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Submission Title: Statistical Multi-path Propagation Modeling and Fading Analysis in Terahertz Band Communication Networks

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Source: Chong Han, Josep Miquel Jornet and Ian F. Akyildiz, Georgia Institute of Technology
Address: 777 Atlantic Drive NW, Atlanta, GA 30332, USA
Voice: +1 404 894 6616, Fax:+1 404 894 7883, E-Mail: {chong.han, jmjornet, ian}@ece.gatech.edu

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Abstract: In Terahertz Band, molecular absorption and rough surface scattering exert significant impact on ultra-broadband channels, which make the existing multipath models inaccurate for Terahertz communication. In this work, a statistical multi-path channel is proposed for indoor environment, which captures: (i) the spreading loss and molecular absorption loss in free space propagation, by means of radiative transfer theory, and (ii) multi-path fading loss due to stochastically distributed scatters. The resulting distance-dependent channel behavior requires the development of dynamic distance-adaptive solutions for Terahertz Band communication networks.

Purpose: Statistical Multi-path channel model in Terahertz Band.

Statistical Multi-path Propagation Modeling and Fading Analysis in Terahertz Band Communication Networks

Chong Han, Josep Miquel Jornet and Ian F. Akyildiz

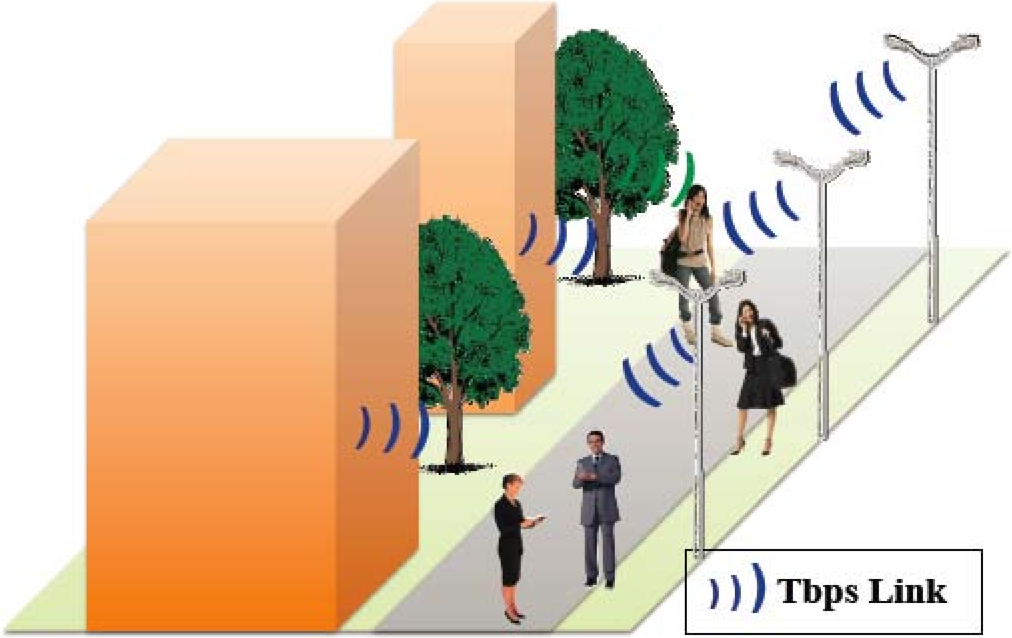
Broadband Wireless Networking Laboratory
School of Electrical and Computer Engineering
Georgia Institute of Technology
http://www.ece.gatech.edu/research/labs/bwn/

Outline

- Introduction
- Related Work
- Free Space Propagation Model
- Specular Scattering Model
- Statistical Multi-path Channel Model
- Conclusions

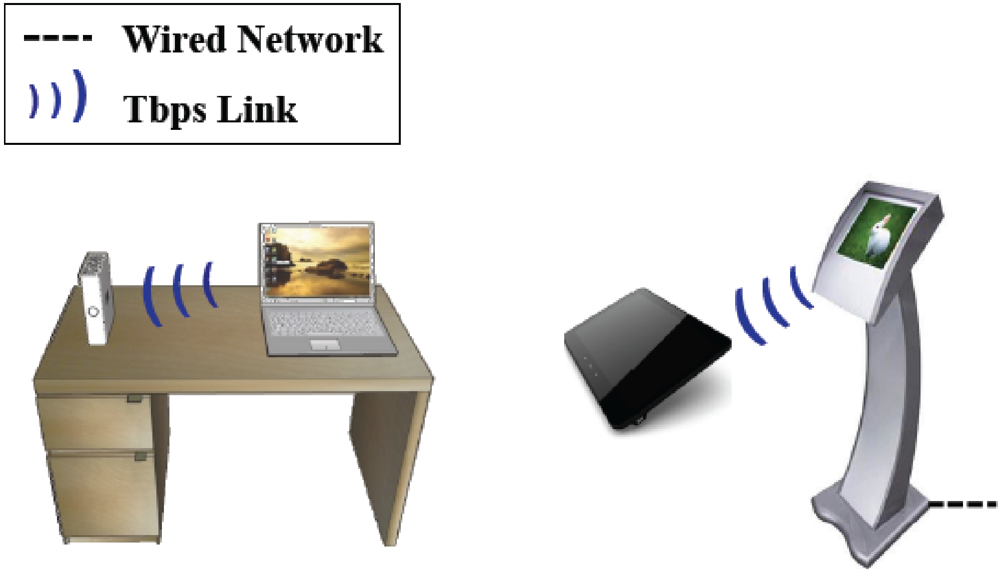
Terahertz Band Communication Applications in the Macroscale (1)

- Ultra-high-speed cellular networks
  - Terahertz Band communication can be used in future *small-cell systems*, i.e., as a part of hierarchical cellular networks



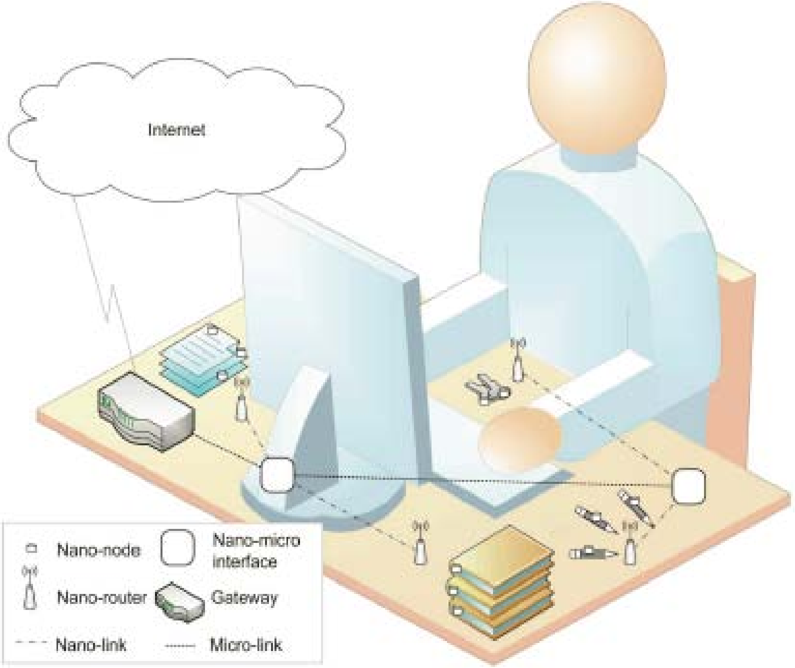
Terahertz Band Communication Applications in the Macroscale (2)

- Terabit/second (Tbps) short-range interconnected devices
  - Tbps links among devices in close proximity are possible with Terahertz Band communication (e.g., multimedia kiosks).



Terahertz Band Communication Applications in the Nanoscale

- Nanoscale machine communication and networks
  - The state of the art in nanoscale antennas and transceiver design points to the Terahertz Band as the frequency range for nano-machines communication



EM Wave Transmission Scheme

- Multi-path is present in many scenarios
  - both in classical networking scenarios, such as in small cell systems, as well as novel networking paradigms at the nanoscale

- High-directivity/gain antennas (e.g., 35 dBi) are advocated
  - Combat the channel impairments
  - Infeasible for mobile devices
  - Impossible for nano-antennas

→ We need generic multi-path channel model for Terahertz Band

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Relevant Multi-path Channel Model (1)

- Rayleigh and Rician fading models assume that
  - There is a large number of statistically independent reflected and scattered path
  - Each tap gain is modeled as a circular symmetric Complex Gaussian random variable

  →The magnitude of each channel tap follows a Rayleigh distribution when LOS is absent and a Rician distribution when LOS is dominant

- However, these models neglect the high propagation loss and scattering loss of THz Band communication

Relevant Multi-path Channel Model (2)

Priebe, S., Jacob, M., Kürner, T., “AoA, AoD and ToA Characteristics of Scattered Multipath Clusters for THz Indoor Channel Modeling”, 17th European Wireless Conference (EW), April 2011

- Existing Terahertz multi-path channel models
  - Capture the peculiarities of the EM wave transmission in Terahertz Band
  - Conduct ray-tracing techniques to measure the channel response at 300 GHz
- However, these models are subject to specific experimental settings and focus on the single transmission window (300 GHz) instead of the entire Terahertz Band
- Therefore, an analytical multi-path channel model that is adaptive for stochastically varying scenarios and generic for the entire Terahertz Band is demanded

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Motivation for Free Space Channel Model in Terahertz Band

- Due to the very high attenuation created by molecular absorption, current efforts both on:
  - device development and
  - channel characterization

  are focused on the absorption-defined window at 300 GHz with transmission distance in the order of meters

- However, some of the properties of this band in the very short range and higher frequencies need to be better understood and analyzed

Terahertz Band Free Space Channel Model

J. M. Jornet and I. F. Akyildiz, “Channel Modeling and Capacity Analysis of Electromagnetic Wireless Nanonetworks in the Terahertz Band”, IEEE Trans. On Wireless Communications, October 2011

- Based on the radiative transfer theory, the free space frequency response consists of
  - Spreading loss: accounts for the attenuation due to the expansion of the wave as it propagates in the medium
  - Absorption loss: accounts for the attenuation that the propagating wave suffers because of molecular absorption, i.e., the process that the EM wave energy is converted into vibrational kinetic energy in gaseous molecules

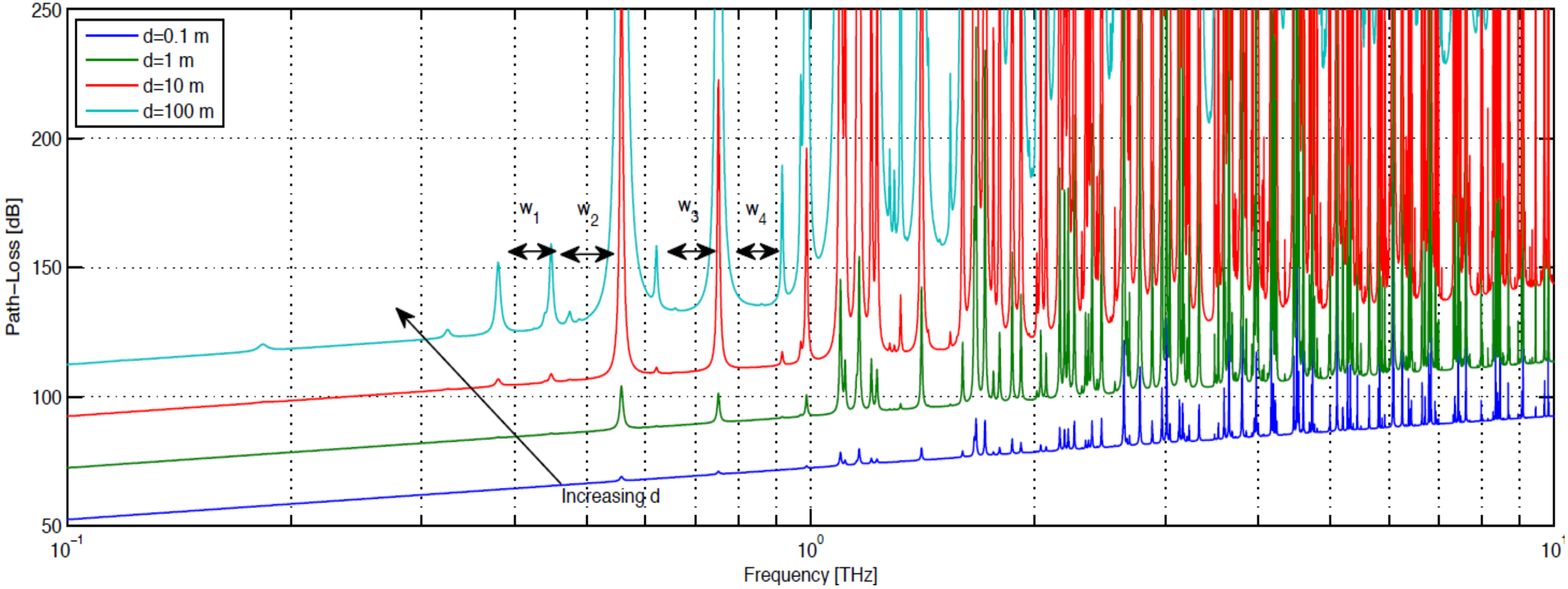
$$H^{LOS}(f,r) = H_{spread}(f,r) \cdot H_{abs}(f,r) = \left(\frac{c}{4\pi fr} \right) e^{-j2\pi fr/c} e^{-\frac{1}{2}k(f)r}$$

Parameter Notations

- H_{spread} : spreading loss
- H_{abs} : molecular absorption loss
- c : speed of light
- f : signal frequency
- r : transmission distance (Tx-Rx)
- $k(f)$: frequency-dependent medium absorption coefficient, dependent on the system pressure in atm, the temperature in Kelvin, the molecular volume density in molecules/m^3 and the molecular absorption cross-section m^2/molecule

$$k(f)=\sum_{i,g}\frac{p}{p_0}\frac{T_{\mathrm{STP}}}{T}Q^{i,g}\sigma^{i,g}(f)$$

LOS Path-loss in dB



- The Terahertz Band communication channel has a strong dependence on:
  - Signal frequency
  - Transmission distance

Terahertz Band Free Space Channel Properties

- In Terahertz Band, free space channel path-loss increases with frequency due to the spreading loss
- The path-loss can easily go above 100 dB for transmission distances in the order of just a few meters
- The molecular absorption defines several transmission windows (w1, w2, w3, w4), whose position and width depend on the transmission distance
  - For longer transmission links, more molecular resonances become significant, and the windows become narrower
  - For short range (less than 1m) communication, Terahertz Band offers incredibly huge bandwidth (almost a 10 THz wide window)

Terahertz Band LOS Channel Additional Challenges

- Obtain realistic numbers for the achievable transmission rates of different transmission windows
  - account for the transmitter and the receiver antenna directivity as well as for the gain and noise factor

- Locate the best transmission windows in Terahertz Band in light of information capacity for communication with different transmission distances

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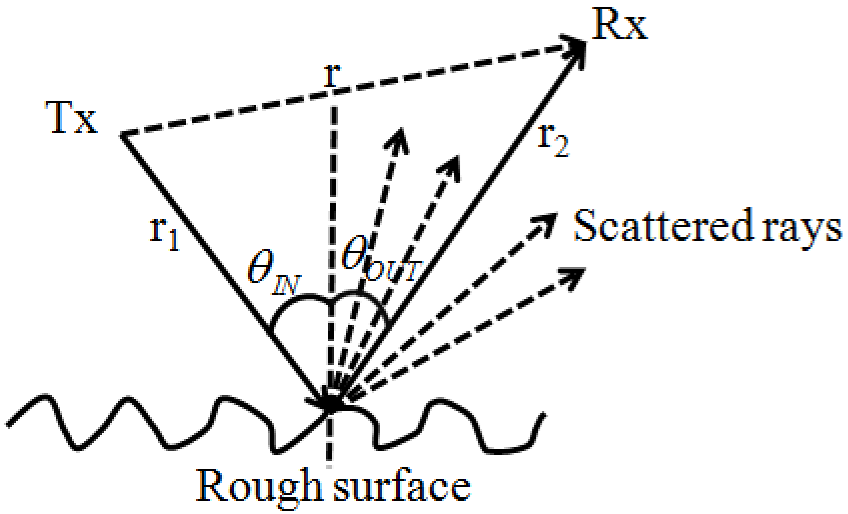
Terahertz Band Reflection Challenge

- When the LOS is blocked by moving people or obstacles, NLOS scenario is considered
  - Introduces the rough surface scattering loss in addition to the free space propagation loss
- Origin: wavelength of EM wave in the Terahertz Band is [0.03 mm, 3 mm]
- Any surface with roughness comparable to the wavelength
  - Scatters the EM wave
  - Has to be considered as rough surface

Terahertz band Specular Scattering Model Considerations

- Scattered rays have no significant contribution to the received signal
- Rays which suffer from multiple consecutive reflections have no significant contribution to the received signal
- No cross-polarization occurs in forward scattering directions (including the specular direction)
- We consider the specular scattering only ($\theta_{IN} = \theta_{OUT}$)



Notations:

r: transmission distance between Tx and Rx

r_1: distance between Tx and the scatter

r_2: distance between the scatter and Rx

θ_{IN} : incident angle of the transmission wave

Reflection Coefficient of Rough Surface

R. Piesiewicz, T. Kurner, “Scattering analysis for the modeling of THz communication systems”, IEEE Transactions on Antennas and Propagation, Nov. 2007

P. Beckmann and A. Spizzichino, “The scattering of electromagnetic waves from rough surfaces," Norwood, MA, Artech House, Inc., 1987

- Definition: the received signal amplitude loss with reference to the incident signal at the scattering point
- Includes the scattering loss as well as the propagation loss between the scatter and the receiver
- The assumptions are
  - In practice when the scattering surface area is large
  - The specularly reflected signal is contained in a single reflected ray as if there is no scattering occurred due to edge effects
  - The effect of the surface roughness is captured in the Rayleigh roughness coefficient

Terahertz Band Specular Scattering Model

- According to Kirchhoff theory for rough surface, the reflection coefficient is obtained as the multiplication of the smooth surface reflection coefficient derived from the Fresnel equations with the Rayleigh roughness factor

$$R(f, r_2, \theta_{IN}) = \left(\frac{2A\cos(\theta_{IN})}{fr_2}\right)\gamma_{TE}\rho$$

A: scattering surface area

- The complete NLOS channel frequency response is

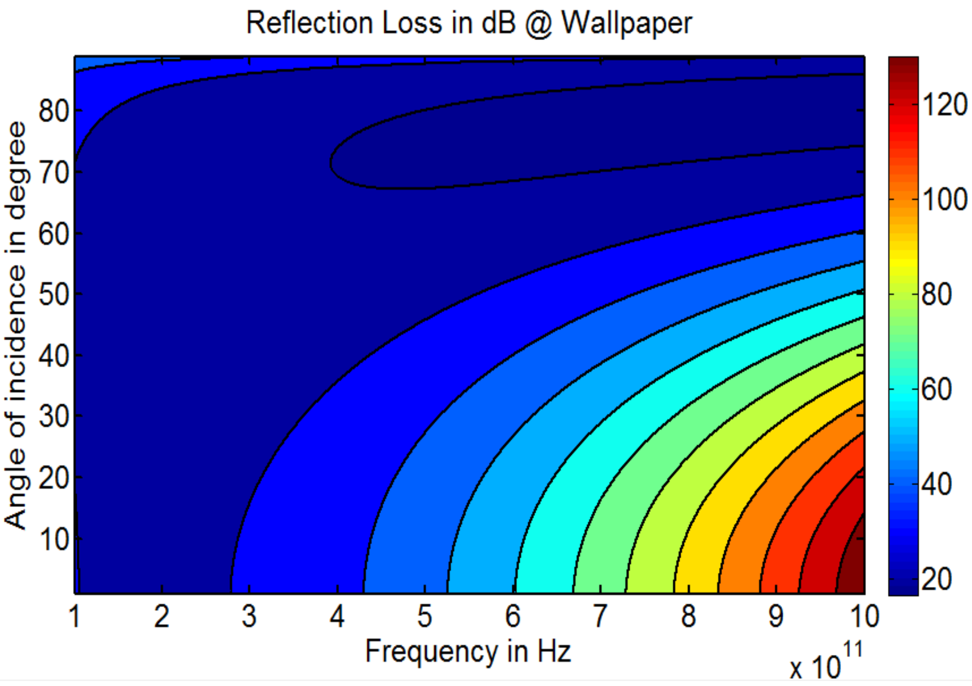
$$H^{NLOS}(f, r_1, r_2, \theta_{IN}) = H_{spread}(f, r_1)H_{abs}(f, r_1)R(f, r_2, \theta_{IN}) = \left(\frac{c^2 A\cos(\theta_{IN})}{2\pi f^2 r_1 r_2}\right)\gamma_{TE}\rho e^{\left(-j\frac{2\pi f r_1}{c} - \frac{1}{2}k(f)r_1\right)}$$

where γ_{TE} : Reflection coefficient of smooth surface for TE part

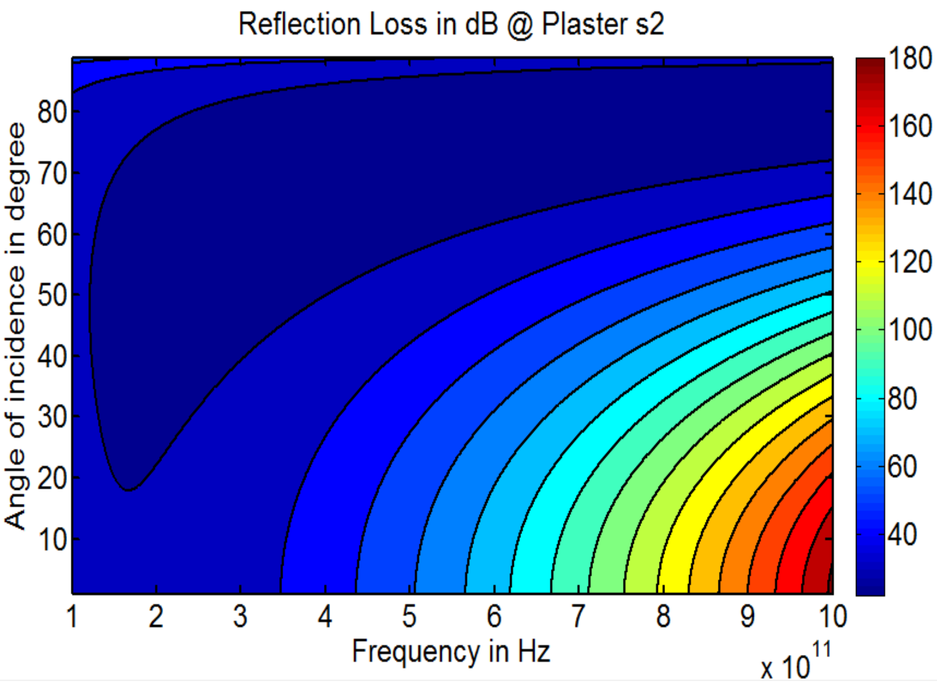
ρ : Rayleigh roughness factor

Reflection Coefficient for Different Materials

- Reflection loss is dependent on the material of rough surface and increases when
  - Angle of incidence wave decreases
  - Frequency increases



Reflection Loss in dB @ Wallpaper



Reflection Loss in dB @ Plaster s2

Terahertz Band NLOS Channel Additional Challenges

- There is a need to determine the reflection coefficients for common materials (e.g., ingrain wallpaper and plaster in indoor environments) for the entire Terahertz Band, in order to obtain realistic values for NLOS path-loss

- NLOS communication deployed with directed reflection on dielectric mirrors will be studied as supplementary for the case when LOS is unavailable

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Statistical Multi-path Channel Model

- The multi-path channel frequency response is

$$H(f,r)=\alpha_{LOS}\,|H^{LOS}(f,r)|\,\mathrm{e}^{-j2\pi f\tau_{LOS}}+\sum_{i=1}^{L_p}|H^{NLOS}(f,\zeta_i)|\,\mathrm{e}^{-j2\pi f\tau_i}$$

Notations:

$\alpha_{LOS}\sim\mathrm{Bernoulli}(P_\alpha)$: the indicator of the LOS

$L_p=a_1\mathrm{e}^{-a_2 r},\quad a_1,a_2>0$: the number of NLOS Multi-Path Components (MPCs) and an indicator of the density of the scatters and reflectors

$\tau_{LOS}=\frac{r}{c},\tau_i=\frac{r_{i1}+r_{i2}}{c}-\frac{\angle\phi_i}{2\pi f}$: the LOS and i^{th} NLOS propagation delay

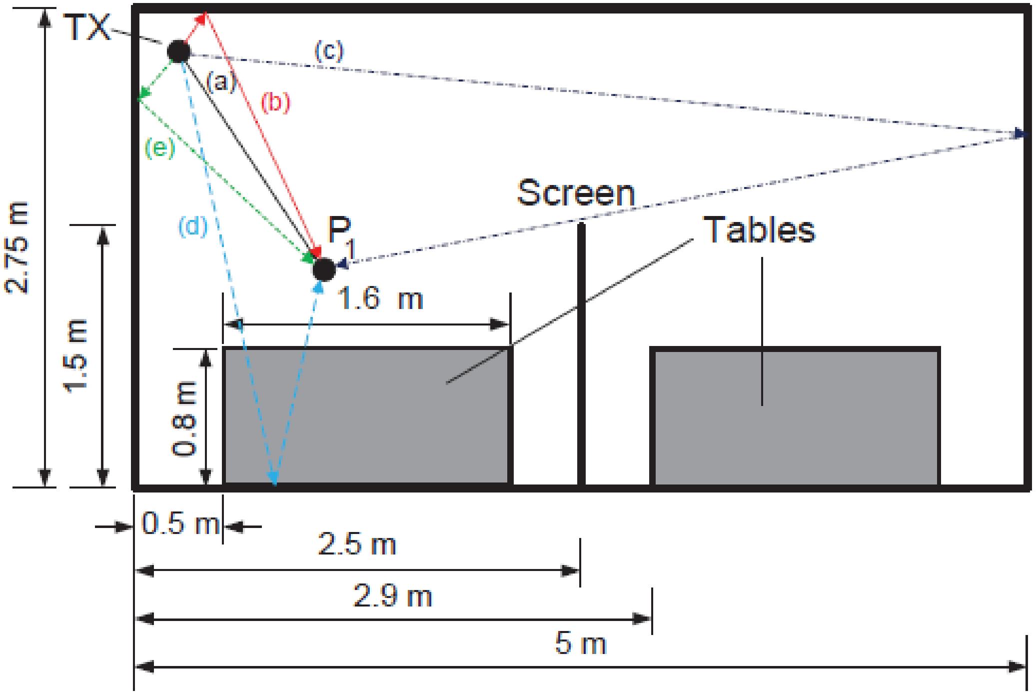
$\angle\phi_i$: the phase change at the scatter

$\zeta_i=(r_{i1},r_{i2},\theta_{iIN})$: i^{th} scatter location

One Static Indoor Scenario

Priebe, S., Jacob, M., Kürner, T., "AoA, AoD and ToA Characteristics of Scattered Multipath Clusters for THz Indoor Channel Modeling", 17th European Wireless Conference (EW), April 2011

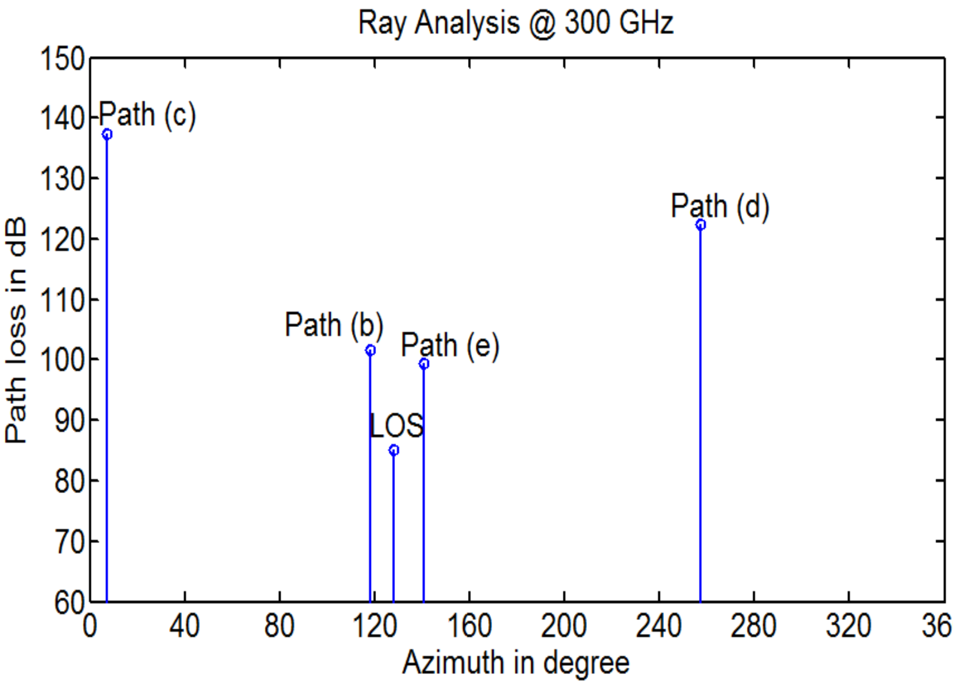
- Aim: validate our channel model by verifying in one deterministic setting case
- Indoor scenarios with scattering on Plaster s2
  - Frequency = 300 GHz
  - Tx location: (0.25 m, 2.5 m, 2.3 m)
  - Rx location: (1.125 m, 1.375 m, 2.3 m)

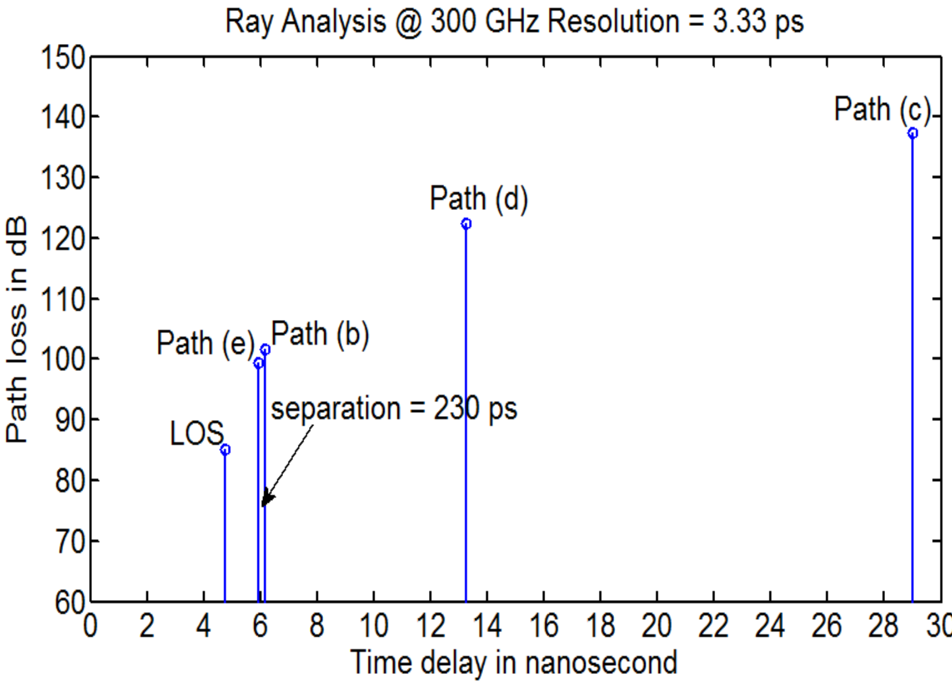


Individual Ray Analysis

- LOS ray arrives first and has the smallest path-loss in dB
  - Smallest free space propagation loss since it travels the shortest distance
  - No scattering loss

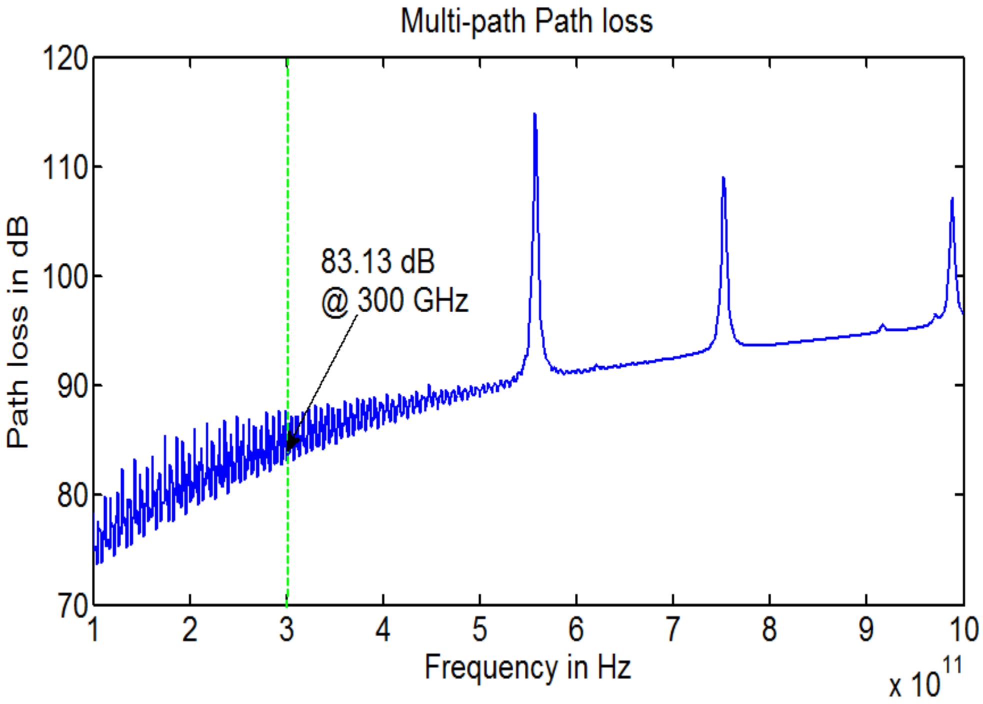
- Two rays are resolvable only if the difference of their Time-of-Arrival (ToA) is larger than 3.33 ps for 300 GHz EM wave





Multi-path Channel Loss Analysis

- Fast fading
  - Due to constructive and destructive interference of the multiple signal paths
  - Characterizes the rapid fluctuations of the received signal strength over short distances or short time duration.
  - Path-loss is 83.13 dB at 300 GHz



Simulation results of our model match with those using ray-tracing techniques

Expected Multi-path Channel Frequency Response

- The p.d.f. of the multi-path channel is

$$P_H(H(f,r)) = \int_z \sum_{\alpha_{LOS}} P_H(H(f,r) \mid z, \alpha_{LOS}) P_{\alpha_{LOS}}(\alpha_{LOS}) f_z(z) d_z \quad , z = [(\zeta_i, \phi_i), i = 1, \ldots, L_P]$$

- The expected channel frequency response can be calculated as

$$E_H[H(f,r)] = E_{z,\alpha_{LOS}}[E_H[H(f,r) \mid z, \alpha_{LOS}]]$$

$$= P_\alpha \mid H_{LOS}(f,r) \mid e^{-j2\pi f \tau_{LOS}} + \sum_{i=1}^{L_P} \int_z E[\mid H_{NLOS}(f,r,\zeta_i) \mid e^{-j2\pi f \tau_i} \mid z] f_z(z) d_z$$

Analytical Form of Expected Channel Frequency Response

- Scatter locations follow Uniform distributions

$$E_H[H(f,r)] = P_\alpha \,|H_{LOS}(f,r)|\, e^{-j2\pi f \tau_{LOS}} + \sum_{i=1}^{L_P}\int_z E[|H_{NLOS}(f,r,\zeta_i)|\, e^{-j2\pi f \tau_i} \,|\, z] f_z(z) d_z$$

  - When r is large $\tau_i = \frac{r_{i1}+r_{i2}}{c} - \frac{\phi_i}{2\pi f}, -j2\pi f \tau_i \sim U[0,2\pi]$

$$E_H[H(f,r)] = P_\alpha \,|H_{LOS}(f,r)|\, e^{-j2\pi f \tau_{LOS}}$$

  - When r is small

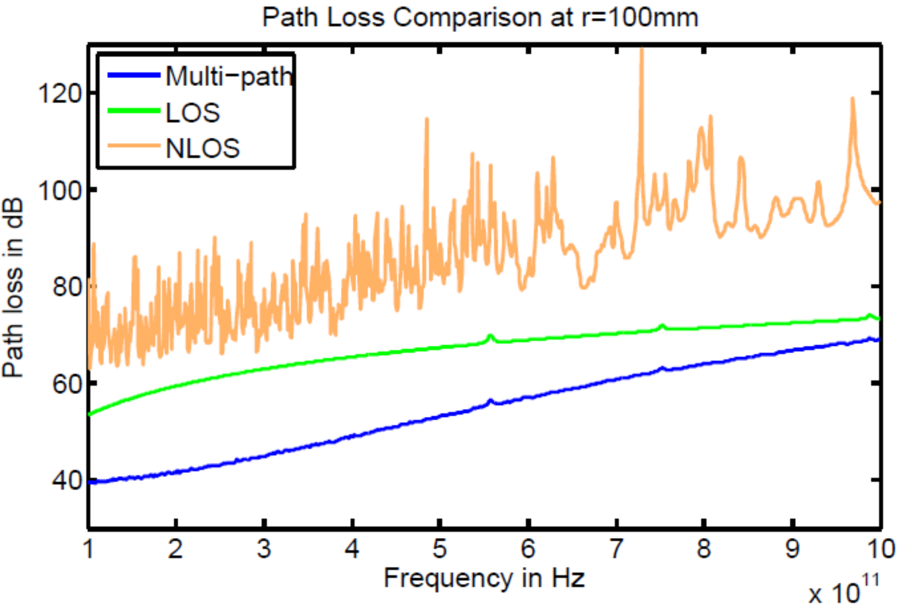
$$E_H[H(f,r)] = P_\alpha \,|H_{LOS}(f,r)|\, e^{-j2\pi f \tau_{LOS}} + \sum_{i=1}^{L_P}\int_z E[|\frac{c}{4\pi f r_{i1}} e^{-\frac{1}{2}k(f) r_{i1}} \frac{2Ac\cos(\theta_{iIN})}{f r_{i2}} \gamma\rho \,|\, e^{-j\frac{2\pi f}{c}(r_{i1}+r_{i2})} e^{j\phi_i} \,|\, z] f_z(z) d_z$$

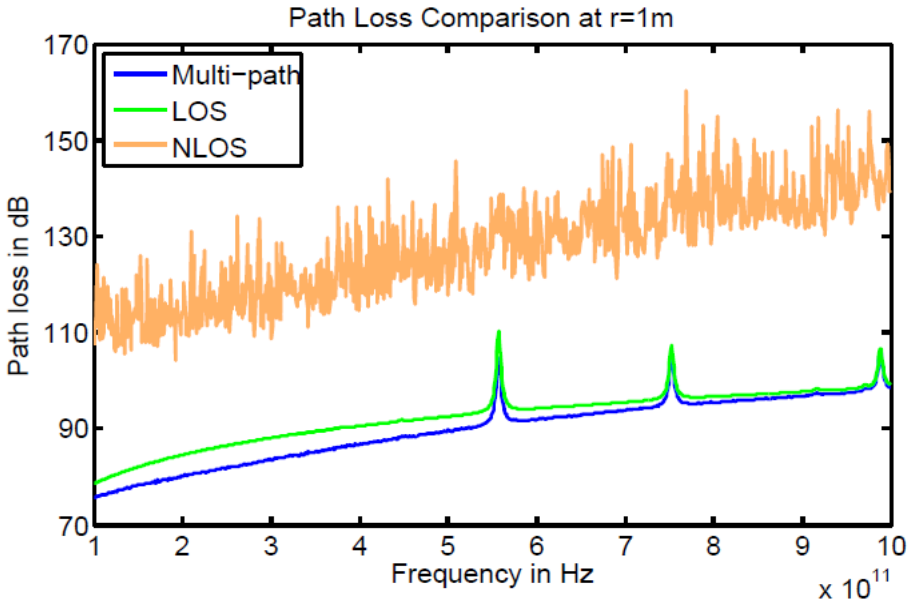
$$= P_\alpha \,|H_{LOS}(f,r)|\, e^{-j2\pi f \tau_{LOS}} + \sum_{i=1}^{L_P}\int_z E[|\gamma|\rho \frac{c}{4\pi f r_{i1}} e^{(-\frac{1}{2}k(f) - j\frac{2\pi f}{c}) r_{i1}} \frac{2Ac\cos(\theta_{iIN})}{f r_{i2}} e^{-j\frac{2\pi f}{c} r_{i2}} e^{j\phi_i} \,|\, z] f_z(z) d_z$$

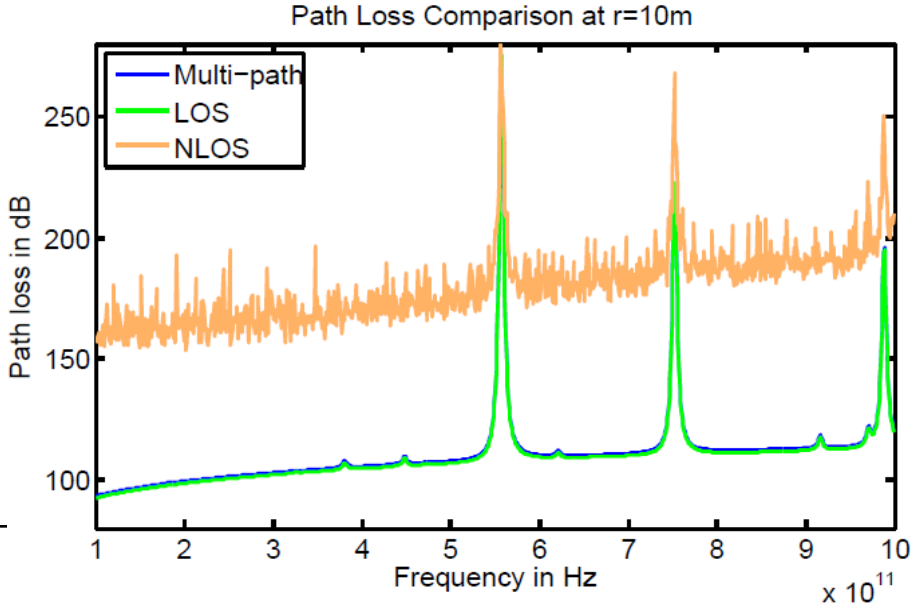
$$\approx P_\alpha \,|\frac{c}{4\pi f r} e^{-\frac{1}{2}k(f) r}\,|\, e^{-j2\pi f\frac{r}{c}} + \sum_{i=1}^{L_P} |\gamma|\rho \frac{c}{4\pi f} \frac{2Ac\cos(\theta_{iIN})}{f} \frac{1}{(r_{i1}^{\max} - r_{i1}^{\min})(r_{i2}^{\max} - r_{i2}^{\min})} 2e^{j\frac{\pi}{2}}.$$

$$[\ln|\frac{r_{i1}^{\max}}{r_{i1}^{\min}}| + \sum_{n=1}^{\infty} \frac{(-\frac{1}{2}k(f) - j\frac{2\pi f}{c})^n ((r_{i1}^{\max})^n - (r_{i1}^{\min})^n)}{n n!}][\ln|\frac{r_{i2}^{\max}}{r_{i2}^{\min}}| + \sum_{n=1}^{\infty} \frac{(-j\frac{2\pi f}{c})^n ((r_{i2}^{\max})^n - (r_{i2}^{\min})^n)}{n n!}]$$

Simulations Results (1)

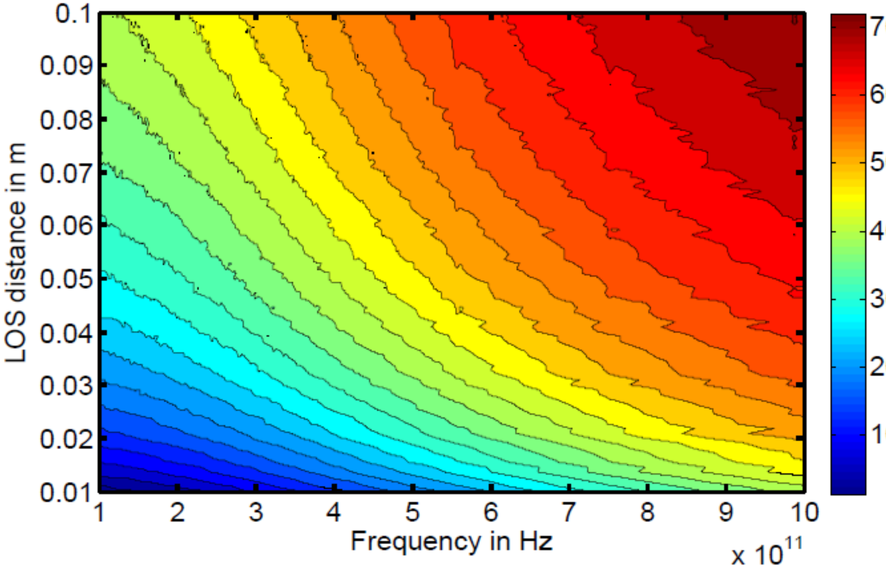




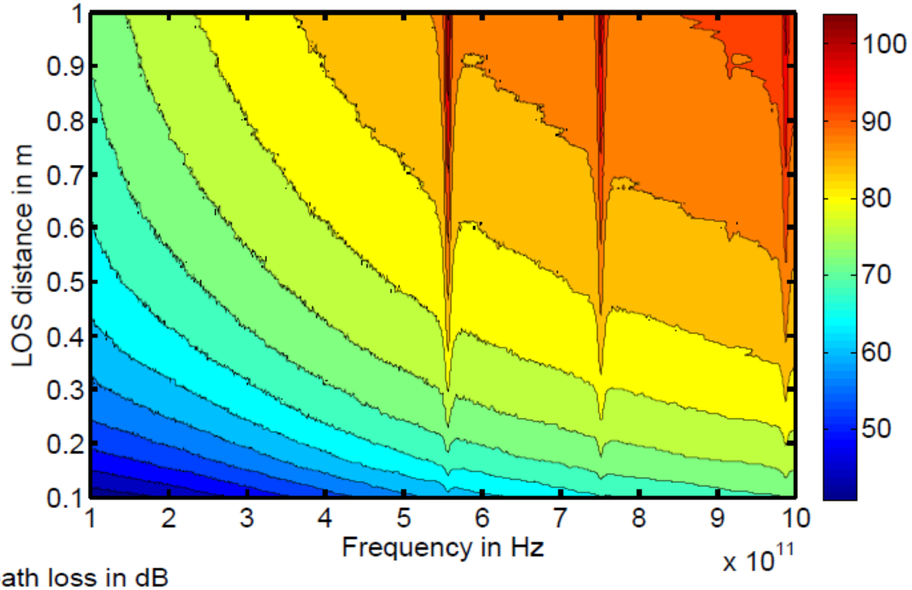


Simulations Results (2)

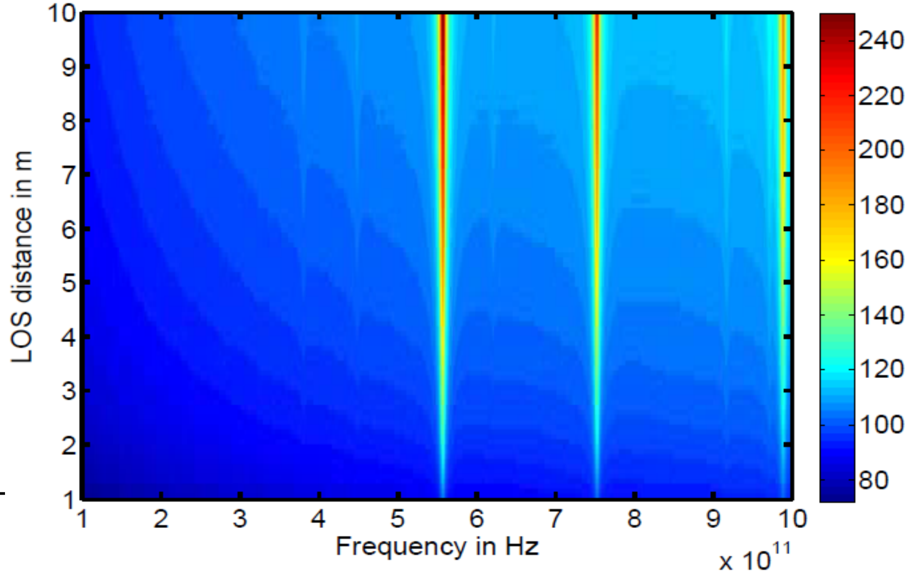
Multi−path channel path loss in dB



Multi−path channel path loss in dB



Multi−path channel path loss in dB



Terahertz Band Multi-path Channel Properties

- The total path-loss of the multi-path channel in the Terahertz Band
  - Increases with the transmission distance as well as the system frequency
  - Depends on the composition of the transmission medium and the properties of the reflected rough surfaces
- For short transmission distances (below one meter)
  - Terahertz Band channel behaves as a single transmission window almost 10-THz wide
  - Multi-path fading plays an important role
- With increasing transmission distance (larger than one meter)
  - The impact of scattered rays diminishes
  - Molecular absorption limits the Terahertz Band channel to a set of multi-GHz-wide windows

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Conclusions

- The proposed multi-path channel model captures
  - Spreading loss and molecular absorption loss in free space propagation, by means of radiative transfer theory
  - Reflection loss due to scattering in rough surfaces, by means of Kirchhoff theory
  - Multi-path fading loss due to stochastically distributed scatters

- The model is adaptive for stochastically varying scenarios and generic for the entire Terahertz Band (0.1 – 10 THz)
  - The simulation is conducted over (0.1 – 1 THz) due to the lack of physical characterization for the materials at beyond frequencies

- The distance-dependent channel behavior requires the development of dynamic distance-adaptive solutions for Terahertz Band communication networks

Thank You!

Chong Han – chong.han@ece.gatech.edu
Josep Miquel Jornet – jmjornet@ece.gatech.edu
Prof. Dr. Ian F. Akyildiz – ian@ece.gatech.edu

Broadband Wireless Networking Laboratory @ Georgia Tech
www.ece.gatech.edu/research/labs/bwn