Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: THz Wireless Communications: New Opportunities and Challenges
Date Submitted: 5 January 2017

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Abstract: This talk focuses on chip-to-chip interconnects where wire-based interconnects are becoming a bottleneck for performance and scalability. Among wire-replacement candidates, wireless interconnect is especially promising because wireless links between chips would circumvent the pin-count problem. Currently investigated mm-wave wireless interconnects face two problems: not enough bandwidth and antennas that are too big for successful integration. Both problems call for terahertz (THz)-range communications. We will talk about THz propagation and channel modeling in chip-to-chip environments.

Purpose: Information of IEEE 802.15 IG THz

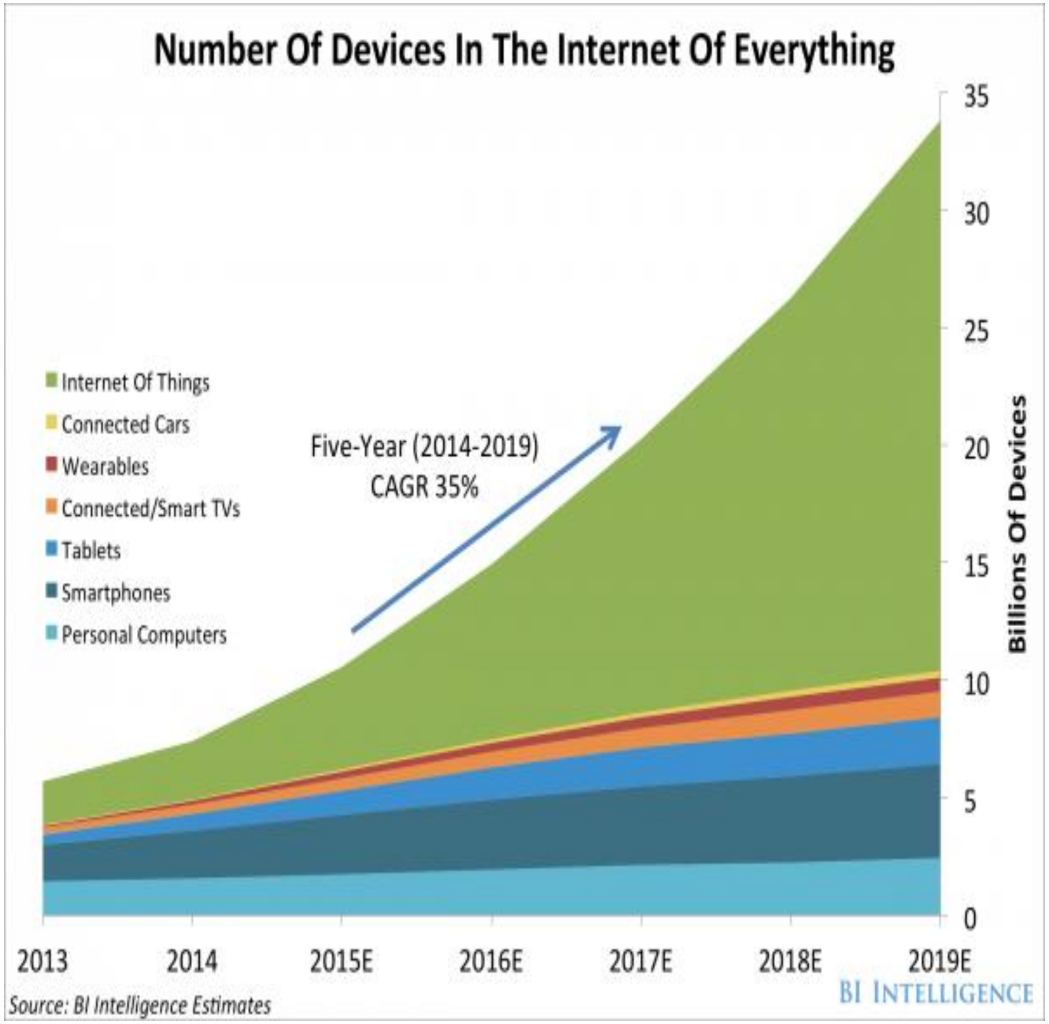
THZ Wireless Communications: New Opportunities and Challenges

Prof. Alenka Zajić

Georgia Institute of Technology

January 2017

❖Internet of Everything



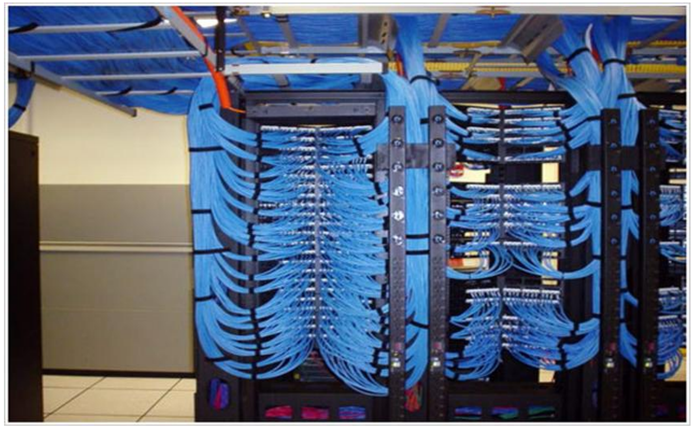
Source: BI Intelligence Estimates

❖Challenges for IoT and Wearable Devices

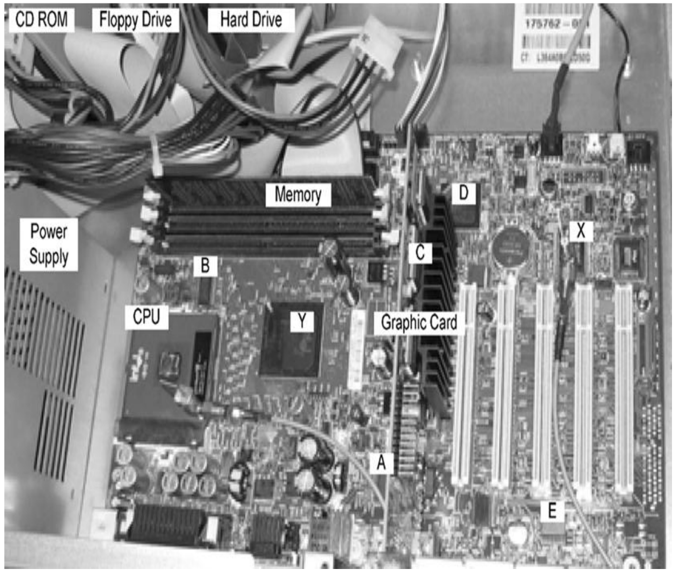
- **Sensing a complex environment -**Innovative ways to sense and deliver information from the physical world to the cloud
- **Connectivity-** Variety of wireless networks needed
- **Cloud is important -** IoT will require significant increase in data storage → needs better rack-to-rack, device-to-device, and chip-to-chip communication
- **Security is vital -** Detecting and blocking malicious activity
- **IoT is complex** IoT application development needs to be easy for all developers, not just to experts
- **Power is critical**

❖Applications That Need THz Communication

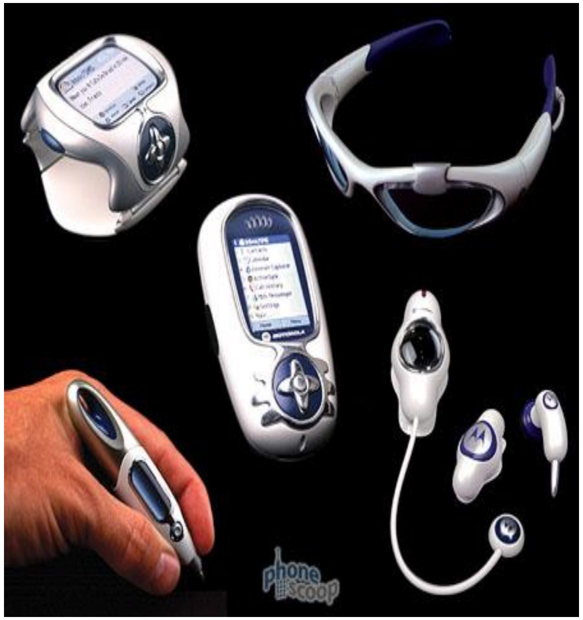
Interconnects in Data Centers



Chip-to-Chip On Motherboard



Wearable Devices



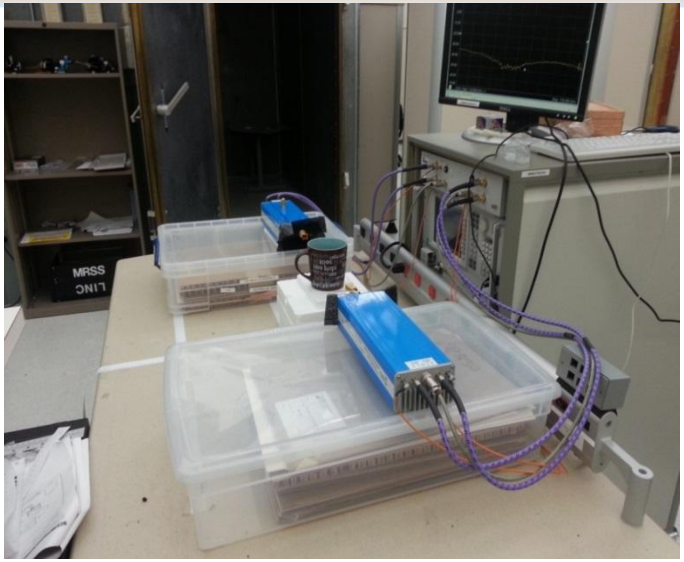
❖Current Wireless Interconnects

- + antenna size/integration with chips
- +adding bandwidth without adding pins or fiber connectors to the chip package.

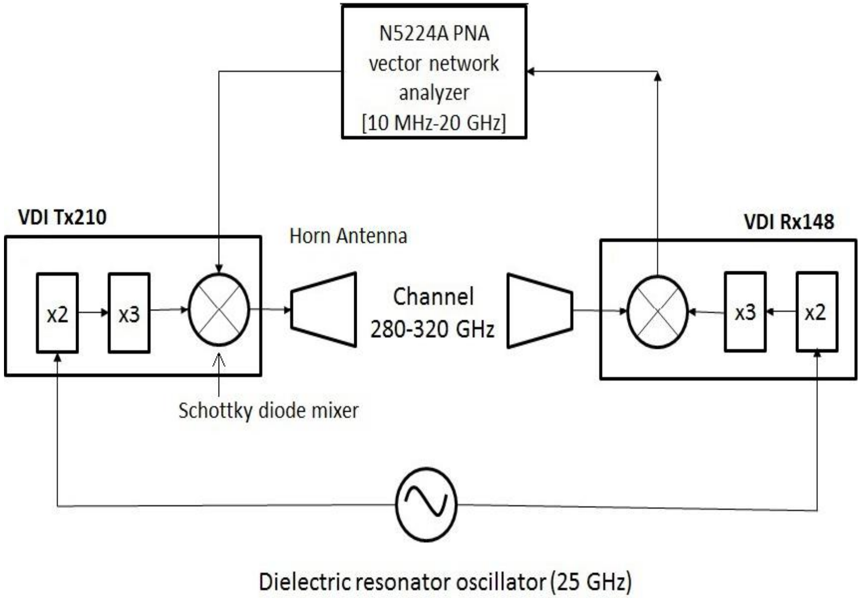
- - limited bandwidth
- For example, a computer in a typical high performance cluster gets 56 Gbits/s
- Wireless communication at mm- Wave frequencies: WiGig uses 60 GHz frequency range to provide up to 7 Gbits/s using OFDM, 64- QAM, and sophisticated coding.
- Power hungry systems

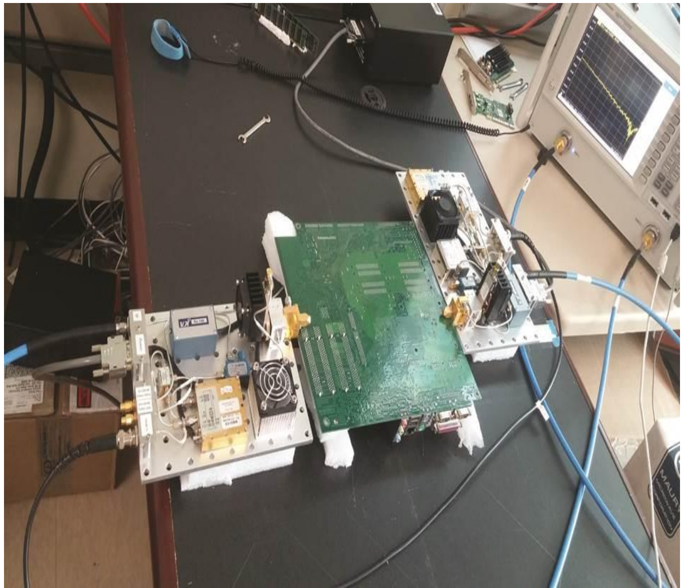
❖ THz Transmitter and Receiver

110-170 GHz Measurement System



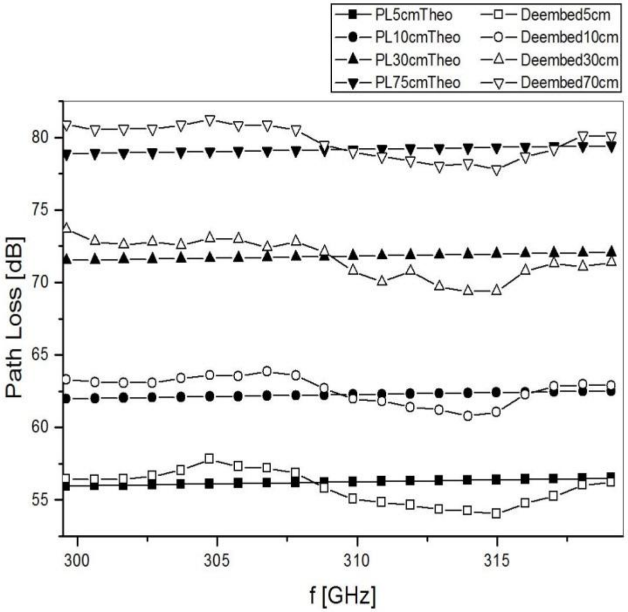
300-320 GHz Measurement System



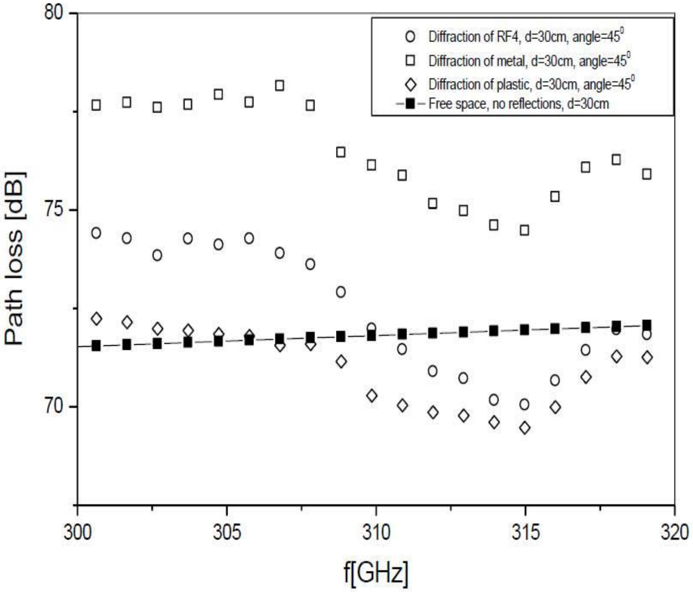


❖ Path Loss Measurement

- ➢ LoS



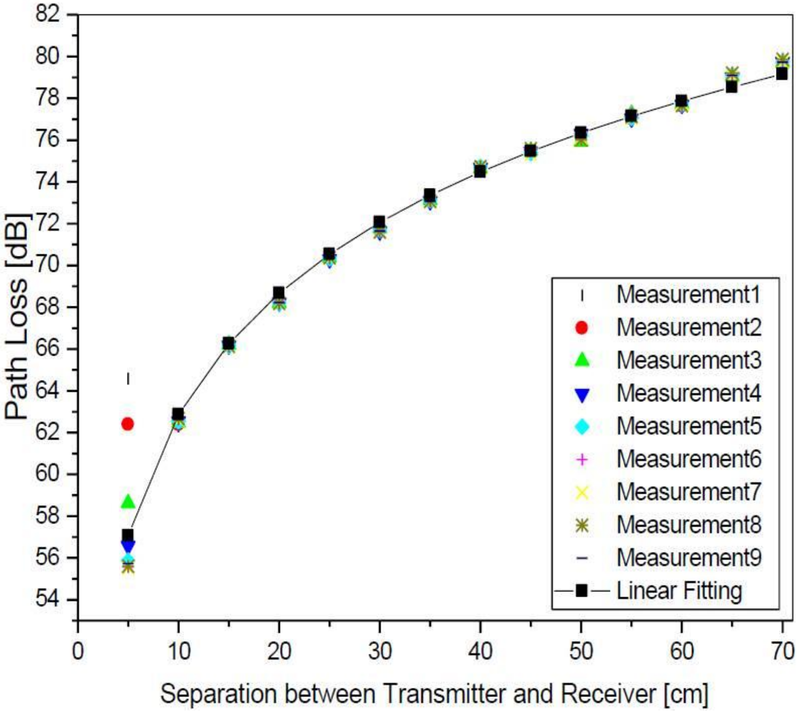
- ➢ NLoS

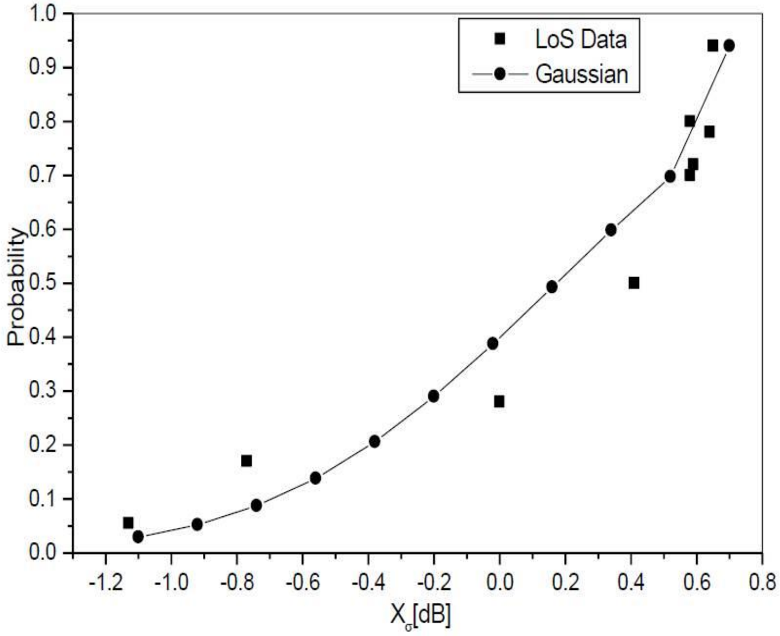


- Varying diffraction loss with different materials (FR4, metal, plastic)

[1] S. Kim and A. Zajić, “Statistical characterization of 300-GHz propagation on a desktop,” *IEEE Transactions on Vehicular Technology*, vol. 64, no. 8, pp. 3330-3338, Aug. 2015.

❖Path Loss vs. Distance





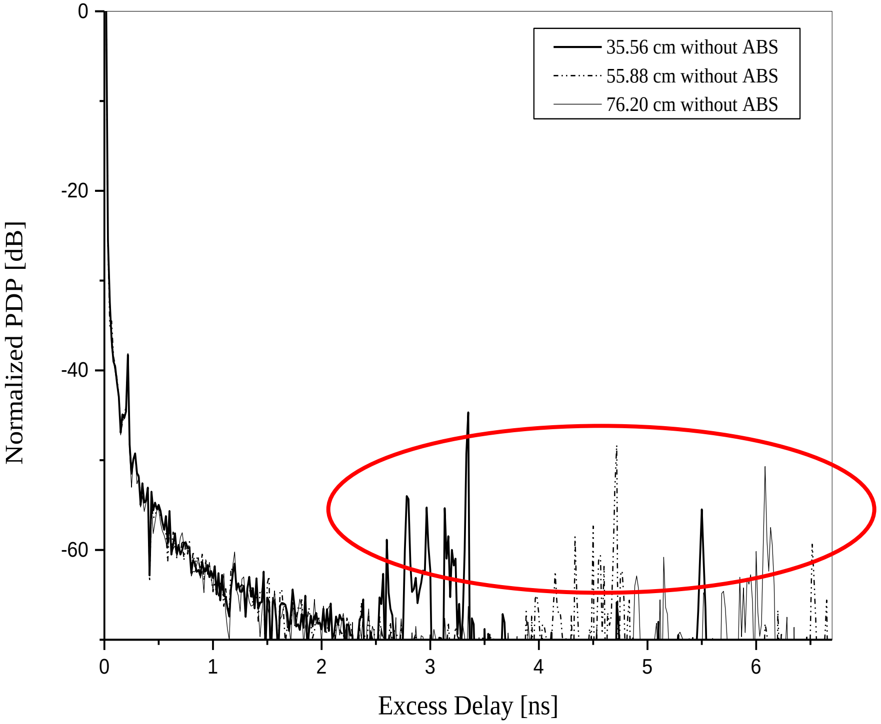
Freq. bands [GHz]	**Path Loss exponent (γ)**	**σ [dB]**
300-320	1.927	0.67
300-302.5	1.916	0.67
305-307.5	1.886	0.715
310-312.5	1.93	0.737
315-317.5	1.95	0.71

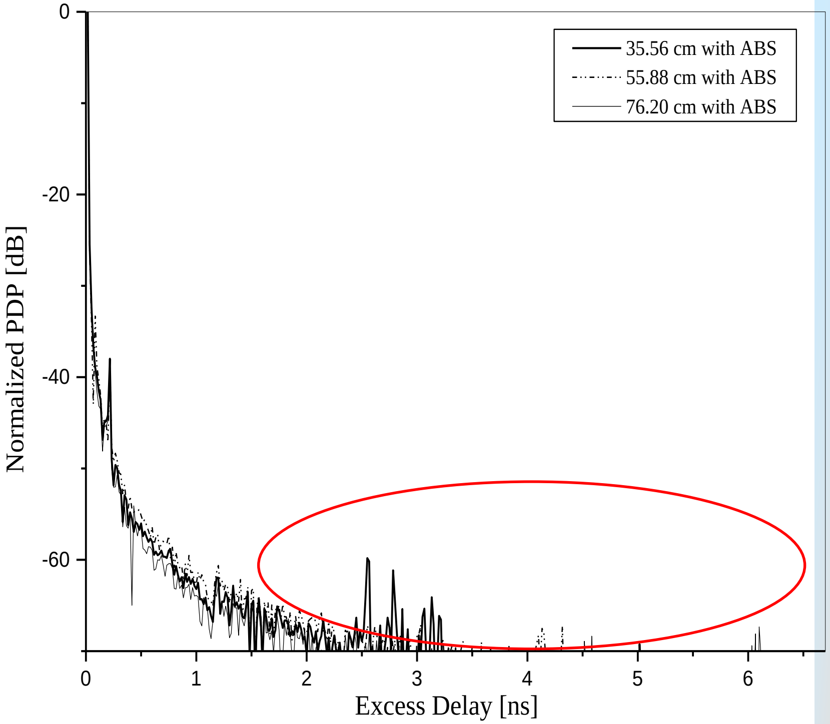
- Log-normality of path loss variation introduced by misalignment:

$$PL = PL_0 + \gamma 10 log_{10}\left(\frac{d}{d_0}\right) + X_\sigma$$

PL_0= 81.97 dB $(d_0 = 1 \text{ m})$

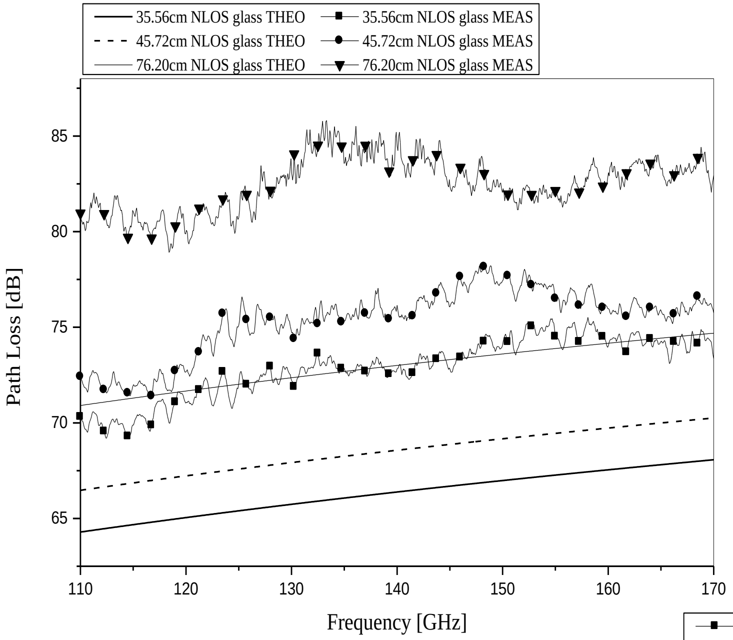
❖ Multipath Characterization (LoS)



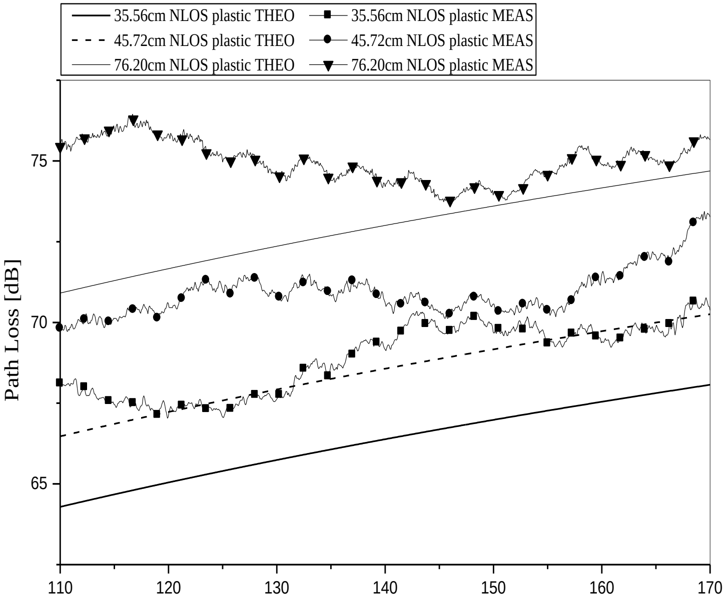


[2] S. Kim, W. T. Khan, A. Zajić, and J. Papapolymerou, “D-band channel measurements and characterization for indoor applications,” *IEEE Transactions on Antennas and Propagation*, vol. 63, no. 7, pp. 3198-3207, July 2015.

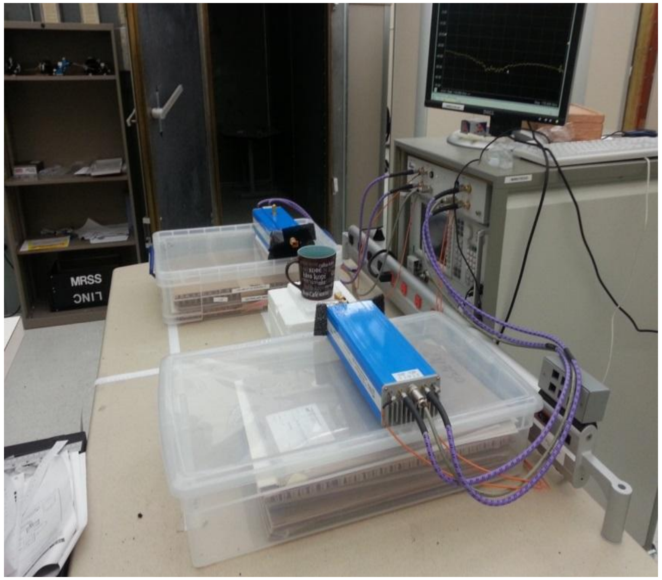
❖ Path Loss with Cylindrical Obstructions

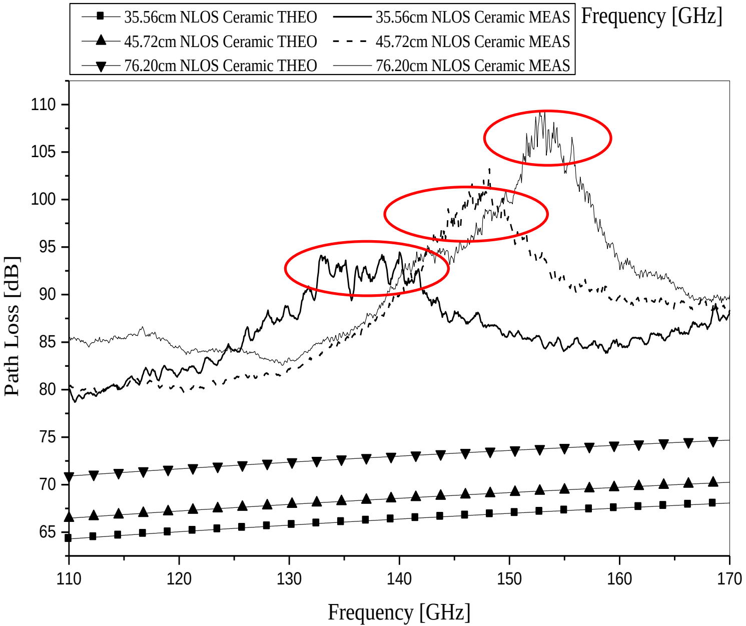


(Glass)



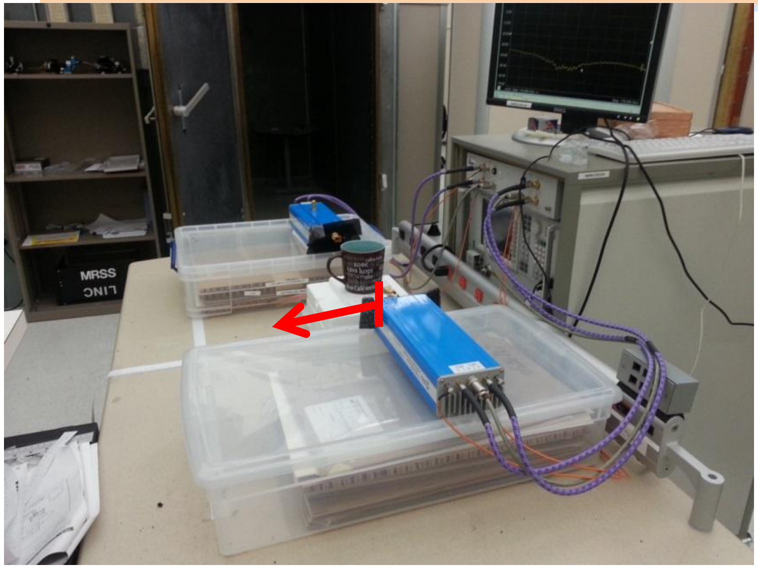
(Plastic)

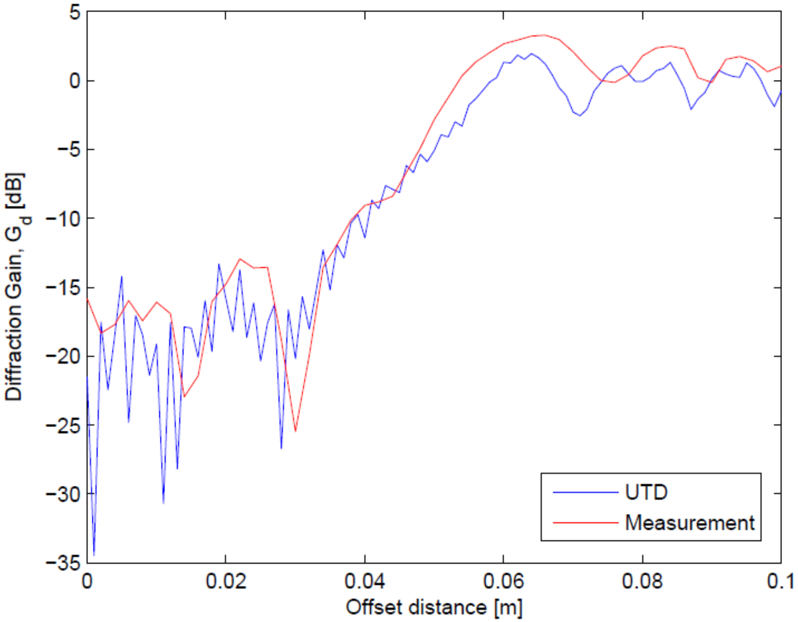


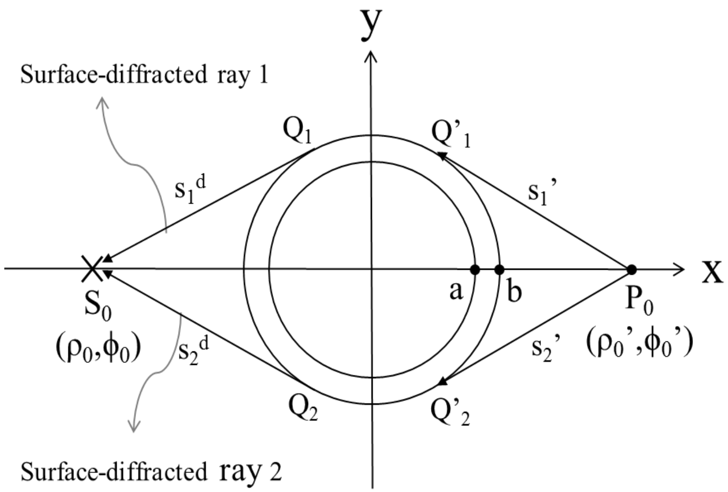


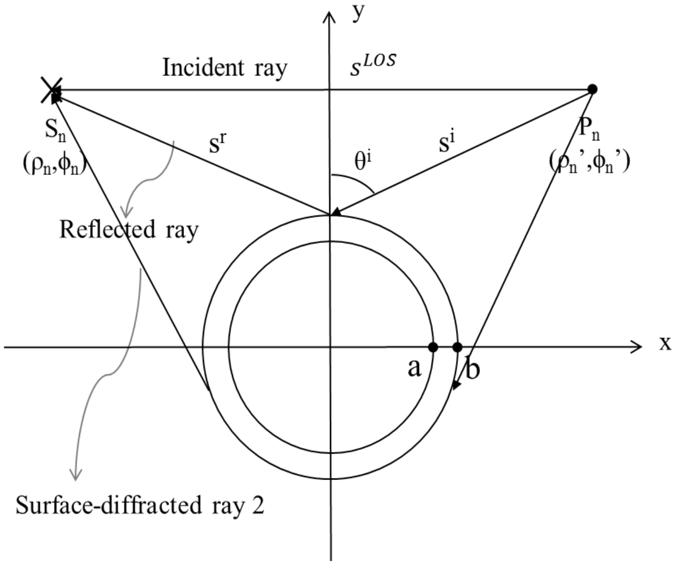
(Ceramic)

❖ Diffraction



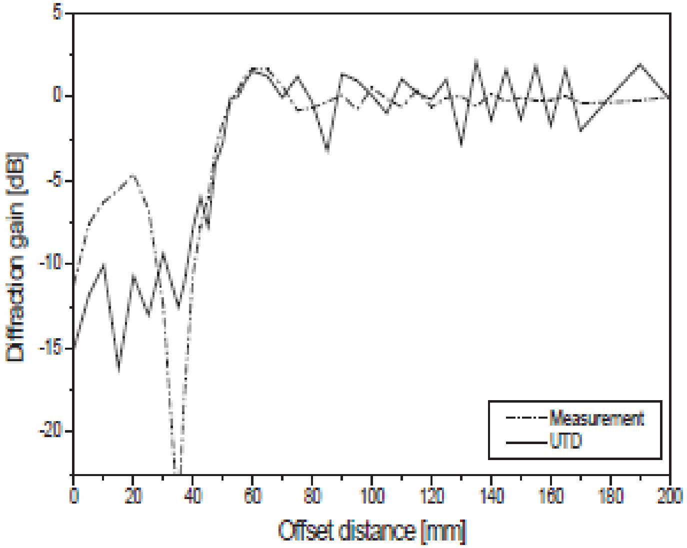




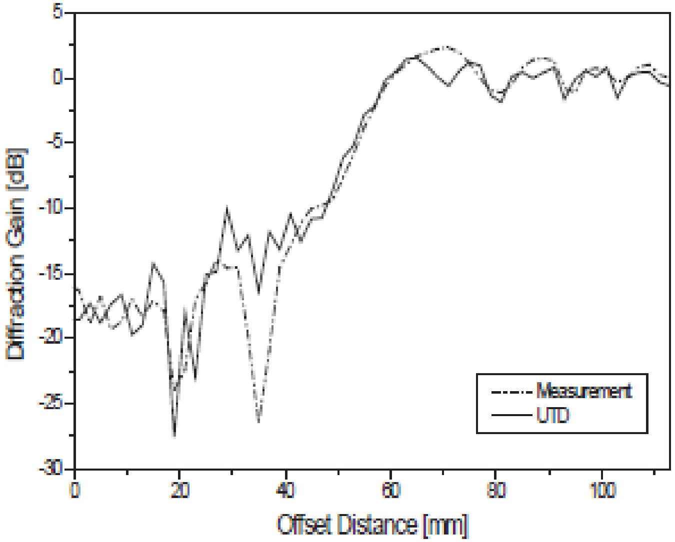


[3] S. Kim and A. Zajić, "UTD-Based Modeling of Diffraction Loss by Dielectric Circular Cylinders at D-band," *Proceedings of IEEE International Symposium on Antennas and Propagation*, pp. 1-2, June 26-July 1, 2016, Fajardo, Puerto Rico.

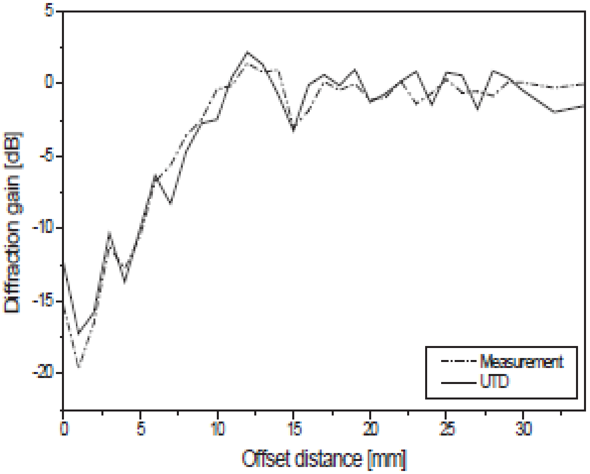
❖ Diffraction



33 GHz

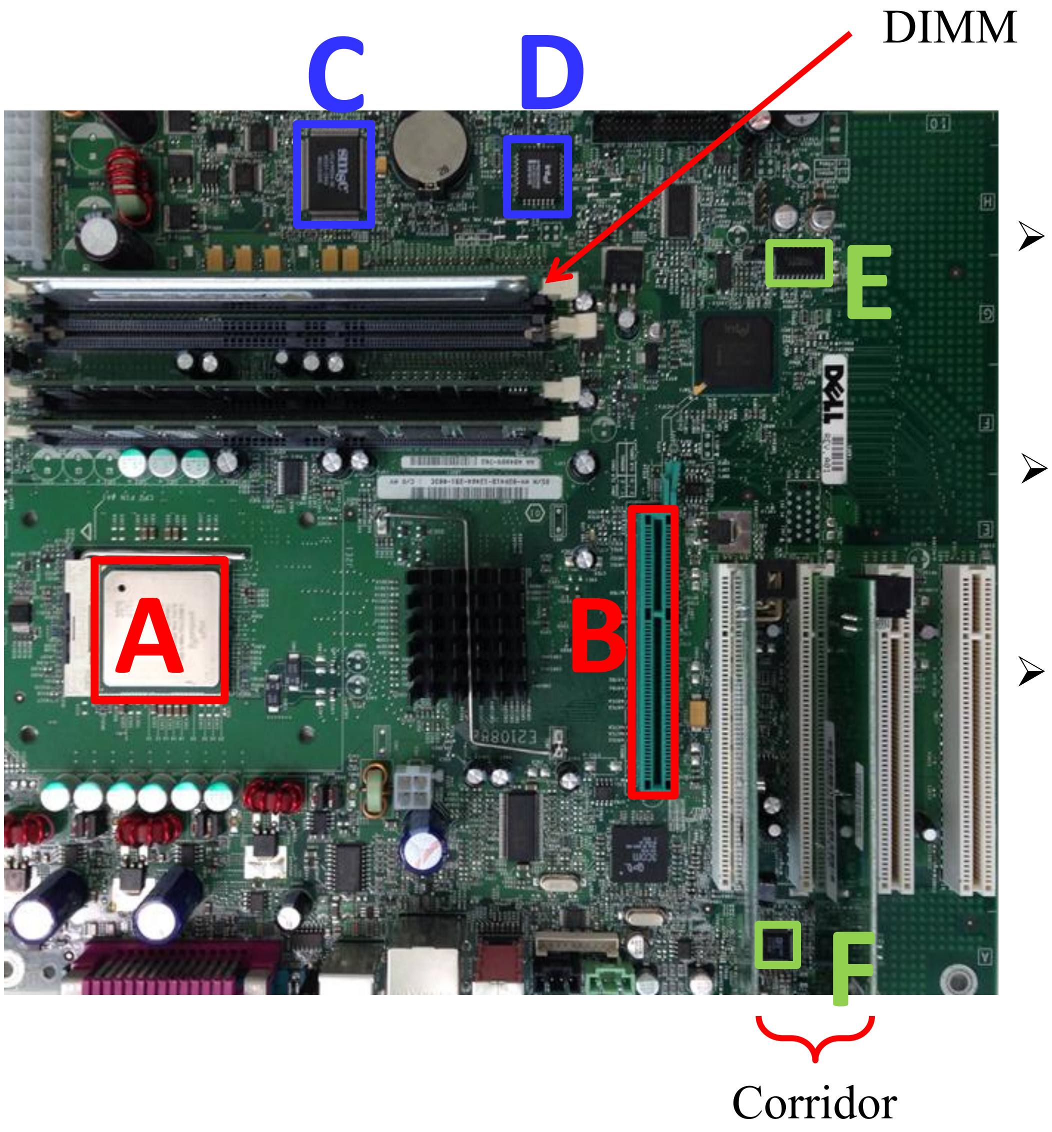


140 GHz



307 GHz

❖ Chip-to-Chip Measurement Scenarios



- Link A-B: CPU-AGP (Accelerated Graphics Port)
  - LoS with T-R height difference
- Link C-D: Directed NLoS with DIMM as reflecting surface
- Link E-F: OLoS through parallel-plate structure (i.e., DIMM's, cards)

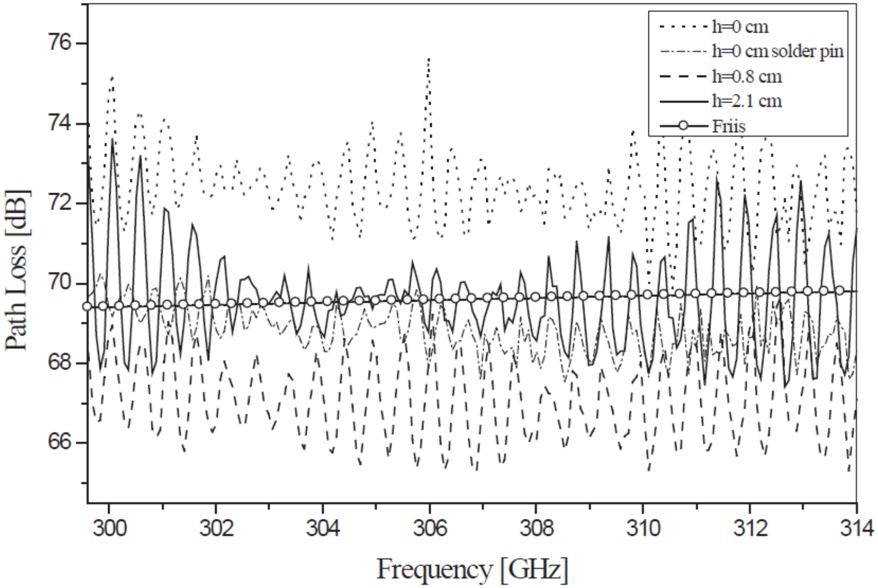
Measurement Scenarios

- 1) LoS propagation between the Tx and Rx over the large ground plane
- 2) Processor-Memory Link (A-B Channel)
- 3) OLoS Link through Guided Metal Parallel-plate Structures (C-D Channel)
- 4) Heatsink Channel

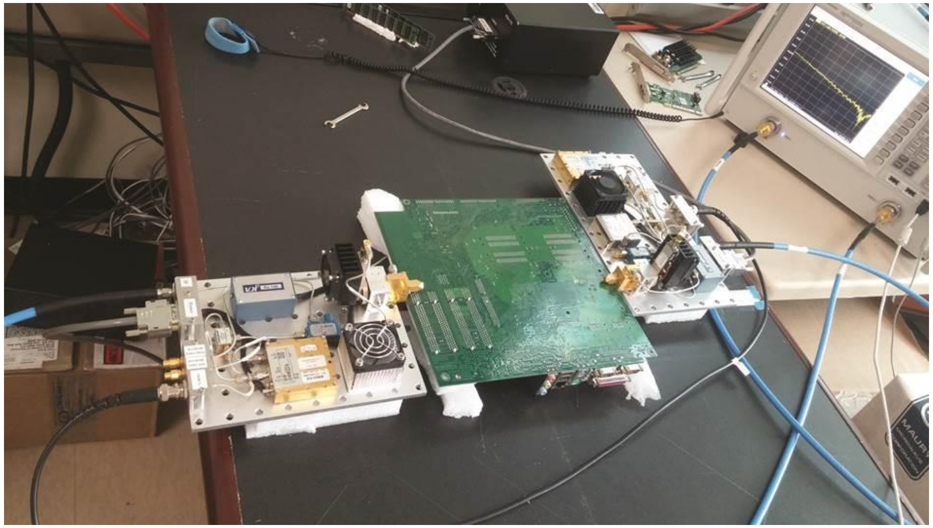
[4] S. Kim and A. Zajić, "Characterization of 300-GHz Wireless Channel on a Computer Motherboard," in *IEEE Transactions on Antennas and Propagation*, vol. 64, no. 12, pp. 5411-5423, Dec. 2016.

❖LoS over large ground plane

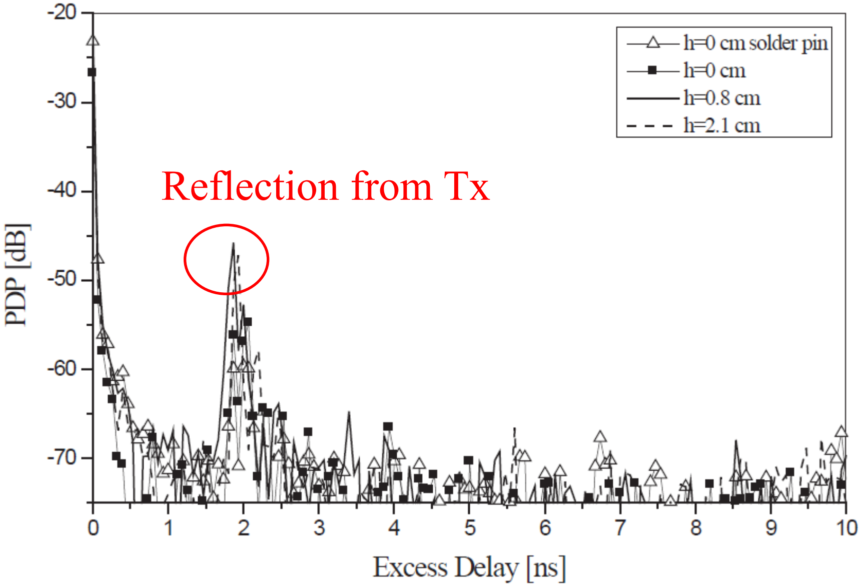
- ➢ Path Loss



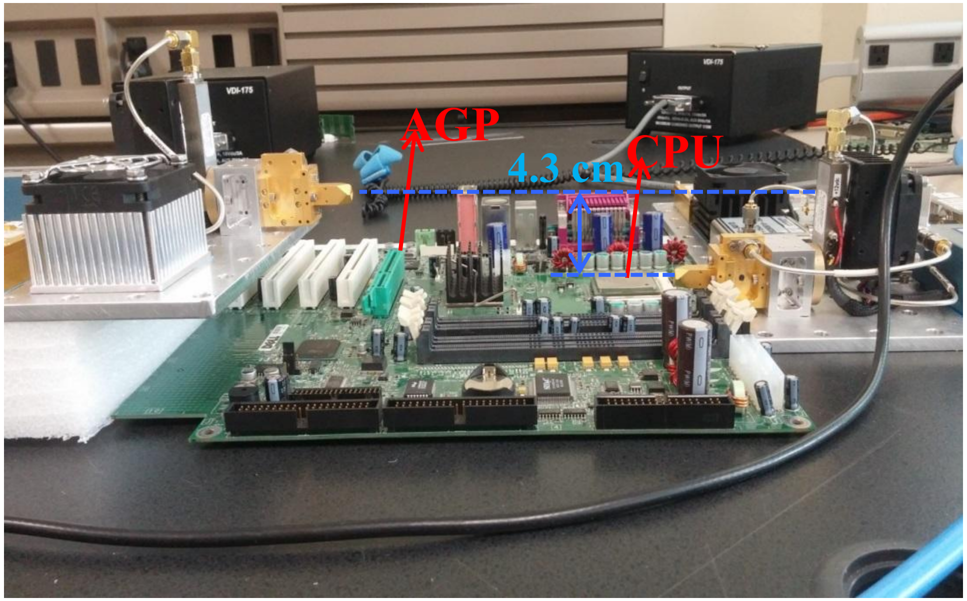
- ➢ Received power dependent on antenna height and the location of ground-reflection
- ➢ Oscillation due to reflection from Tx hardware



- ➢ PDP



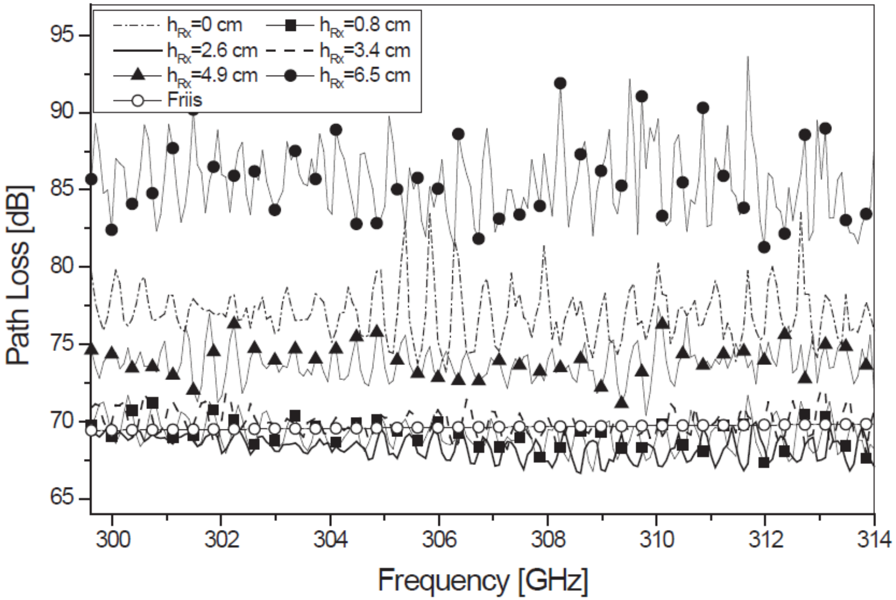
❖ LoS with T-R height difference



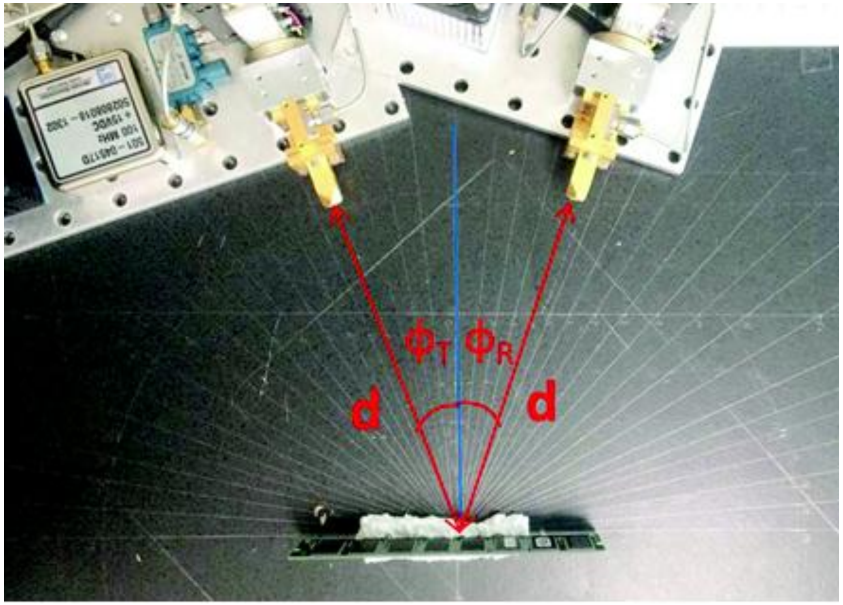
- h_{Tx}=2.1 cm, 0 cm < h_{Rx}< 6.5 cm

- For Δh > 1.3 cm, path loss starts deviating from theoretical value

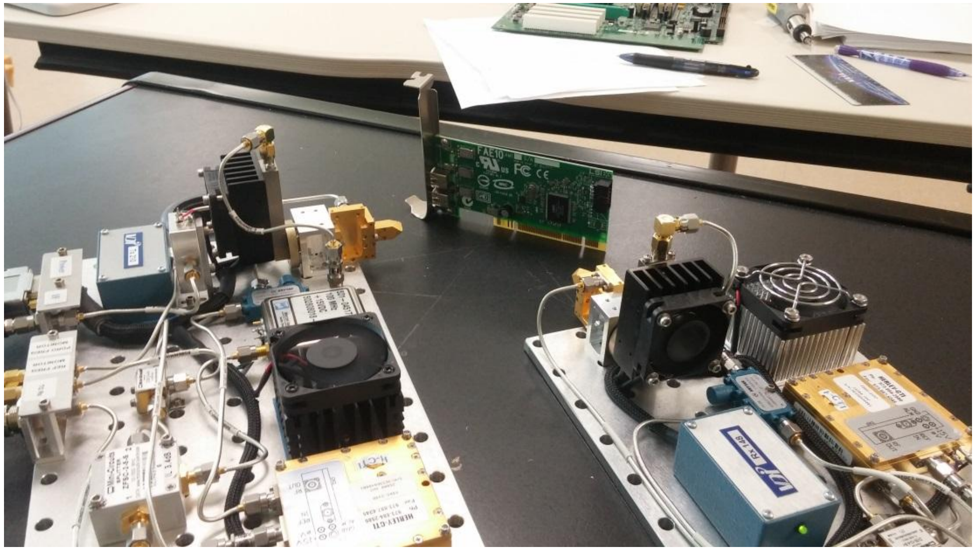
- Height difference in the order of few centimeters (> 10λ) will suffer from significant loss



❖Directed NLoS



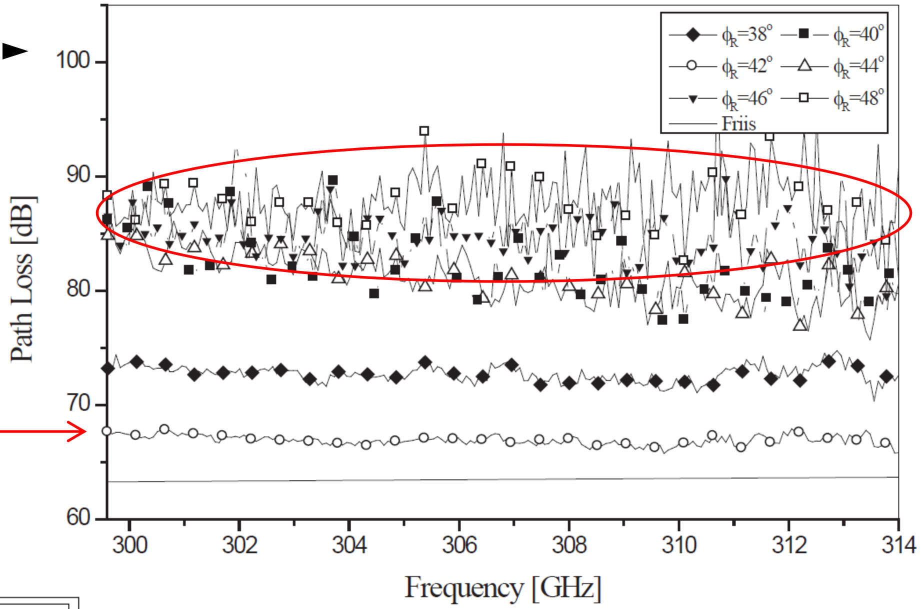
- Front and Back surfaces of a DIMM (Dual Inline Memory Module)



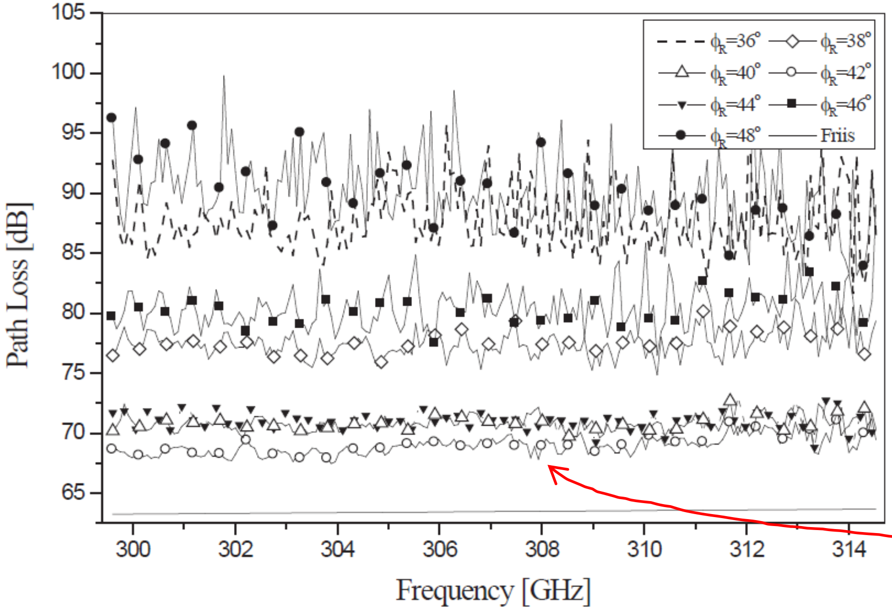
- Front and Back surfaces of a graphic card

❖Path Loss (Directed NLoS)

Front surface of DIMM ►



($\phi_T = \phi_R = 42^\circ$)



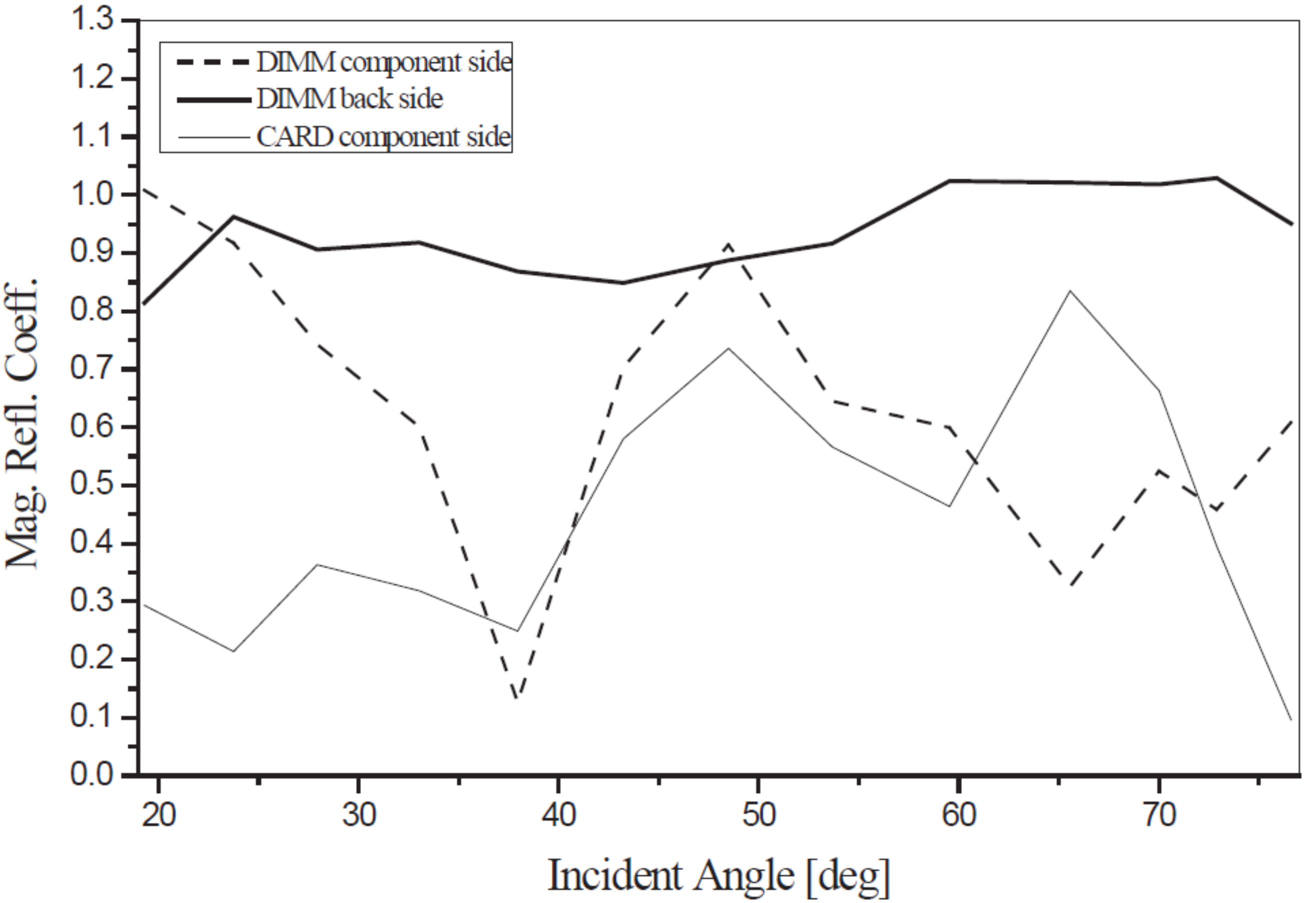
◄ Back surface of DIMM

PL increasing linearly with the deviation from ϕ_T

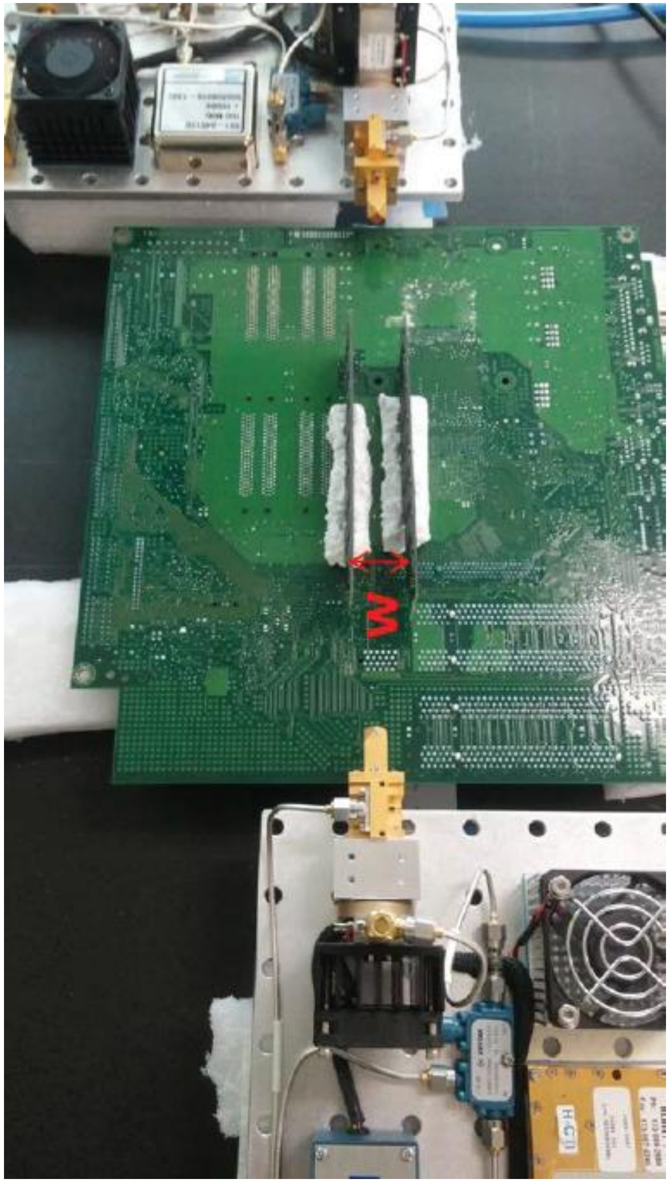
($\phi_T = \phi_R = 42^\circ$)

❖ Reflection Coefficient (Directed NLoS)

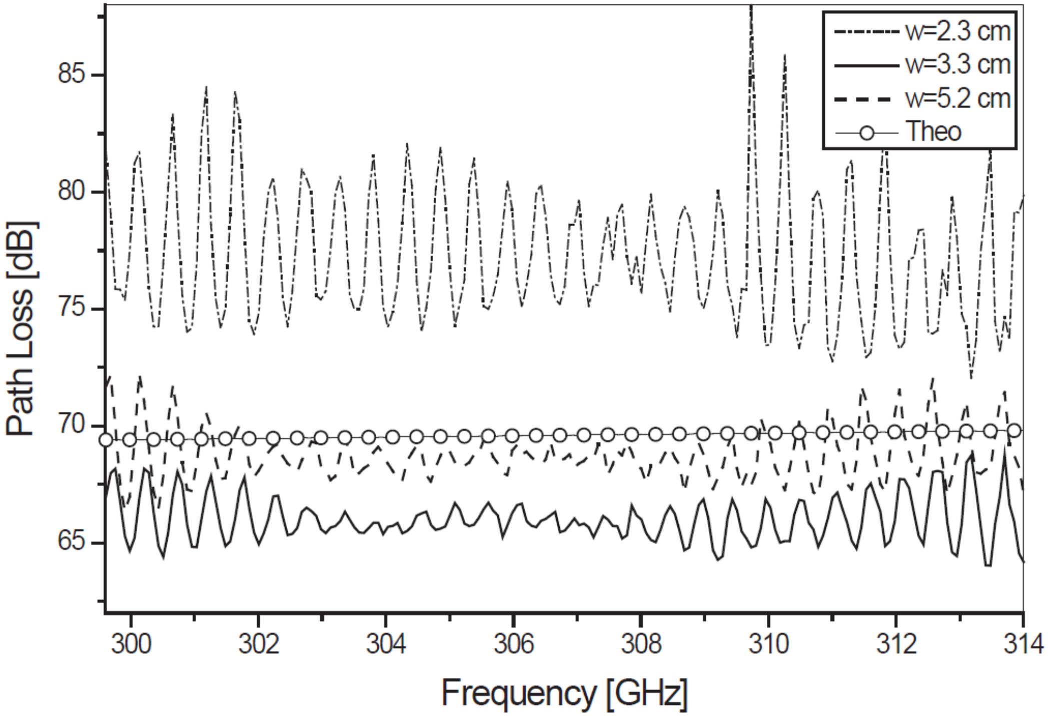
- $RL = \underbrace{P_t - P_r + G_t + G_r}_{\textit{Measured PL}} - \widetilde{PL}$ $\qquad |\Gamma| = 10^{-RL/20}$



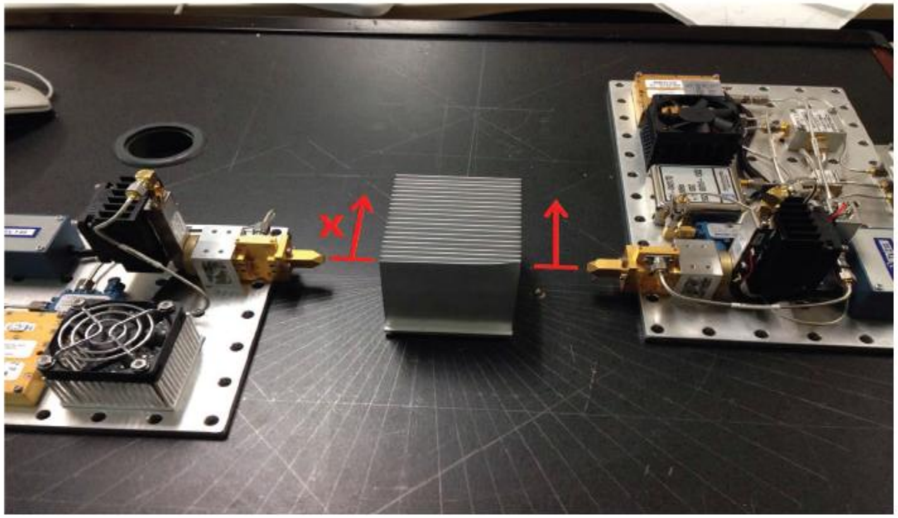
❖ OLoS Link through Parallel-Plate Structure

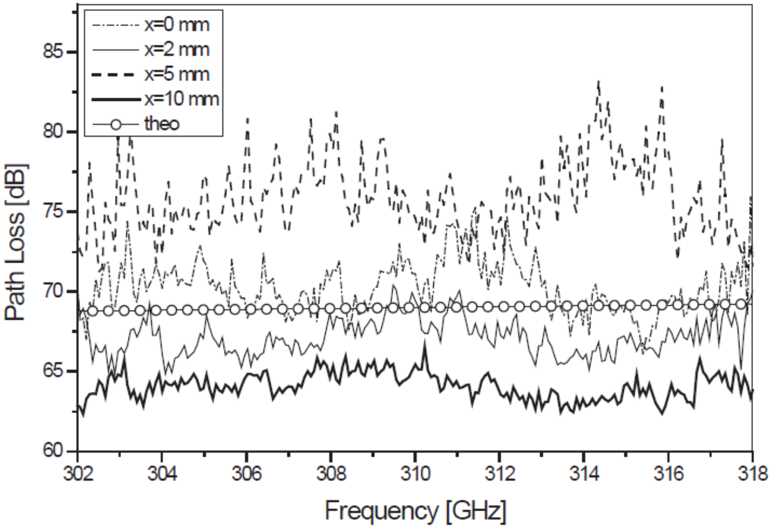


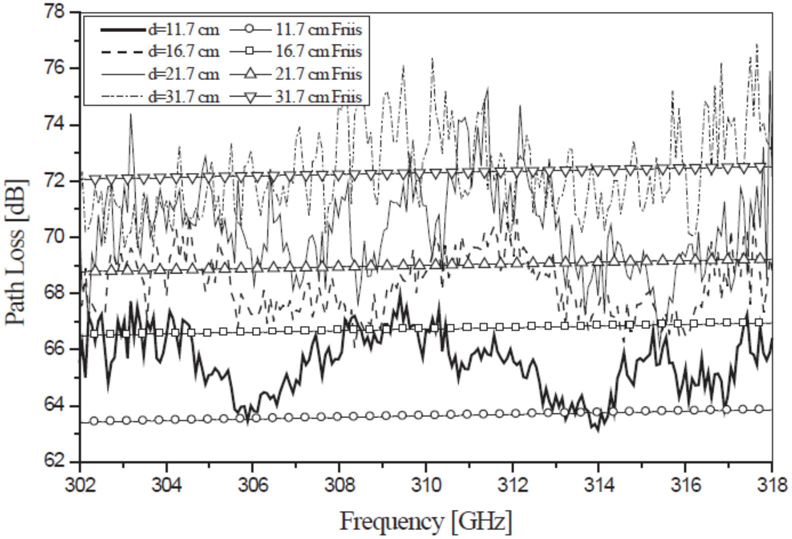
- 2.3 cm < w < 5.2 cm

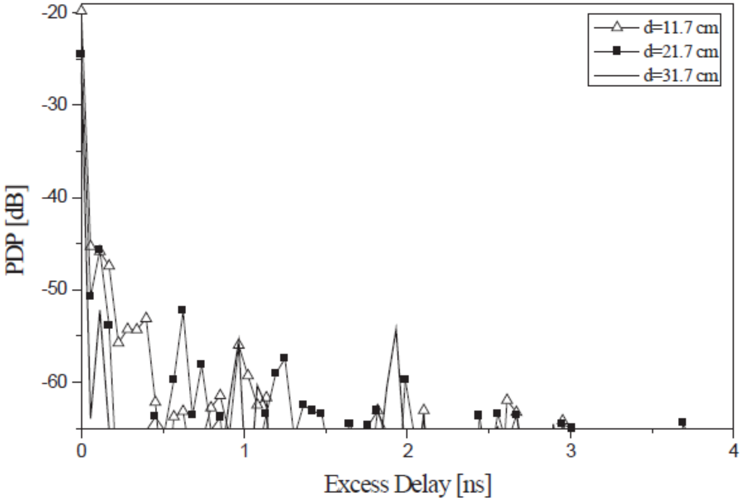


❖ NLOS- Through Heatsink

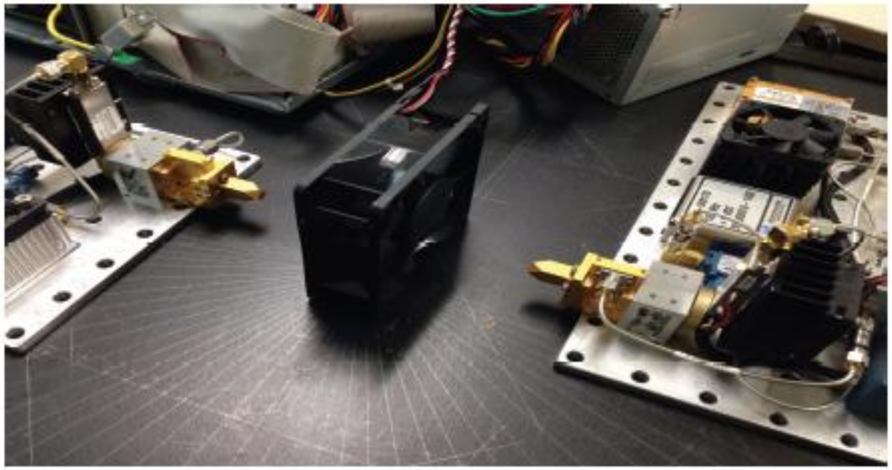


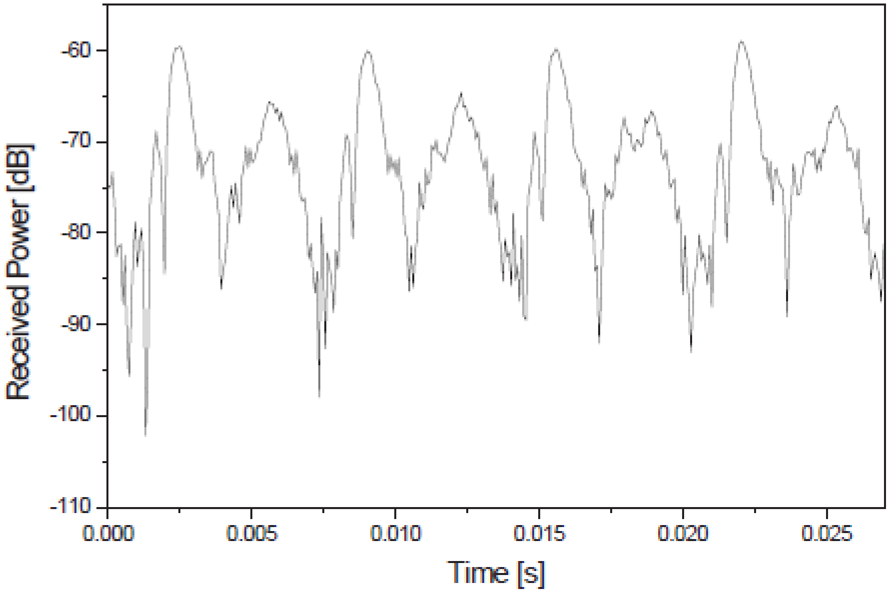




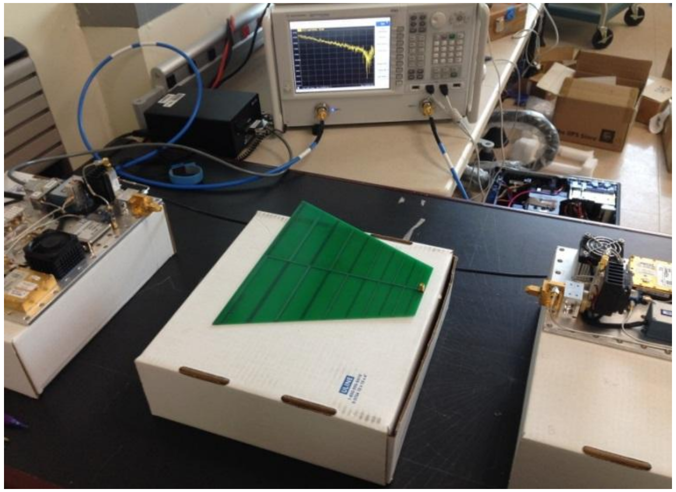


❖ NLOS- Through Rotating Fan

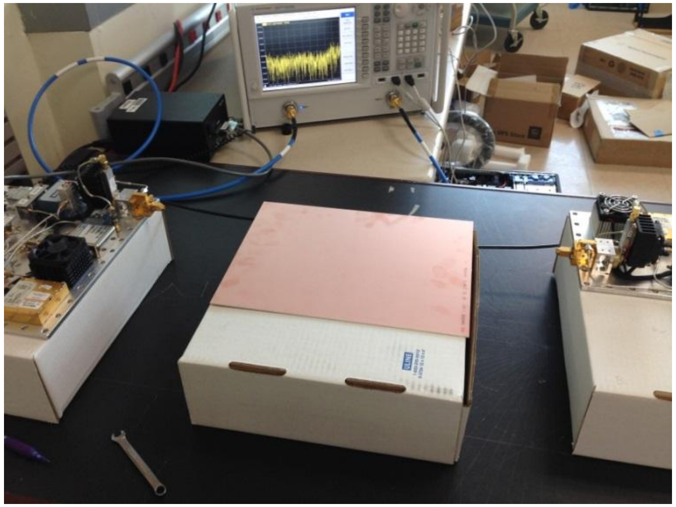




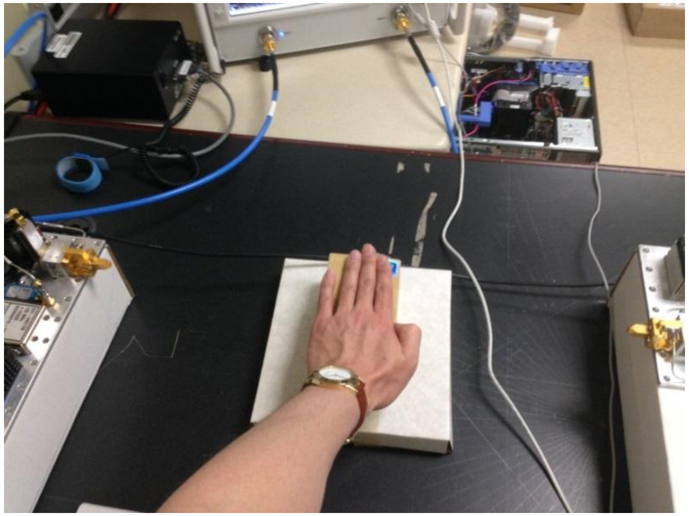
❖Impact of Human Hand on THz Propagation



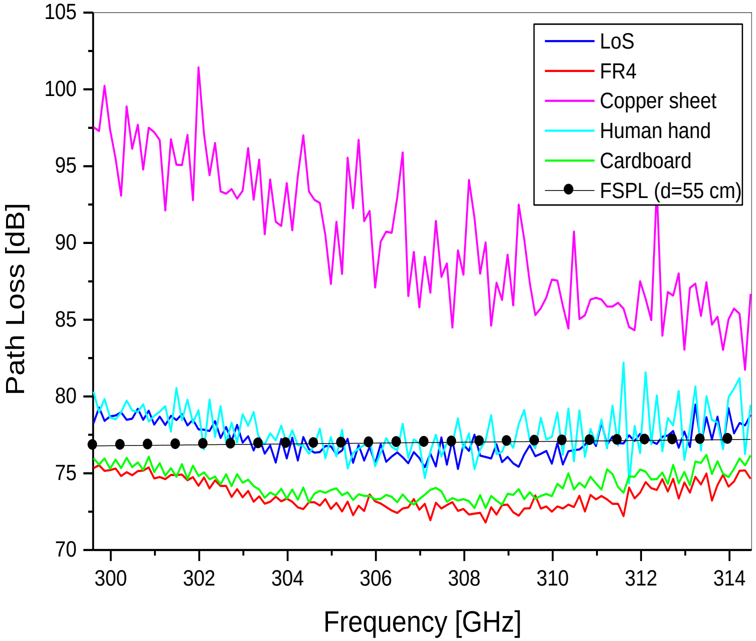
Ground reflection (FR4)



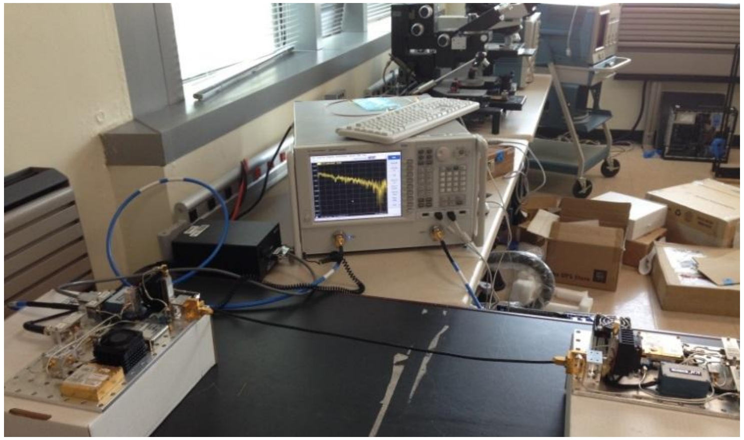
Ground reflection (Copper sheet)

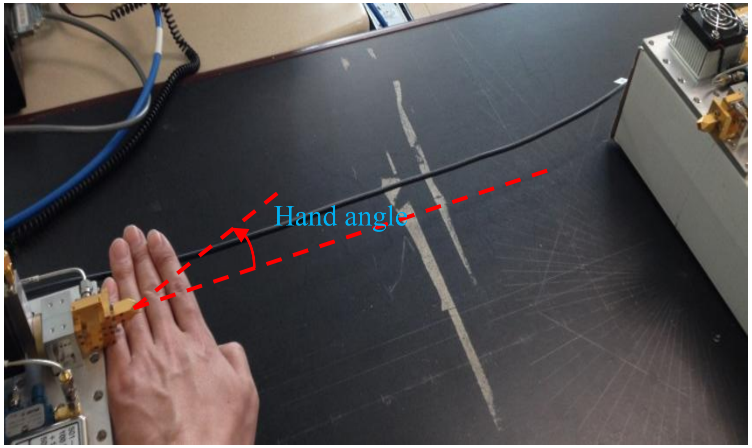


Ground reflection (Human hand)



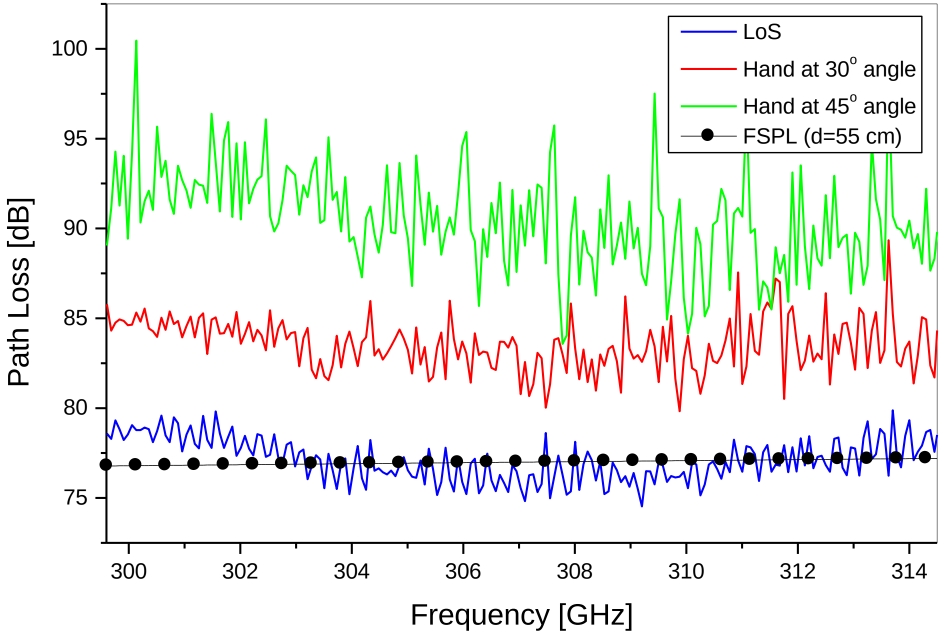
❖Impact of Human Hand on THz Propagation



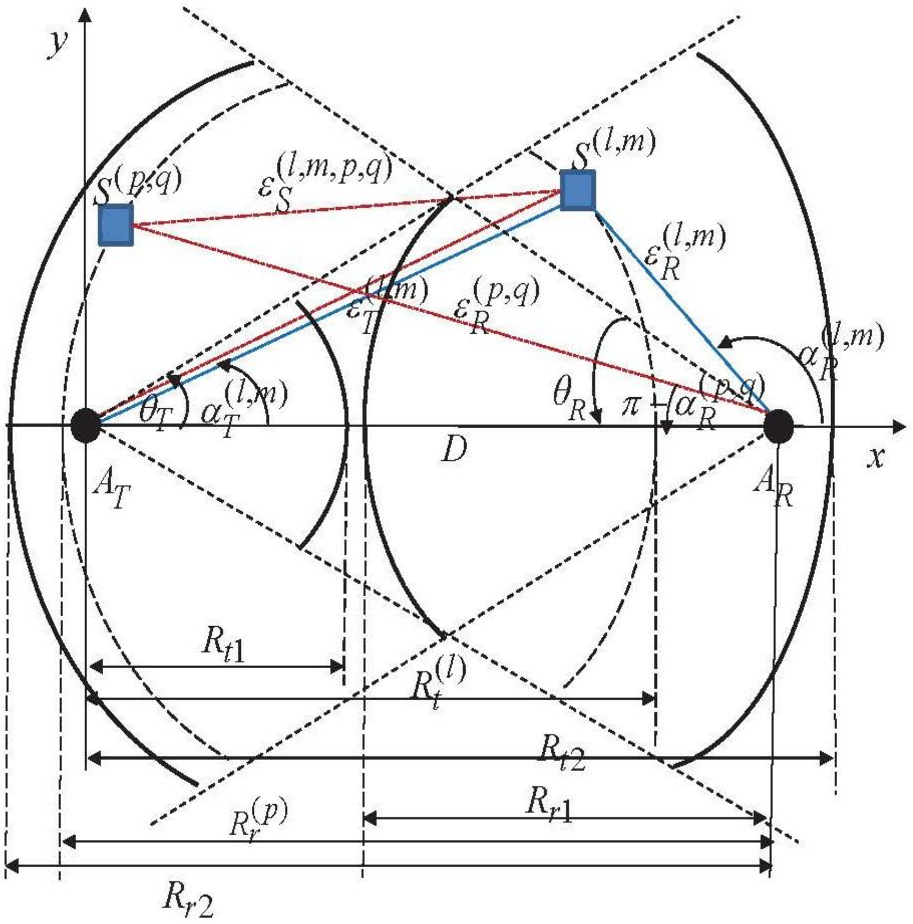


Perturbation by hand

LoS



❖ 2-D Geometrical Propagation Model

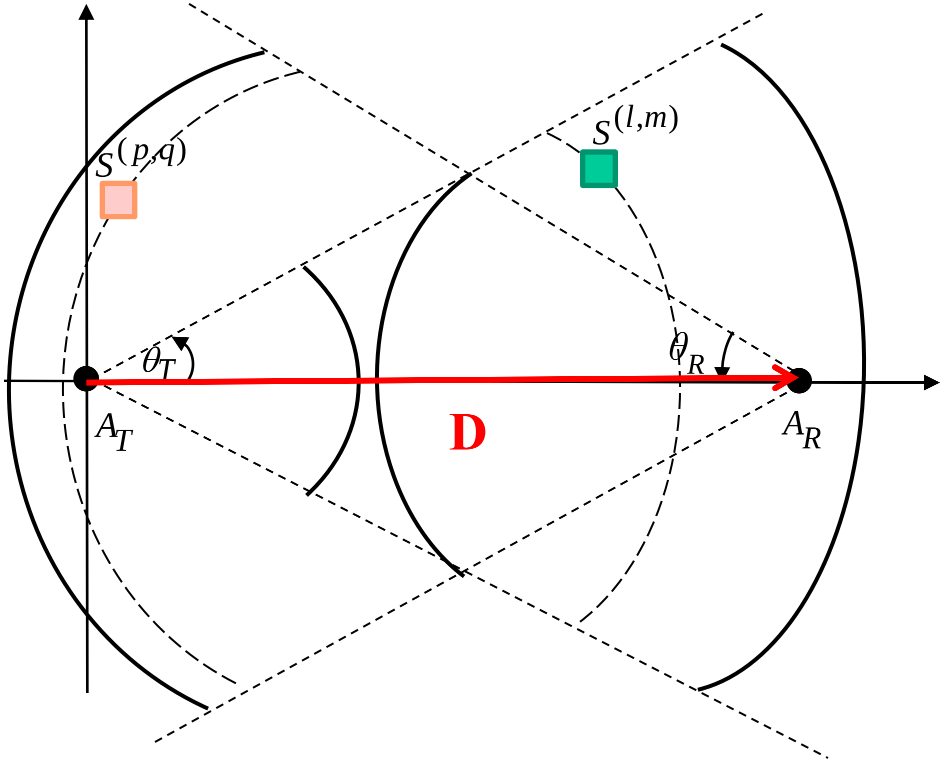


- ➢ Three components:
  - LoS
  - Single-Reflected
  - Double-Reflected

- ➢ Quasi-static channel
  → Time-invariant delay-spread function,
  $h(\tau)$

[5] S. Kim and A. Zajić, “Statistical modeling and simulation of short-range device-to-device communication channels at sub-THz frequencies,” *IEEE Transactions on Wireless Communications,* vol. 15, no. 9*,* pp. 6423 – 6433, Sept. 2016

❖ LoS Ray

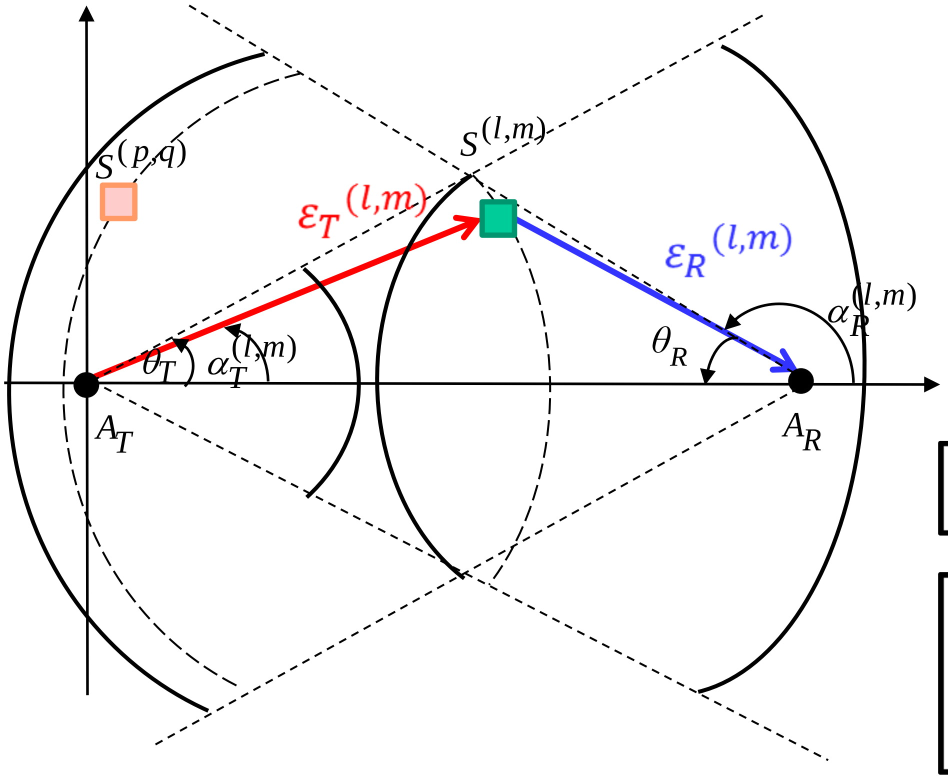


$$A_{LoS} = \frac{\lambda\sqrt{G_T G_R}}{4\pi D^{\gamma/2}}$$

$$\tau_{LoS} = \frac{D}{c_0}$$

$$h^{LoS}(\tau) = \sqrt{\frac{K}{K+1}} A_{LoS} e^{j\phi_{LoS}} \delta(\tau - \tau_{LoS})$$

❖ Single-Reflected Ray



$$A_{l,m} = \frac{\lambda\sqrt{G_T G_R}}{4\pi\left(\varepsilon_T{}^{(l,m)} + \varepsilon_R{}^{(l,m)}\right)^{\gamma/2}}$$

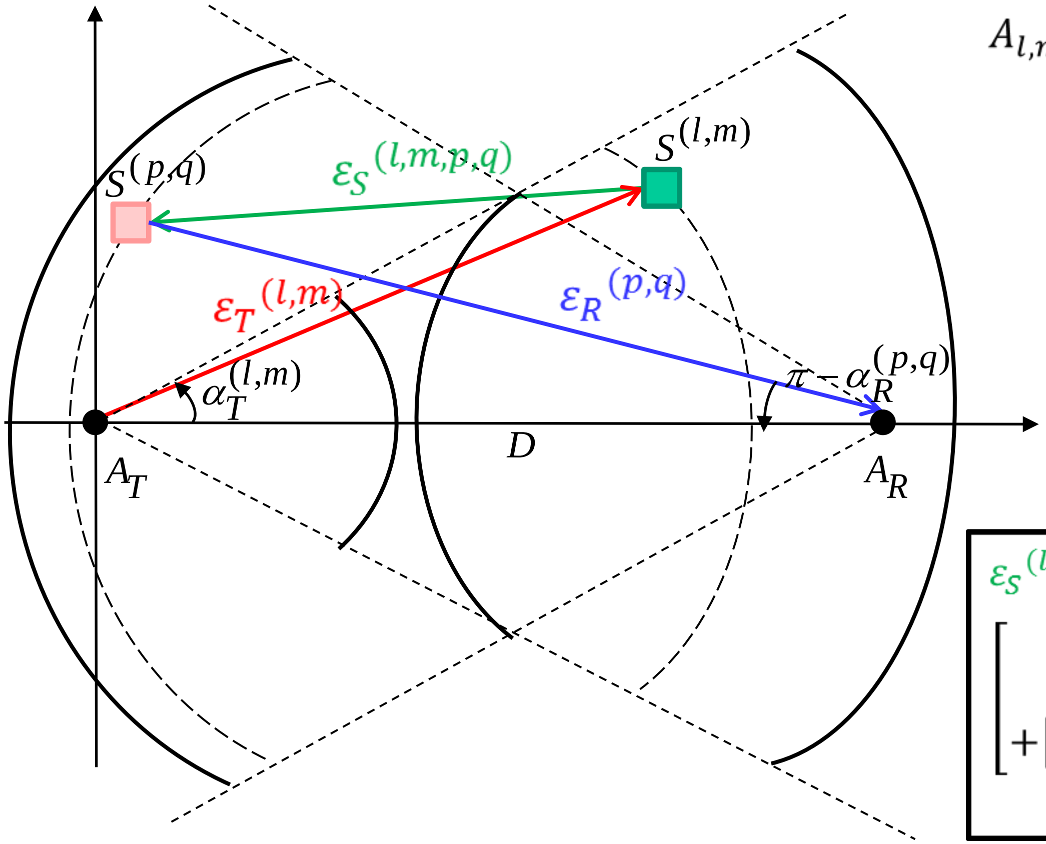
$$\tau_{l,m} = \frac{\varepsilon_T{}^{(l,m)} + \varepsilon_R{}^{(l,m)}}{c_0}$$

$$\boxed{\varepsilon_T{}^{(l,m)} = R_t{}^{(l)}}$$

$$\boxed{\varepsilon_R{}^{(l,m)} = \frac{R_t{}^{(l)}\cos\alpha_T{}^{(l,m)} - D}{\cos\left[\tan^{-1}\left(-\frac{R_t{}^{(l)}\sin\alpha_T{}^{(l,m)}}{D - R_t{}^{(l)}\cos\alpha_T{}^{(l,m)}}\right) + \pi\right]}}$$

$$h^{SR}(\tau) = \sqrt{\frac{\eta_{SR}}{K+1}}\lim_{M\to\infty}\frac{1}{\sqrt{M}}\sum_{l=1}^{L}\sum_{m=1}^{M^{(l)}} A_{l,m}e^{j\phi_{l,m}}\delta(\tau - \tau_{l,m})$$

❖ Double-Reflected Ray



$$A_{l,m,p,q} = \frac{\lambda\sqrt{G_T G_R}}{4\pi\left(\varepsilon_T{}^{(l,m)} + \varepsilon_R{}^{(l,m)} + \varepsilon_S{}^{(l,m,p,q)}\right)^{\gamma/2}}$$

$$\tau_{l,m,p,q} = \frac{\varepsilon_T{}^{(l,m)} + \varepsilon_R{}^{(l,m)} + \varepsilon_S{}^{(l,m,p,q)}}{c_0}$$

$$\boxed{\varepsilon_T{}^{(l,m)} = R_t{}^{(l)}} \quad \boxed{\varepsilon_R{}^{(p,q)} = R_r{}^{(p)}}$$

$$\boxed{\begin{aligned}&\varepsilon_S{}^{(l,m,p,q)} = \\ &\left[\begin{aligned}&\left|R_t{}^{(l)}\sin\alpha_T{}^{(l,m)} - R_r{}^{(p)}\sin\alpha_R{}^{(p,q)}\right|^2 \\ &+\left|R_t{}^{(l)}\cos\alpha_T{}^{(l,m)} - R_r{}^{(p)}\cos\alpha_R{}^{(p,q)} - D\right|^2\end{aligned}\right]^{1/2}\end{aligned}}$$

$$h^{DR}(\tau) = \sqrt{\frac{\eta_{DR}}{K+1}} \lim_{M,Q\to\infty} \frac{1}{\sqrt{MQ}} \sum_{l,m=1}^{L,M^{(l)}} \sum_{p,q=1}^{P,Q^{(p)}} A_{l,m,p,q} e^{j\phi_{l,m,p,q}} \delta(\tau - \tau_{l,m,p,q})$$

❖Distribution of Scatterers

- AoD's ($\alpha_T{}^{(l,m)}$), AoA's, ($\alpha_R{}^{(p,q)}$), and sector radii ($R_t{}^{(l)}$, $R_r{}^{(p)}$) are independent and uniformly distributed random variables.
  - Such a distribution implies that the scatterers will have a uniform density between the concentric-sectors, if the scattering is isotropic

- The joint PDF:

$$f(R,\alpha) = f(R) \cdot f(\alpha) = \frac{2R}{(\alpha_2 - \alpha_1)({R_2}^2 - {R_1}^2)}$$

- Phases (ϕ_{LoS}, $\phi_{l,m}$, $\phi_{l,m,p,q}$) are uniformly distributed random variables on the interval [-π, π), and independent from any other R.V.'s

❖ Correlation Function

- Transfer function is the FFT pair of the delay-spread function

$$T(f) = \mathcal{F}\{h(\tau)\} = T^{LoS}(f) + T^{SR}(f) + T^{DR}(f)$$

- Frequency Correlation Function (FCF) is a measure of the channel's frequency selectivity; an indicator of a required frequency difference (Δf) between sample points for the values to be effectively uncorrelated

$$\mathrm{R}(\Delta f) = \frac{E[T^*(f)\,T(f + \Delta f)]}{\sqrt{VAR[T^*(f)]VAR[T(f + \Delta f)]}}$$

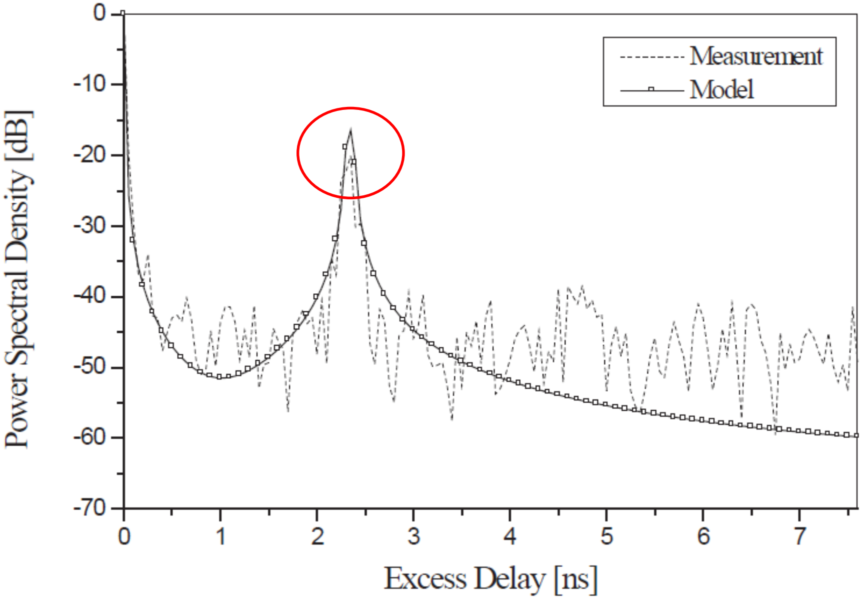
- Since $T^{LoS}(f)$, $T^{SR}(f)$, $T^{DR}(f)$ are independent zero-mean complex Gaussian random processes,

$$\mathrm{R}(\Delta f) = R^{LoS}(\Delta f) + R^{SR}(\Delta f) + R^{DR}(\Delta f)$$

❖ Reference Model Validation

- LoS desktop scenario (300~320 GHz) :

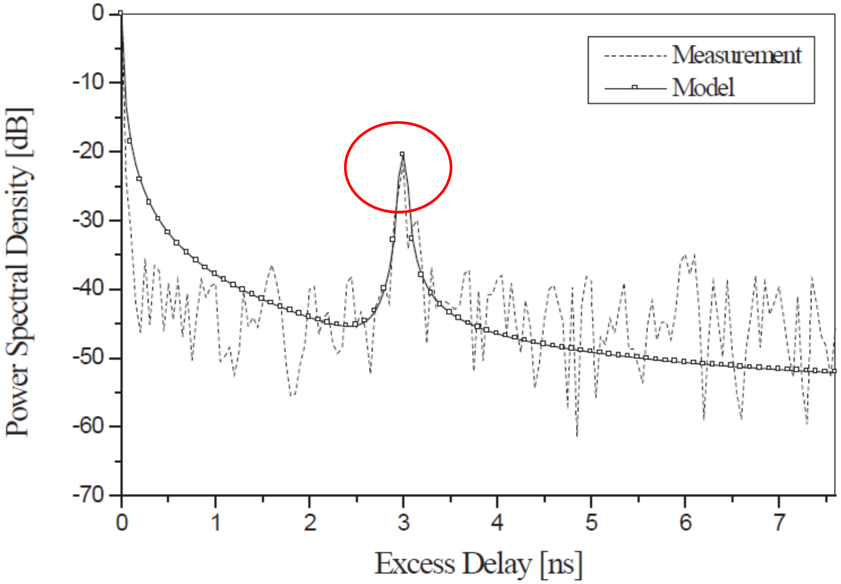
$$2\theta_T = 2\theta_R = 10^{\circ}, \eta_{SR} = 0, \eta_{DR} = 1, \quad K = 0.4$$



D = 30cm

$$R_{t1} = R_{r1} = 32\text{cm}$$

$$R_{t2} = R_{r2} = 33\text{cm}$$



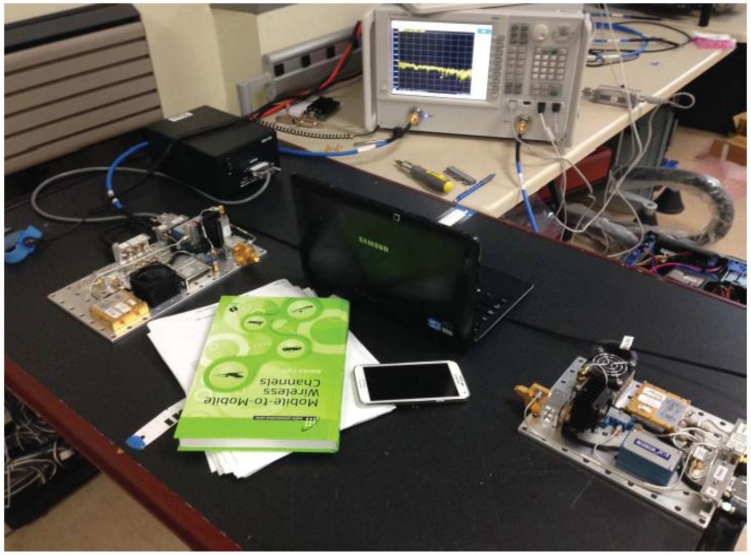
D = 40cm

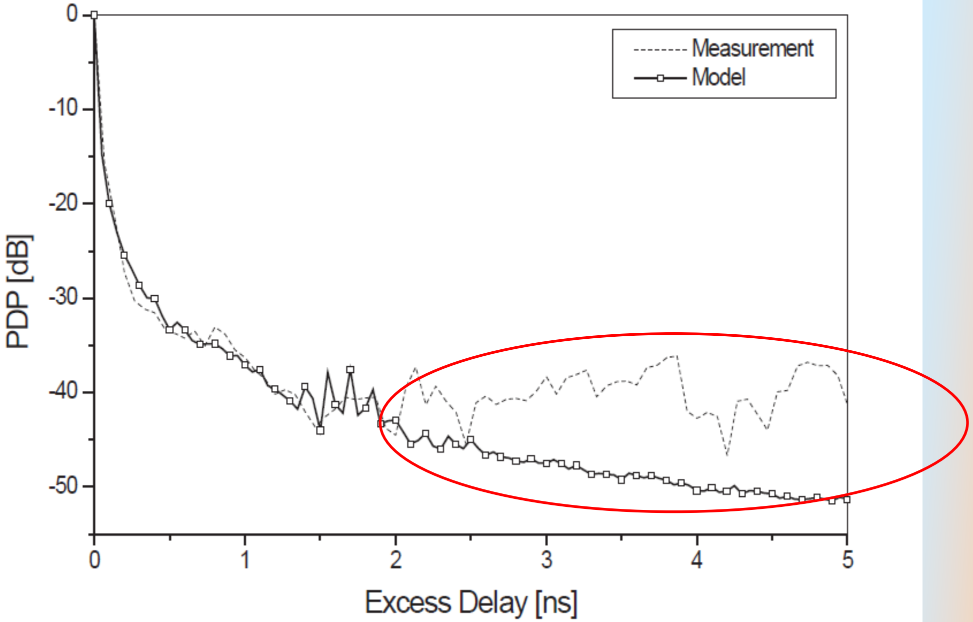
$$R_{t1} = R_{r1} = 42\text{cm}$$

$$R_{t2} = R_{r2} = 43\text{cm}$$

❖ Reference Model Validation

- ➢ Realistic desktop scenario with clutters (300~320 GHz) :





$\eta_{SR} = 0.3, \eta_{DR} = 0.7,$

$K = 0.5$

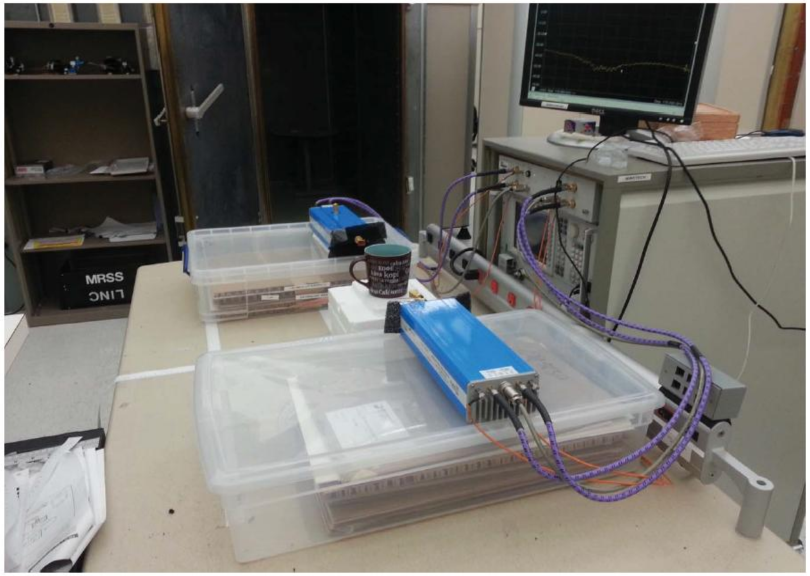
D = 55cm

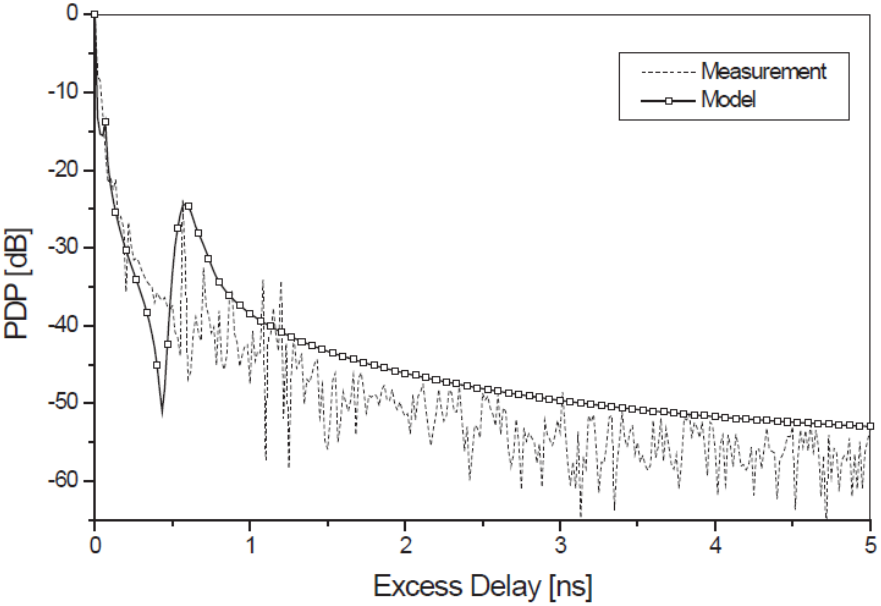
$R_{t1} = R_{r1} = 10\text{cm}$

$R_{t2} = R_{r2} = 50\text{cm}$

❖ Reference Model Validation

- NLoS desktop scenario with cylindrical obstruction (110~170 GHz) :





$\eta_{SR} = \eta_{DR} = 0.5,$

$K = 0.15$

D = 35.56 cm

$R_{t1} = R_{r1} = 21.5$ cm

$R_{t2} = R_{r2} = 22.5$ cm

❖Research Challenges

- Cost and energy efficient transceivers
- Antenna design for efficient communication over small distances
- Channel modeling at THz frequencies
- Low-complexity modulation and coding schemes
- Channel equalization over wide frequency bandwidth
- Medium access protocols suitable for ultra-dense networks

THANK YOU

Questions?