limited systems at large distances and more realistic when modeling signal strengths at close-in distances.

S. Sun *et al.*, "Investigation of prediction accuracy, sensitivity, and parameter stability of large-scale propagation path loss models for 5G wireless communications," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 5, pp. 2843-2860, May 2016. http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7434656

Multi-Frequency Path Loss Model Prediction Accuracy and Sensitivity Analysis



Shadow fading standard deviation of the ABG, CI, and CIF path loss models for prediction in distance when the prediction set is closer to the transmitter in the **InH office scenario**



Parameters of the ABG, CI, and CIF path loss models for prediction in distance when the prediction set is closer to the transmitter in the **InH office scenario**

ABG: Current 3GPP model has large, unstable shadow fading standard deviation; Significant variation of model parameters

CI/CIF: Small and stable shadow fading standard deviation; Little variation of model parameters

S. Sun *et al.*, "Investigation of prediction accuracy, sensitivity, and parameter stability of large-scale propagation path loss models for 5G wireless communications," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 5, pp. 2843-2860, May 2016. http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7434656

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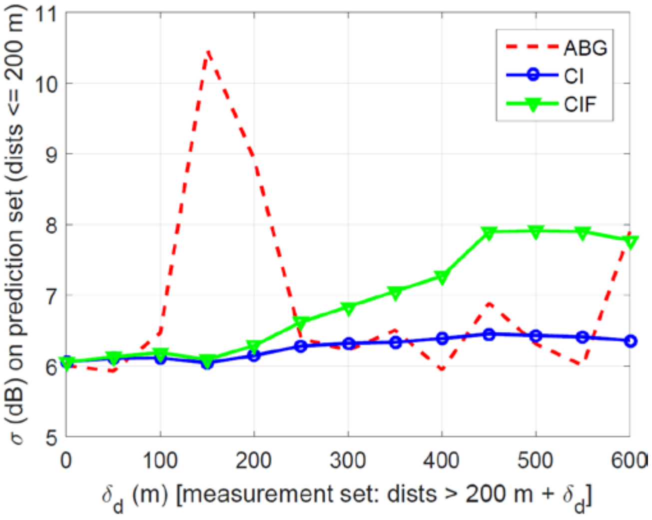
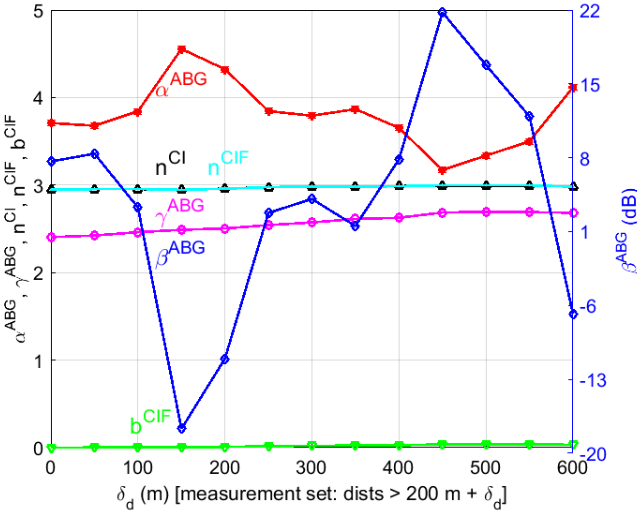
Multi-Frequency Path Loss Model Prediction Accuracy and Sensitivity Analysis



Shadow fading standard deviation of the ABG, CI, and CIF path loss models for prediction in distance when the prediction set is closer to the transmitter in the UMa scenario



Parameters of the ABG, CI, and CIF path loss models for prediction in distance when the prediction set is closer to the transmitter in the UMa scenario

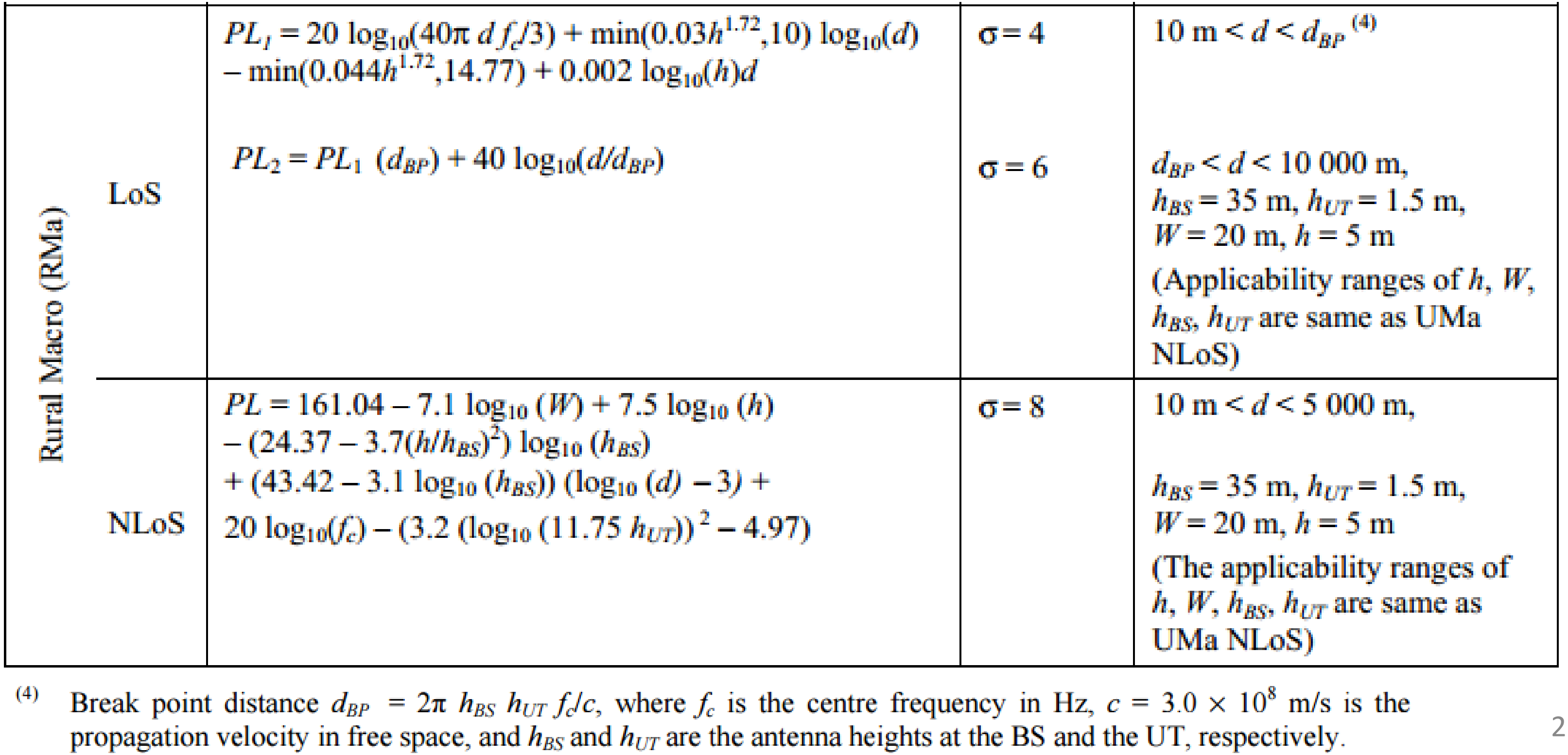
ABG: Current 3GPP model has large, unstable shadow fading standard deviation; Significant variation of model parameters

CI/CIF: Small and stable shadow fading standard deviation; Little variation of model parameters

S. Sun *et al.*, "Investigation of prediction accuracy, sensitivity, and parameter stability of large-scale propagation path loss models for 5G wireless communications," *IEEE Transactions on Vehicular Technology*, vol. 65, no. 5, pp. 2843-2860, May 2016. http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7434656

Path Loss Models for RMa Scenario

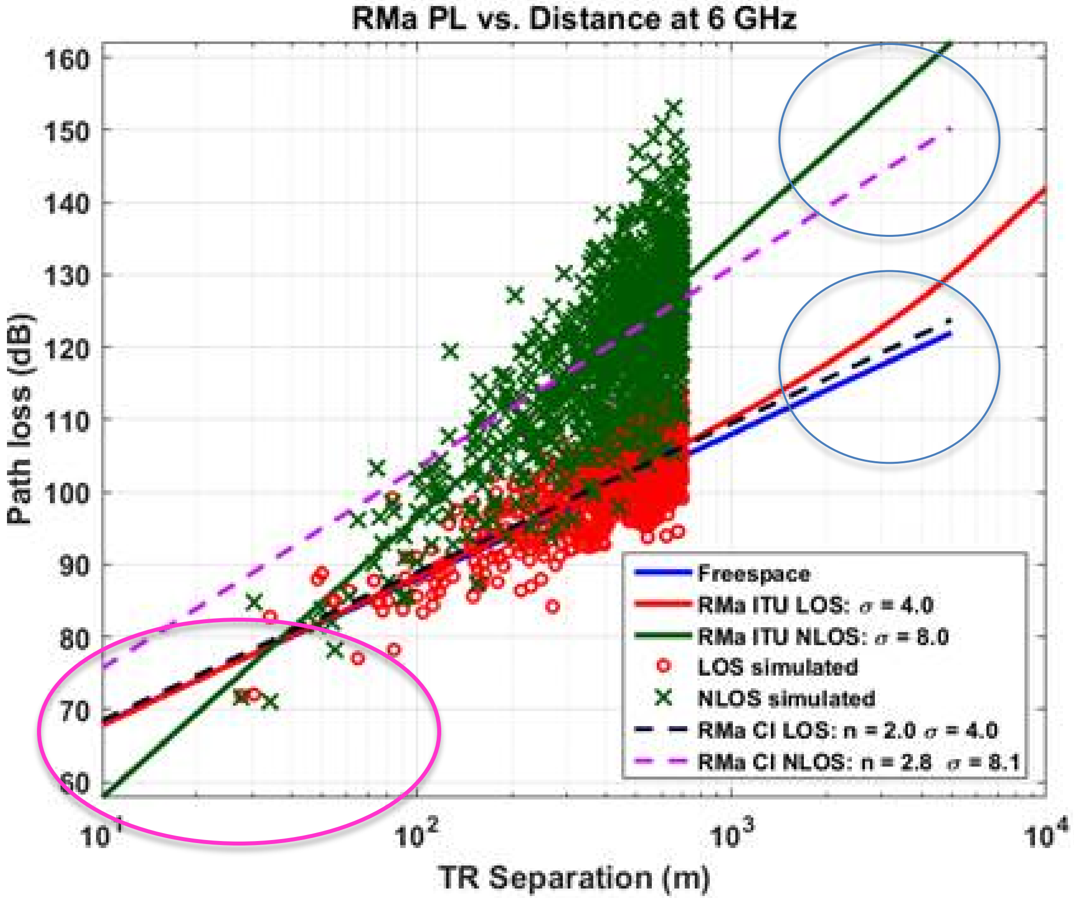
1. **Rural Macro will be possible with mmWave – many km’s possible w/o rain or foliage!**
2. Existing ITU-R M.2135 RMa model only defined to 6 GHz, VERY COMPLEX, non-physical!



Rural Macro (RMa)	LoS	$PL_1 = 20\log_{10}(40\pi d f_c/3) + \min(0.03h^{1.72},10)\log_{10}(d) - \min(0.044h^{1.72},14.77) + 0.002\log_{10}(h)d$	$\sigma = 4$	$10\text{ m} < d < d_{BP}$ (4)
		$PL_2 = PL_1(d_{BP}) + 40\log_{10}(d/d_{BP})$	$\sigma = 6$	$d_{BP} < d < 10\,000$ m, $h_{BS} = 35$ m, $h_{UT} = 1.5$ m, $W = 20$ m, $h = 5$ m (Applicability ranges of h, W, h_{BS}, h_{UT} are same as UMa NLoS)
	NLoS	$PL = 161.04 - 7.1\log_{10}(W) + 7.5\log_{10}(h) - (24.37 - 3.7(h/h_{BS})^2)\log_{10}(h_{BS}) + (43.42 - 3.1\log_{10}(h_{BS}))(\log_{10}(d) - 3) + 20\log_{10}(f_c) - (3.2(\log_{10}(11.75h_{UT}))^2 - 4.97)$	$\sigma = 8$	$10\text{ m} < d < 5\,000$ m, $h_{BS} = 35$ m, $h_{UT} = 1.5$ m, $W = 20$ m, $h = 5$ m (The applicability ranges of h, W, h_{BS}, h_{UT} are same as UMa NLoS)

(4) Break point distance $d_{BP} = 2\pi h_{BS} h_{UT} f_c/c$, where f_c is the centre frequency in Hz, $c = 3.0 \times 10^8$ m/s is the propagation velocity in free space, and h_{BS} and h_{UT} are the antenna heights at the BS and the UT, respectively.

Path Loss Models for RMa Scenario

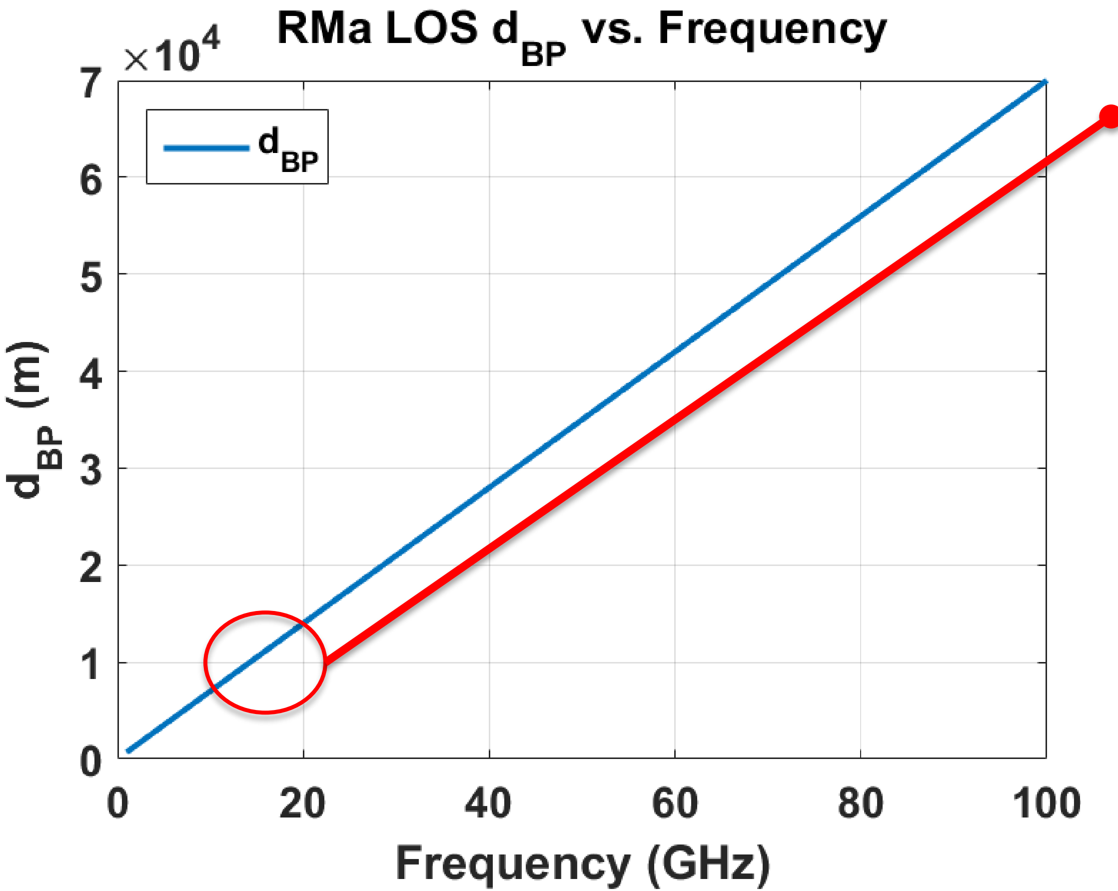


EXAMPLE: We ran current ITU path loss model using monte-carlo simulation (before the breakpoint). This example for 6 GHz.

KEY OBSERVATION: Existing 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 several hundred 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/stamp/stamp.jsp?arnumber=7434656

Path Loss Models for RMa Scenario

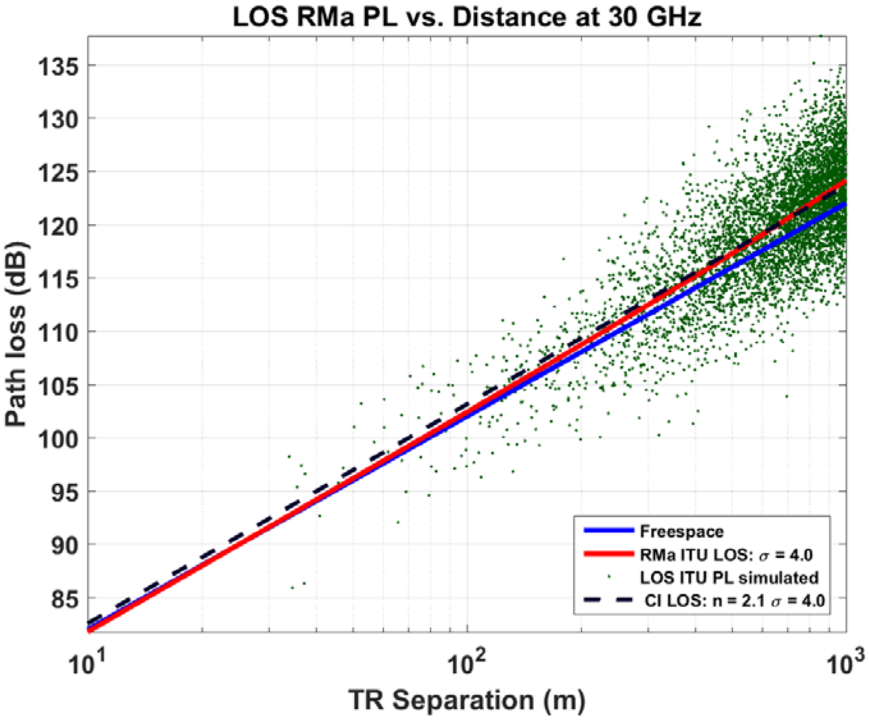


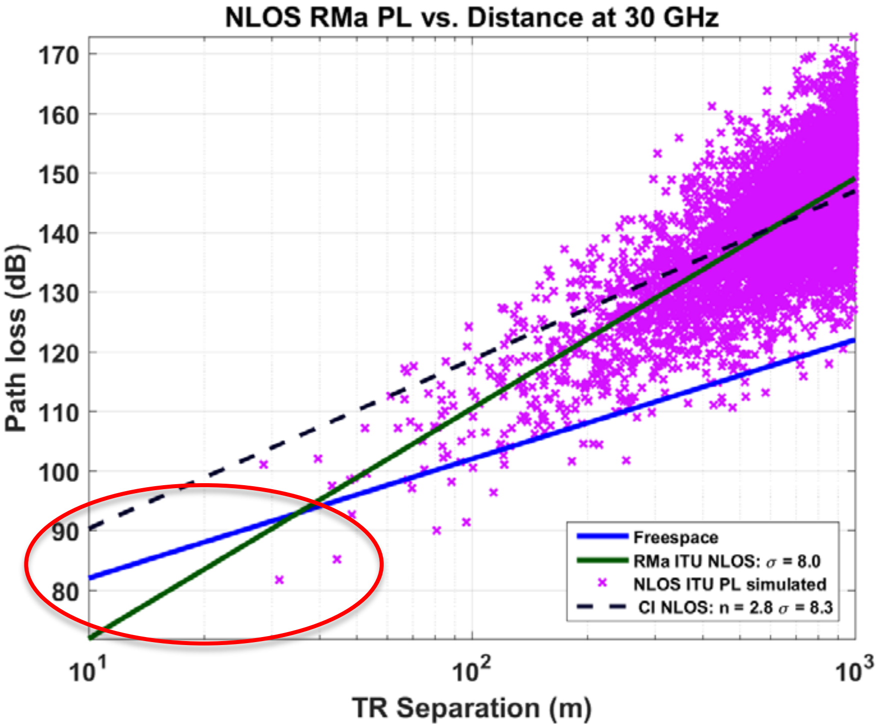
d_{BP} (LOS breakpoint) is unrealistic and invalid for current model beyond approximately 7 GHz, and the model itself is only defined up to 10,000 m (Breakpoint is 10 km for ITU Rma model at 14 GHz!)

Cannot adopt Rma for mmWave in LOS! The breakpoint in ITU makes no sense beyond 7 GHz!

The expression for RMa is not based on anything physical for LOS or NLOS – no tie to close-in Free Space

Path Loss Models for RMa Scenario

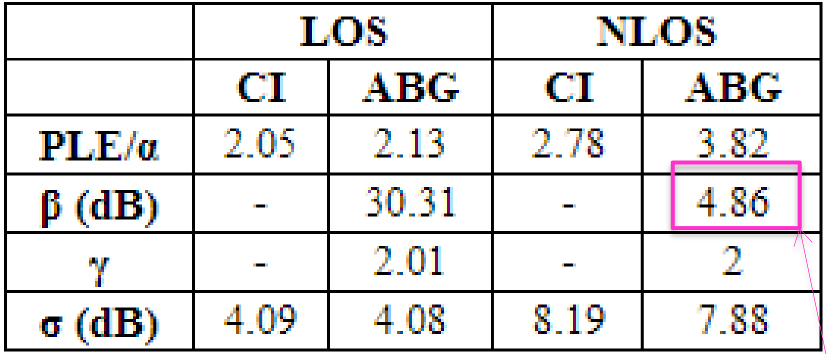




The existing RMa NLOS path loss model underestimates path loss below free space value at close-in distances (50 m), and is inaccurate and unrealistic up to 500 m (NLOS should have more loss than the model predicts). Also diverges from CI model at large distances (> 2 km)

Path Loss Models for RMa Scenario

Simulation for best fit CI model was done using current ITU-R M.2135 RMa model before break point at 1, 2, 6, 15, 28, 38, and 73 GHz using 1000 data points for each frequency, generated from monte-carol simulation. Note ABG problem! Note: simple CI model offers same accuracy to existing complicated, non-physical RMa ITU model!



	LOS		NLOS	
	CI	**ABG**	**CI**	**ABG**
PLE/α	2.05	2.13	2.78	3.82
β (dB)	-	30.31	-	4.86
γ	-	2.01	-	2
σ (dB)	4.09	4.08	8.19	7.88

Much lower loss than free space when close to TX, a 4.86 dB Beta value is tens of dB less than 32.4 dB at 1 m FSPL. This makes no physical sense out to several hundred meters

Proposal for RMa:

a. Adopt CI NLOS model for RMa: $PL(f,d)=27.8\log_{10}(d)+32.4+20\log_{10}(f)$, $\sigma = 8.2$ dB, $d > 1$m

b. Adopt CI LOS model for RMa: $PL(f,d)=20.5\log_{10}(d)+32.4+20\log_{10}(f)$, $\sigma = 4.1$ dB, $d > 1$m

Dealing with Path Loss Frequency Transition

- 3GPP and ITU will want a model that works from 500 MHz to 100 GHz

- Path loss models that do not use a close-in free space reference have inaccuracies and difficulties. For accuracy and stability issues, see:
  http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7434656

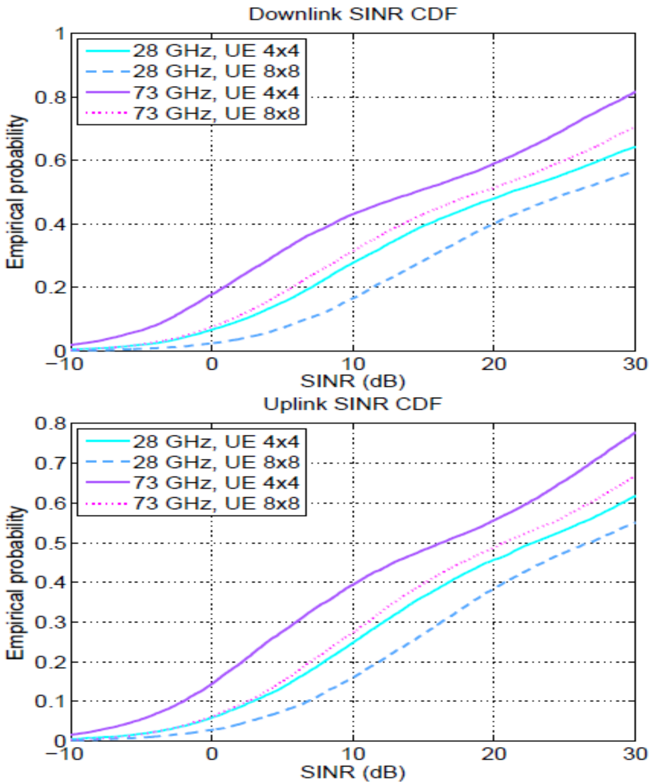
- Using a transition model to fix a discontinuity at 6 GHz (2-10 GHz), without measured data and without addressing sensitivity issues, perpetuates inaccuracies

- 3GPP wants to create a transition model without any data, but why do that?

- A better way: use proven CI models that are already based on measurements for the entire 2 orders of magnitude of frequencies (500 MHz - 100 GHz) for all scenarios. Take more measurements for Rma and fit to CI model.

- 2. Proposal: Use CI model for all scenarios instead of using transition or ABG

Simulations: SNR Distribution



- Simulation assumptions:
  - 200m ISD (1W, 50 dB total Ant. gain)
  - 3-sector hex BS
  - 20 / 30 dBm DL / UL power
  - 8x8 antenna at BS
  - 4x4 (28 GHz), 8x8 (73 GHz) at UE
- A new regime:
  - **High SNR on many links**
  - **Better than current macro-cellular**
  - **Interference is non dominant**

S. Rangan, T. S. Rappaport, and E. Erkip, “Millimeter-Wave Cellular Wireless Networks: Potentials and Challenges,” *Proceedings of the IEEE*, vol. 102, no. 3, pp. 366-385, March 2014.

Comparison to Current LTE

- Initial results (very conservative) show significant gain over LTE
  - Further gains with spatial mux, subband scheduling and wider bandwidths

System antenna	Duplex BW	fc (GHz)	Antenna	Cell throughput (Mbps/cell)		Cell edge rate (Mbps/user, 5%)	
				DL	UL	DL	UL
mmW	1 GHz TDD	28	4x4 UE 8x8 eNB	1514	1468	28.5	19.9
		73	8x8 UE 8x8 eNB	1435	1465	24.8	19.8
Current LTE	20+20 MHz FDD	2.5	(2x2 DL, 2x4 UL)	53.8	47.2	1.80	1.94

10 UEs per cell, ISD=200m,
hex cell layout
LTE capacity estimates from 36.814

~ 25x gain

~ 10x gain

M. R. Akdeniz,Y. Liu, M. K. Samimi, S. Sun, S. Rangan, T. S. Rappaport, E. Erkip, “Millimeter Wave Channel Modeling and Cellular Capacity Evaluation,” IEEE. J. Sel. Areas on Comm., July 2014

Results by Nokia for 73 GHz

* Assumes RF BW of 2.0 GHz, NCP-SC Modulation

* Symbol Rate 1.536 Gigasymbols/sec (50 X LTE)

* Access Point Array: 4 sectors, dual 4X4 polarization

* Ideal Channel State estimator and Fair Scheduler

* Beamforming using uplink signal

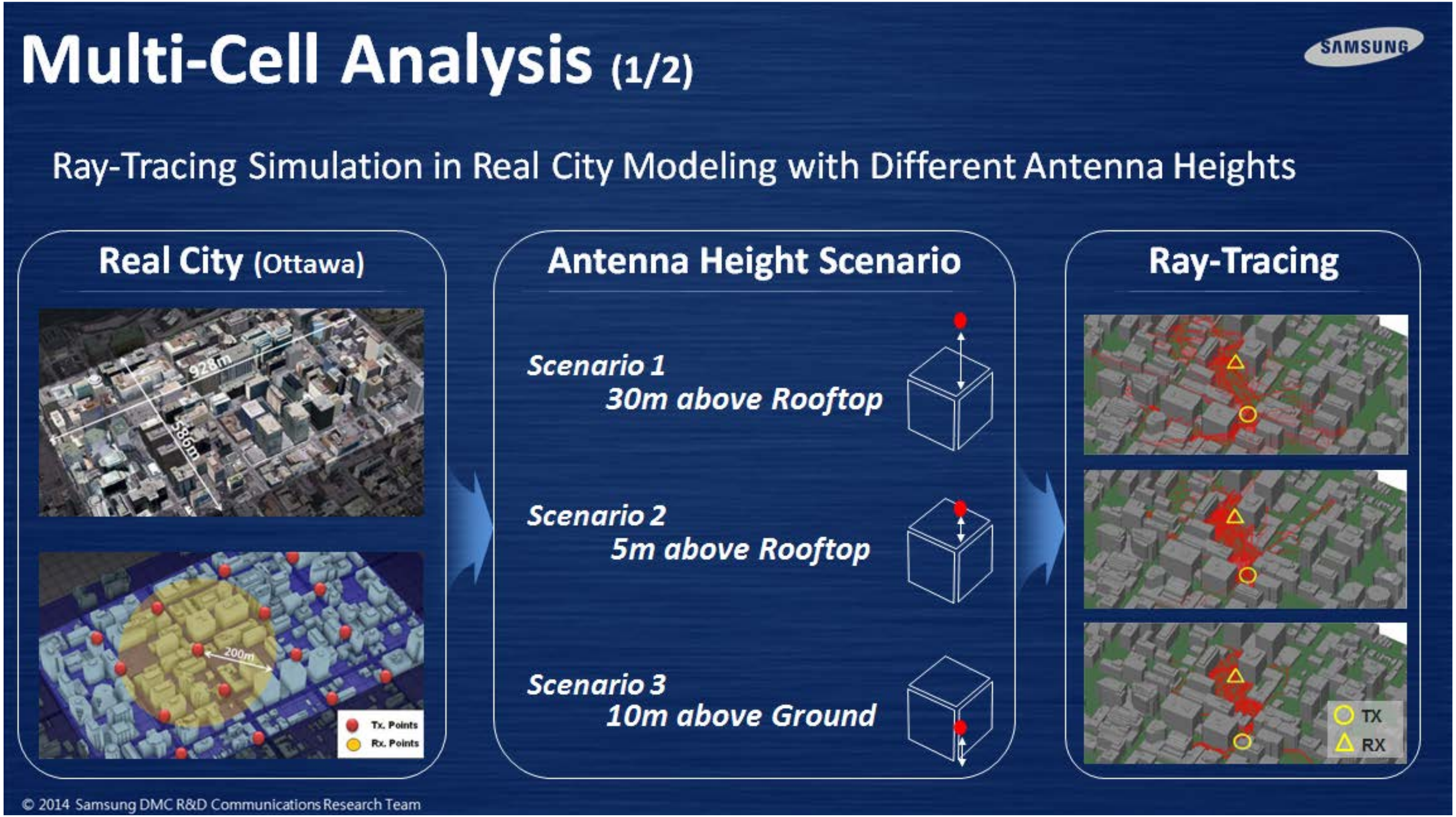
Simulation Results:

4X4 array: 3.2 Gbps (15.7 Gbps peak), 19.7% outage

8X8 array: 4.86 Gbps (15.7 Gbps peak), 11.5% outage

Outage can be reduced by denser cells, smart repeaters/relays

A. Ghosh,T. A. Thomas,M. Cudak, R. Ratasuk,P. Moorut, F. W. Vook, T. S. Rappaport, G. R. MacCartney, Jr., S. Sun, S. Nie, “Millimeter Wave Enhanced Local Area Systems: A High Data Rate Approach for Future Wireless Networks,” IEEE J. on Sel. Areas on Comm., July 2014.



Multi-Cell Analysis (1/2)

Ray-Tracing Simulation in Real City Modeling with Different Antenna Heights

Real City (Ottawa)

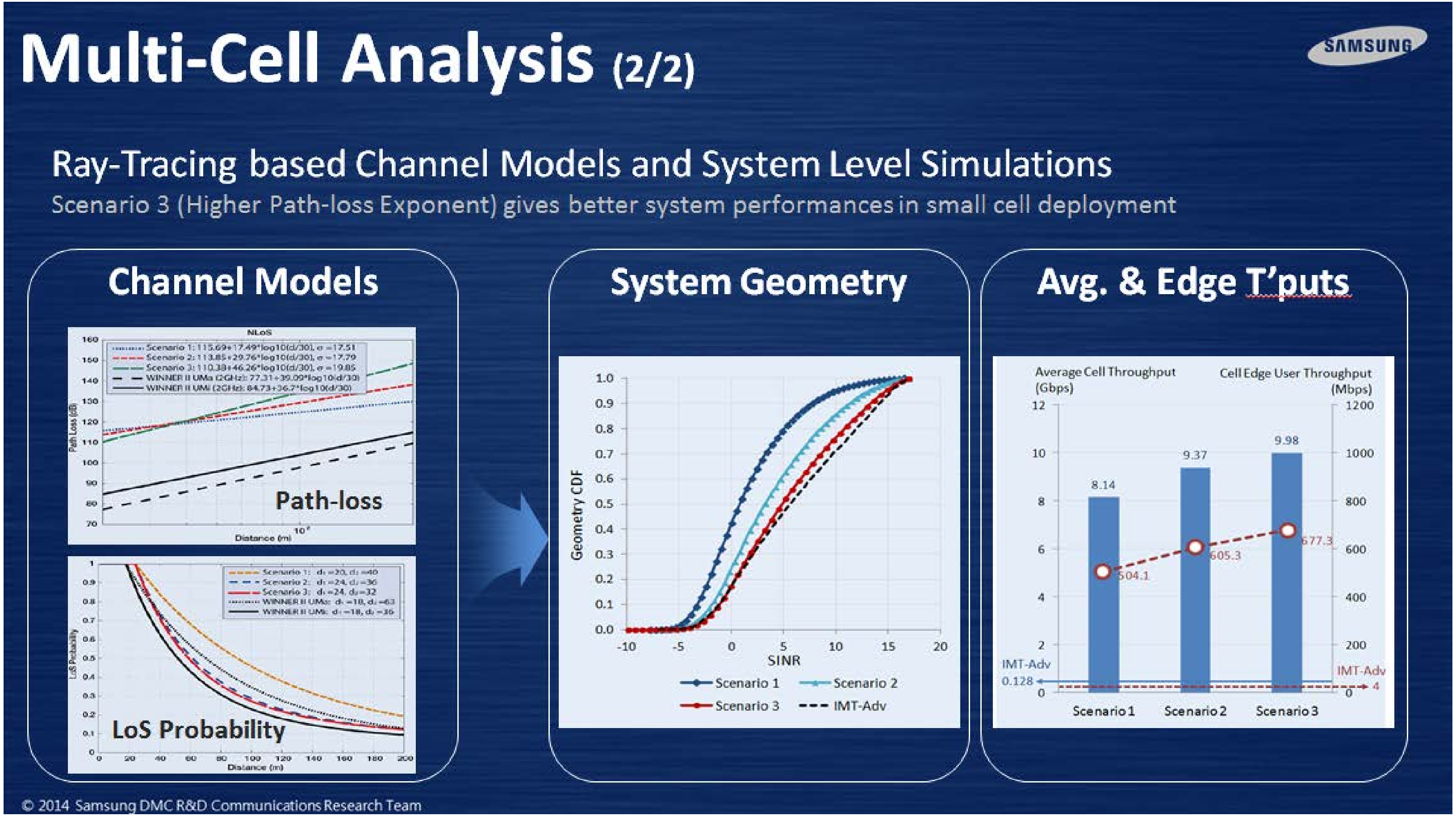
Antenna Height Scenario

Scenario 1
30m above Rooftop

Scenario 2
5m above Rooftop

Scenario 3
10m above Ground

Ray-Tracing



Multi-Cell Analysis (2/2)

SAMSUNG

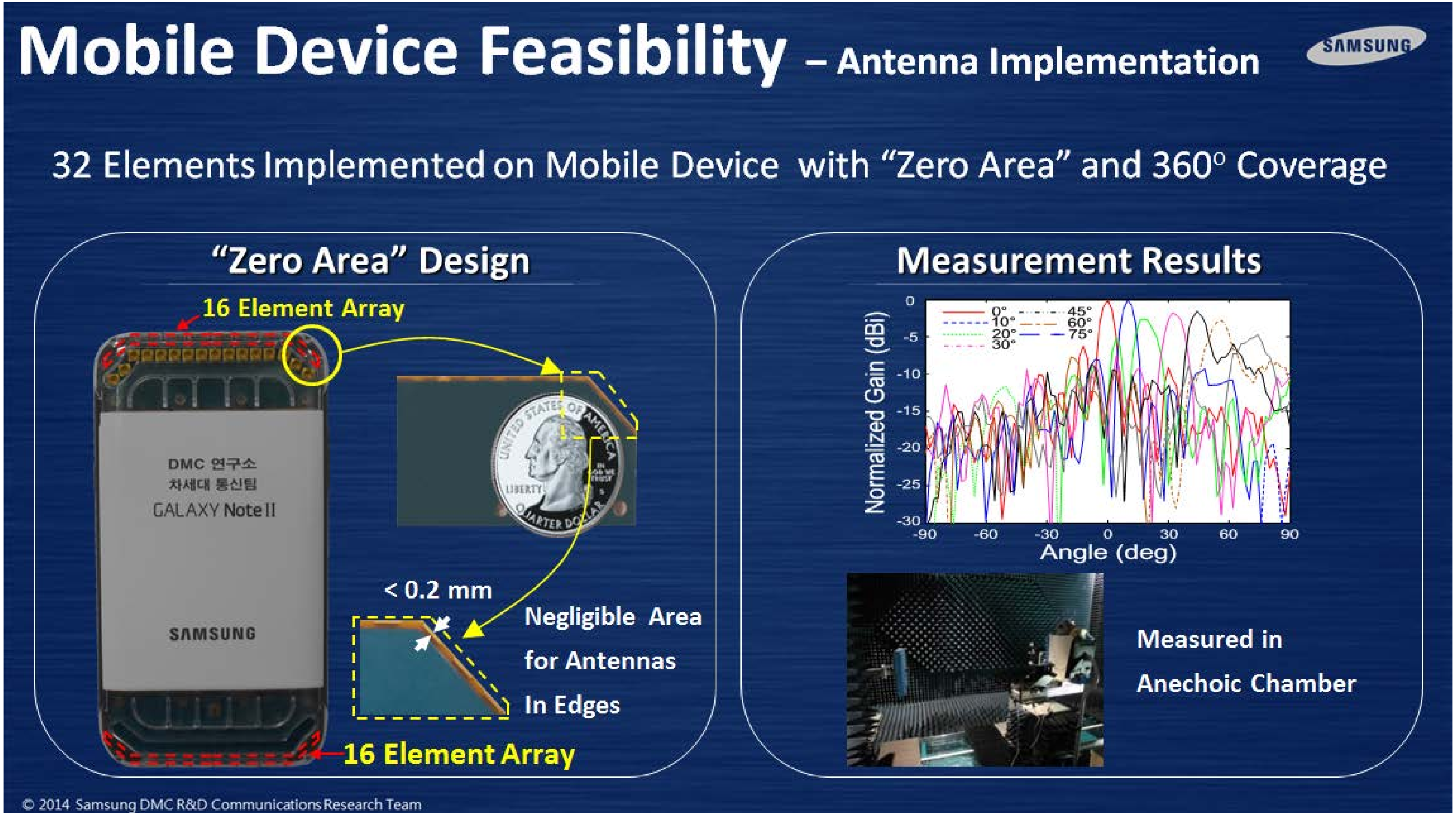
Ray-Tracing based Channel Models and System Level Simulations

Scenario 3 (Higher Path-loss Exponent) gives better system performances in small cell deployment

Channel Models

System Geometry

Avg. & Edge T'puts



Mobile Device Feasibility – Antenna Implementation

SAMSUNG

32 Elements Implemented on Mobile Device with “Zero Area” and 360° Coverage

“Zero Area” Design

16 Element Array

< 0.2 mm

Negligible Area for Antennas In Edges

16 Element Array

Measurement Results

Measured in Anechoic Chamber

© 2014 Samsung DMC R&D Communications Research Team

The Renaissance of Wireless is at hand

- mmW mobile offers 1000x capacity over 4G/LTE
- Experimental confirmation in NYC, Texas in 2011-2014
  - 200 m cell radius very feasible using only 1 Watt
  - Much greater range (>450 m) through beam combining
  - Many km’s possible with 10 W and modest antennas
  - Simulations show multi-Gbps mobile data is viable
  - See prototypes on exhibit at the FCC on March 10, 2016
  - NYU WIRELESS announces Open-Source Statistical Spatial Channel Model software suite for 5G
  - Complete simulator, extensive resources, field data at:
  - http://nyuwireless.com/5g-millimeter-wave-channel-modeling-software/
  - http://bit.ly/1WNPpDX

Acknowledgement to our NYU WIRELESS Industrial Affiliates and NSF

NSF

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NOKIA
QUALCOMM
SAMSUNG
STRAIGHTPATH
KEYSIGHT TECHNOLOGIES
CABLEVISION
UMC
XO communications