Developing New Bands for Wireless Communications and Radars in the EHF

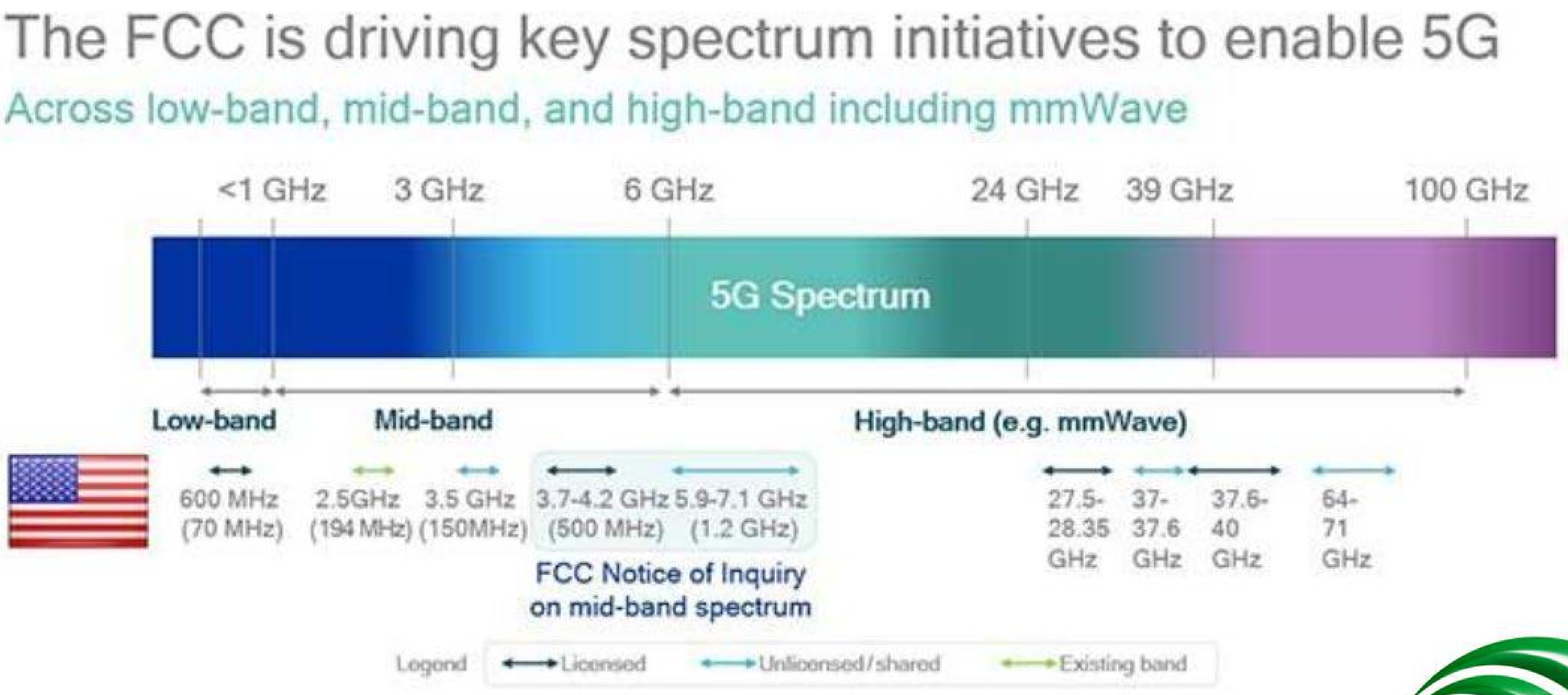
Liat Rapaport, Ariel Etinger
Dr. Gad Pinhasi, Prof. Yosef Pinhasi

November 2018

ARIEL UNIVERSITY

Frequency spectrum for wireless communications

BAND		IEEE	FREQUENCY	WAVELENGTH
Extremely Low Frequency	ELF		3 – 30Hz	
Super Low Frequency	SLF		30 – 300Hz	
Ultra Low Frequency	ULF		300 - 3,000 Hz	1,000 - 100 Km
Very Low Frequency	VLF		3 - 30 KHz	100 – 10 Km
Low Frequency	LF		30 - 300 KHz	10 - 1 Km
Medium Frequency	MF		300 - 3,000 KHz	1 - 0.1 Km
High Frequency	HF		3 - 30 MHz	100 - 10 m
Very High Frequency	VHF		30 - 300 MHz	10 – 1 m
Ultra High Frequency	UHF		300 - 3,000 MHz	1 - 0.1 m
		L	1 - 2 GHz	
		S	2 - 4 GHz	
Super High Frequency	SHF		3 - 30 GHz	10 - 1 cm
		C	4 - 8 GHz	
		X	8 - 12 GHz	
		Ku	12 - 18 GHz	
		K	18 - 26.5 GHz	
		Ka	26.5 - 40 GHz	
Extremely High Frequency	EHF		30 - 300 GHz	1 - 0.1 cm
		V	40 - 75 GHz	
		W	75 - 110 GHz	
Sub-millimeter (TeraHertz)	FIR		300 - 3,000 GHz	1 – 0.1 mm
Mid infra-red	MIR		3 – 30 THz	100 – 10 μm
Near infra-red	NIR		30 – 300 THz	10 – 1 μm


The FCC is driving key spectrum initiatives to enable 5G
Across low-band, mid-band, and high-band including mmWave
<1 GHz
3 GHz
6 GHz
24 GHz
39 GHz
100 GHz
5G Spectrum
Low-band
Mid-band
High-band (e.g. mmWave)
600 MHz (70 MHz)
2.5GHz (194 MHz)
3.5 GHz (150MHz)
3.7-4.2 GHz (500 MHz)
5.9-7.1 GHz (1.2 GHz)
FCC Notice of Inquiry on mid-band spectrum
27.5-28.35 GHz
37-37.6 GHz
37.6-40 GHz
64-71 GHz
Legend
Licensed
Unlicensed/shared
Existing band

*Qualcomm

Outline

Outdoor Challenges

- Atmospheric Attenuation
- Fog Attenuation
- Rain Attenuation

Indoor Challenges

- Quasi-optical Analysis of MMW Propagation
- Fresnel's Equations
- The Effects of Different Building Materials
- The Rayleigh Criterion for Roughness

Two Rays Model

Propagation in Tunnels

- Model Types
- Ray Tracing Model

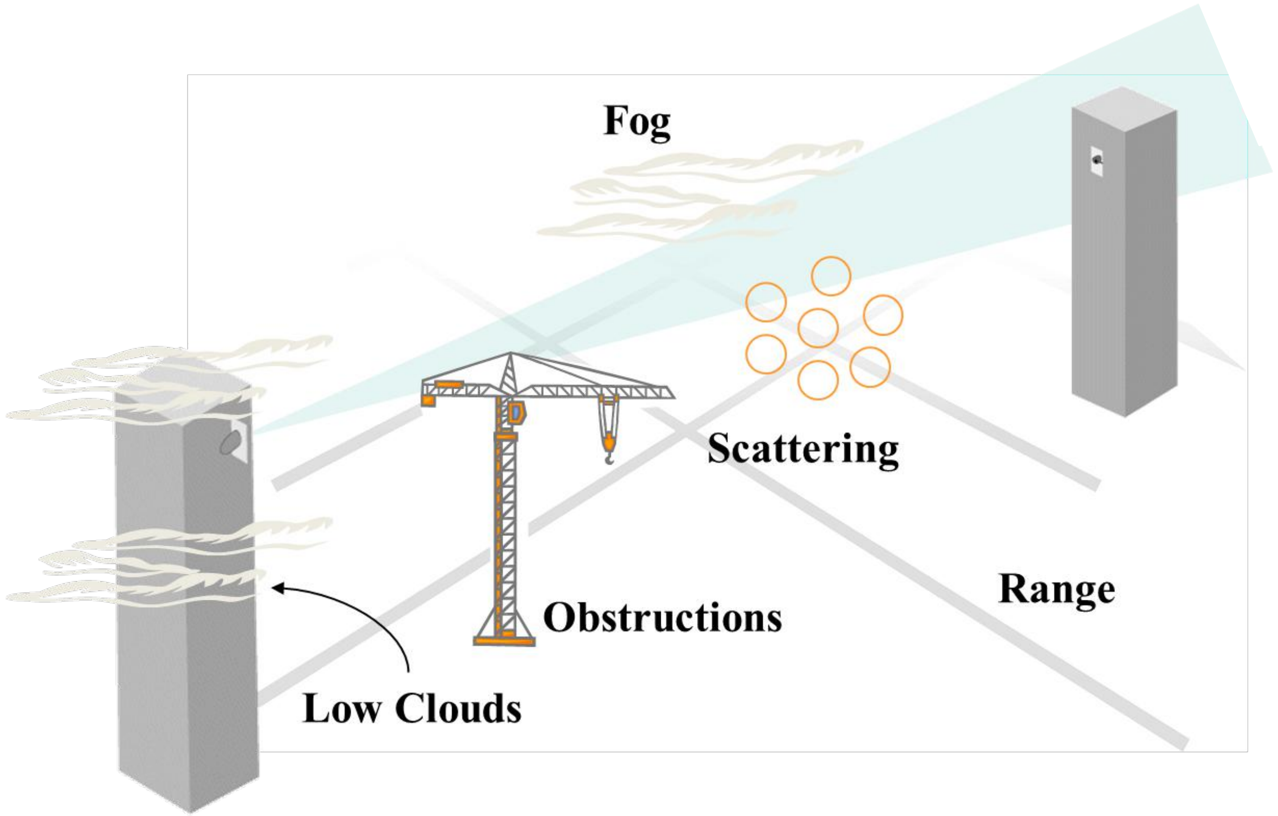
Experiments and Results

Summary and Additional Study

Millimeter Wave Propagation

- Suffers from atmospheric attenuation
- Affected by scattering and absorption
- Reflected by walls

- Useful for densely packed communications networks
- Free spectrum
- Small antennas
- Has frequency reuse potential (due to directivity / atmospheric attenuation)
- Can be analyzed using Geometrical Optics (GO)



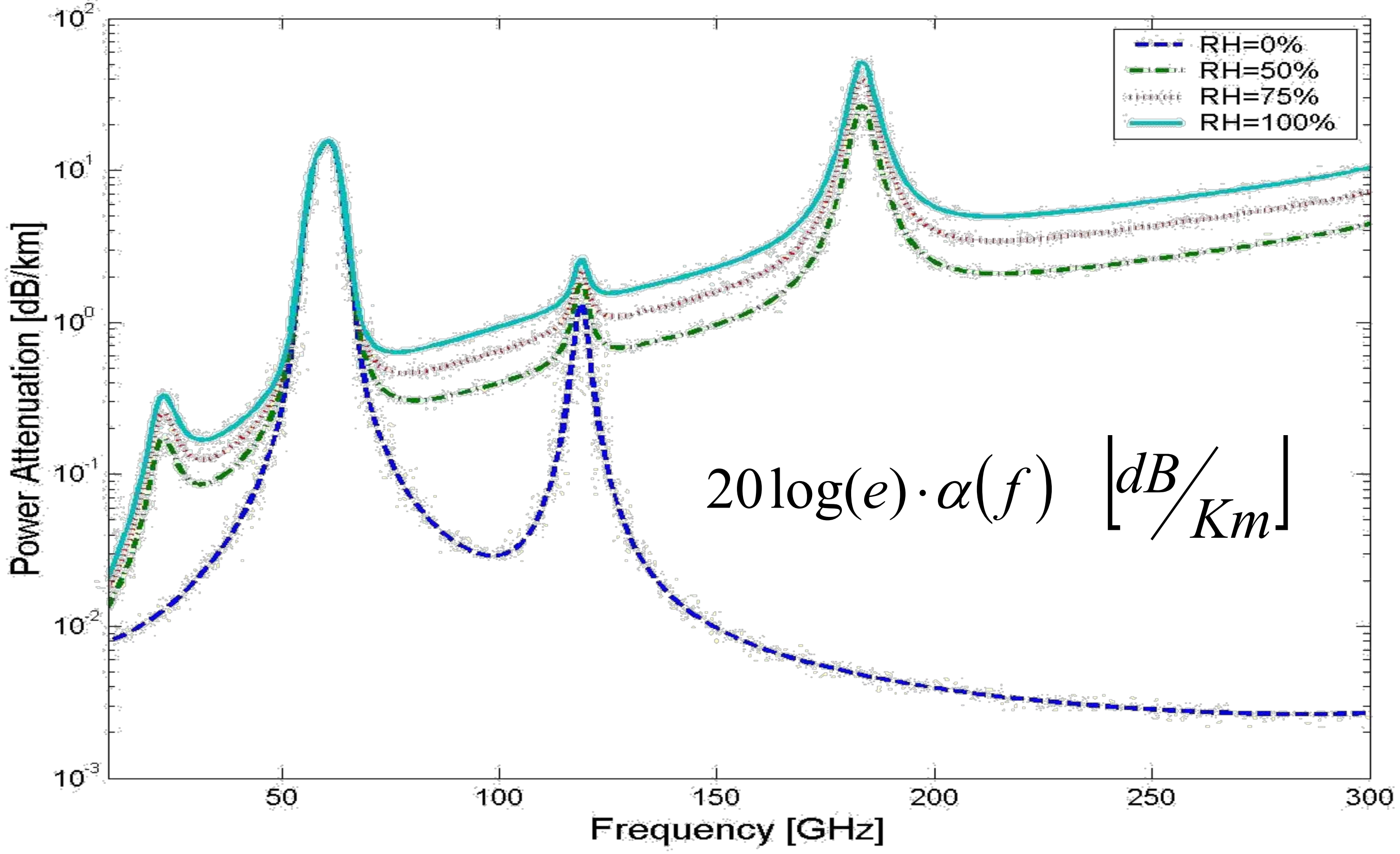
Outdoor Challenges

Atmospheric Attenuation

- Millimeter-wave radiation suffers from molecular absorption and refraction in the atmosphere

- Peaks at 22 GHz and 183 GHz caused by resonance absorption of water (H_2O)

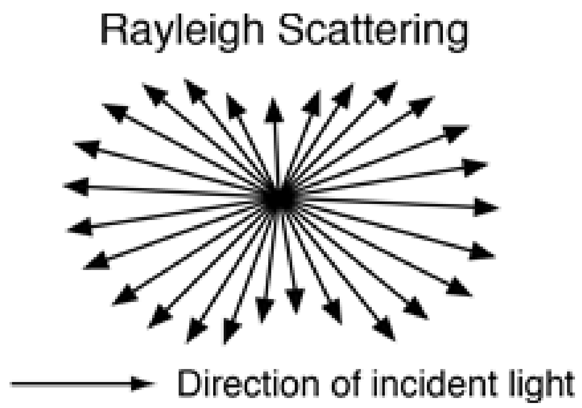
- Peaks at 60 GHz and 119 GHz caused by absorption resonances of oxygen (O_2).

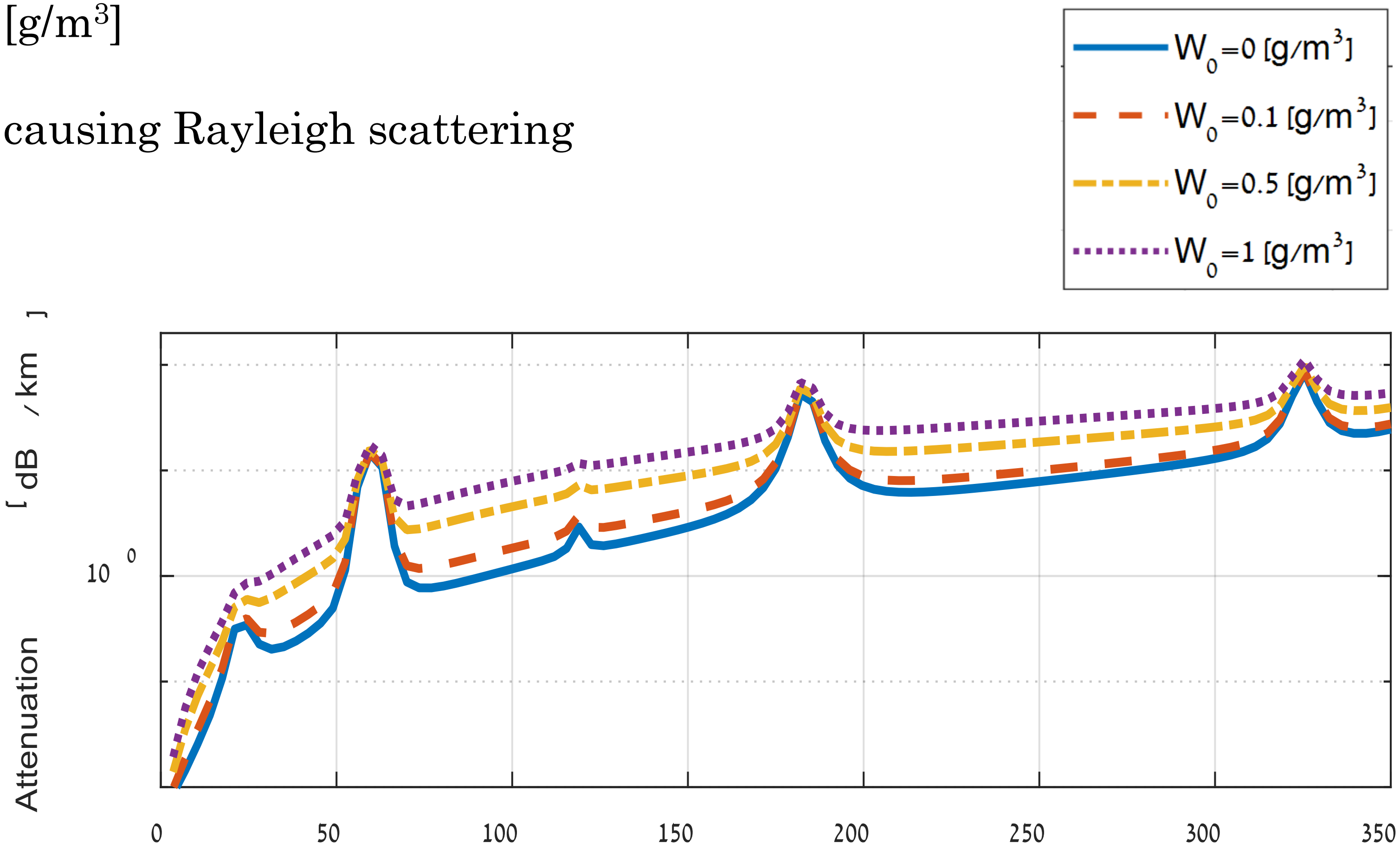


$$20\log(e)\cdot\alpha(f) \quad \left[{dB}/{Km}\right]$$

Fog Attenuation

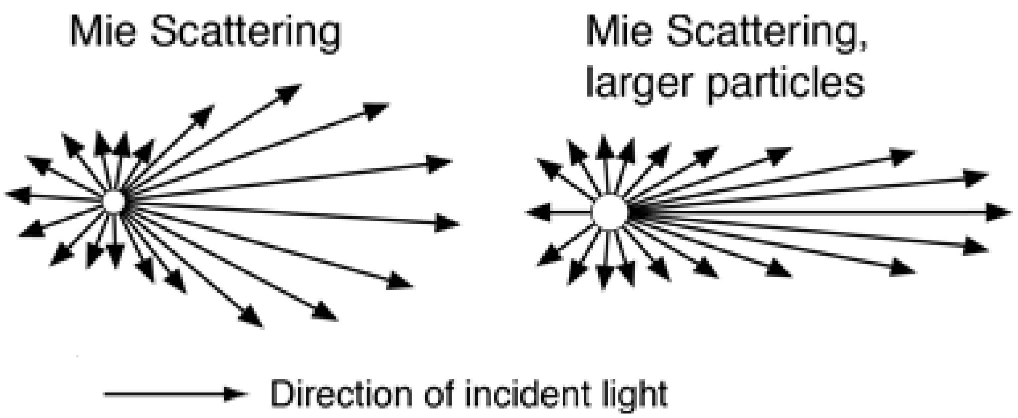
- Fog occurs at 100% relative humidity
- The water steams becomes to water molecules with water droplet concentration, W [g/m^3]
- Relative small molecules causing Rayleigh scattering

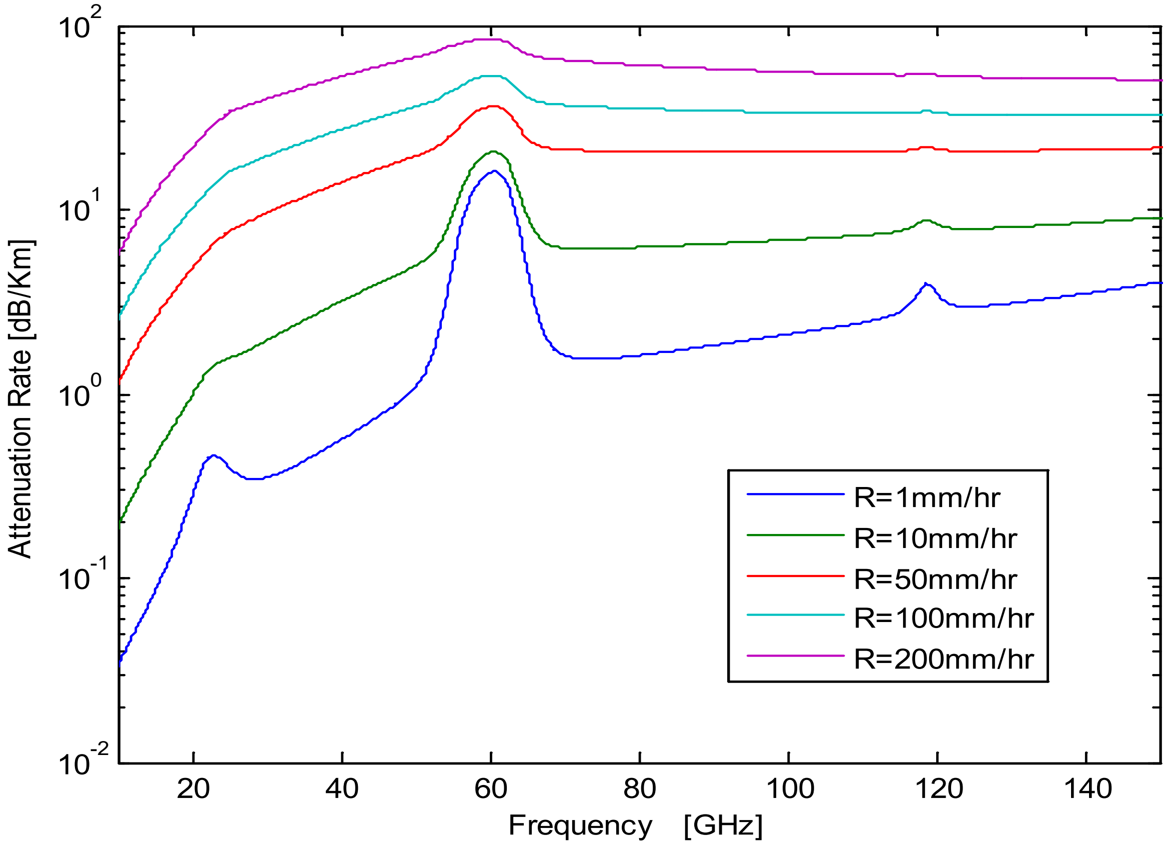


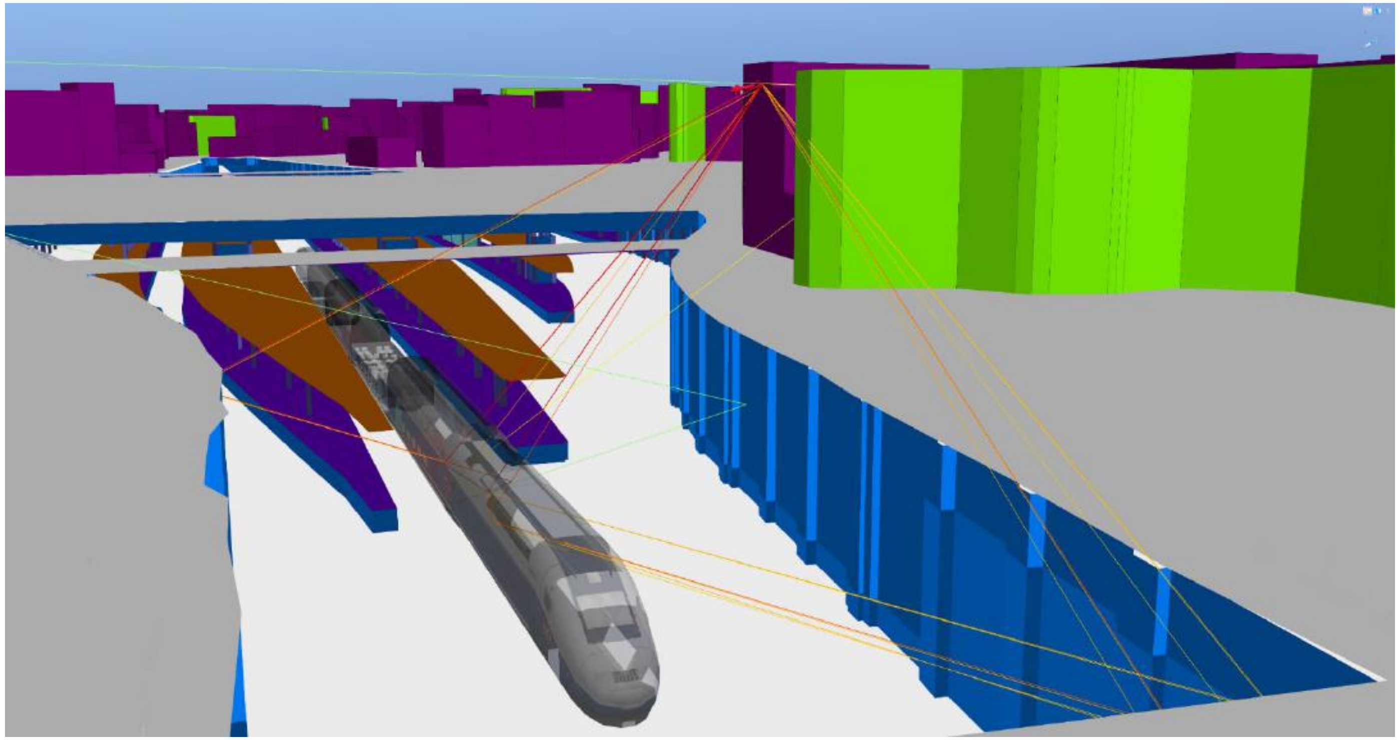


Rain Attenuation

- Relative large water molecules causing Mie scattering





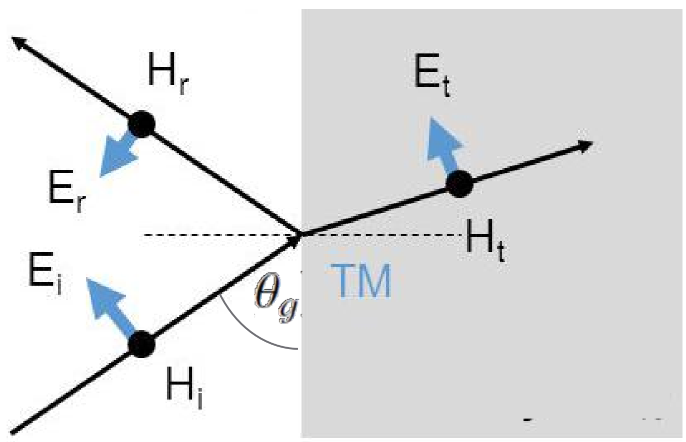


Indoor Challenges

Millimeter Wave Reflection from Dielectric Surfaces

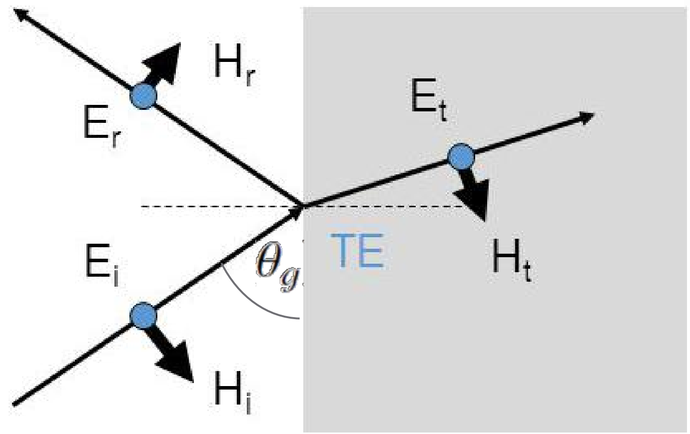
Fresnel's Equations – reflection coefficient

$$\Gamma_{TM_i} = \frac{\epsilon_r \sin(\theta_g) - \sqrt{\epsilon_r - \cos^2(\theta_g)}}{\epsilon_r \sin(\theta_g) + \sqrt{\epsilon_r - \cos^2(\theta_g)}}$$



TM- transverse magnetic:
the magnetic field is parallel to the interface plain

$$\Gamma_{TE_i} = \frac{\sin(\theta_g) - \sqrt{\epsilon_r - \cos^2(\theta_g)}}{\sin(\theta_g) + \sqrt{\epsilon_r - \cos^2(\theta_g)}}$$

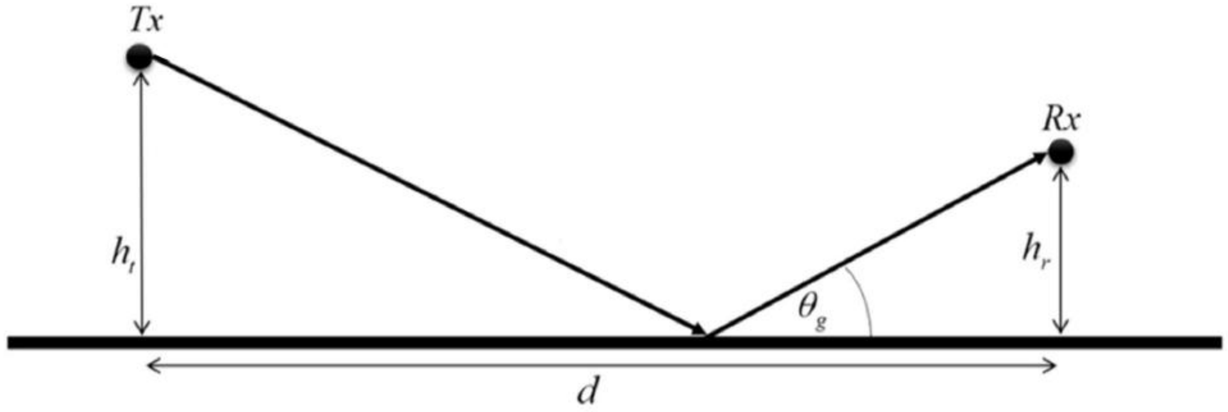


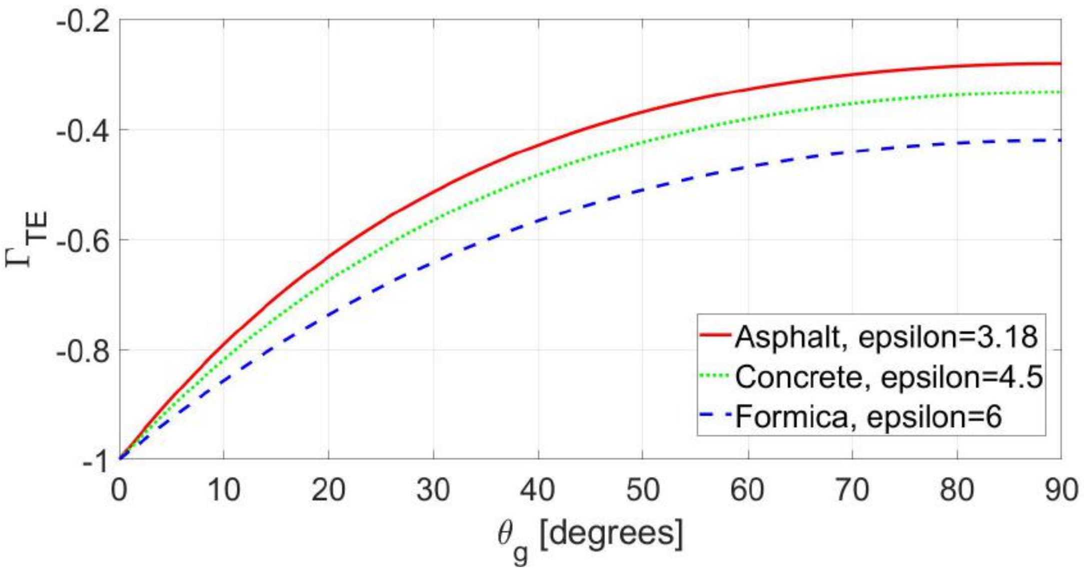
TE- transverse electric:
the electric field is parallel to the interface plain

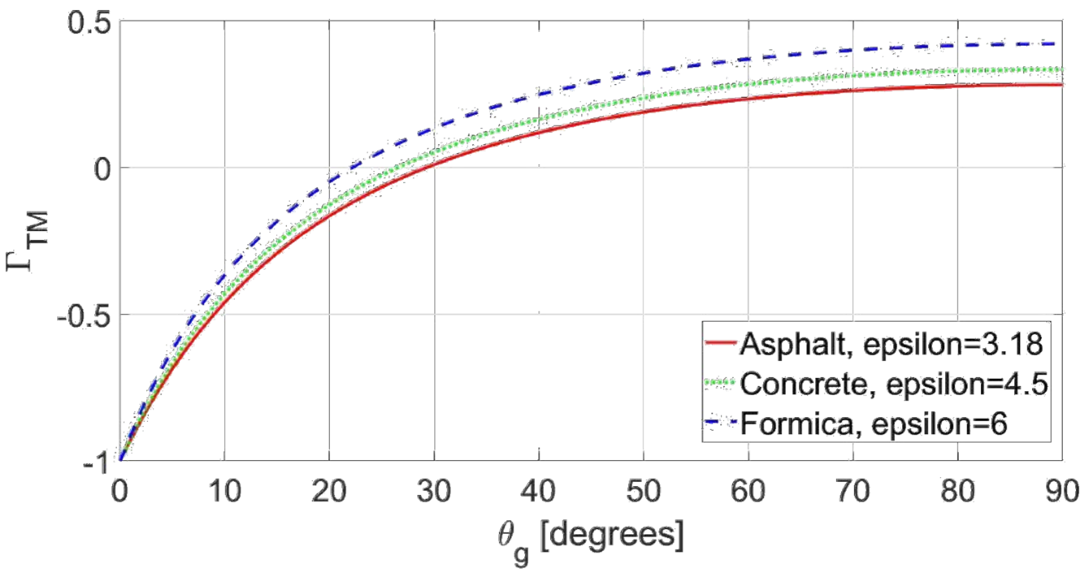
Dielectric constants

Material	Dielectric Constant ϵ_r	Frequency
Fused Silica	3.85	30 GHz
Glass	3.9	25 GHz
HDPA	2.34	27-30 GHz
Nylon	3.2	50 GHz
Teflon	3.0	22 GHz
Concrete	3.2-5	10GHz
Formica	6	-
Asphalt	3.18	-

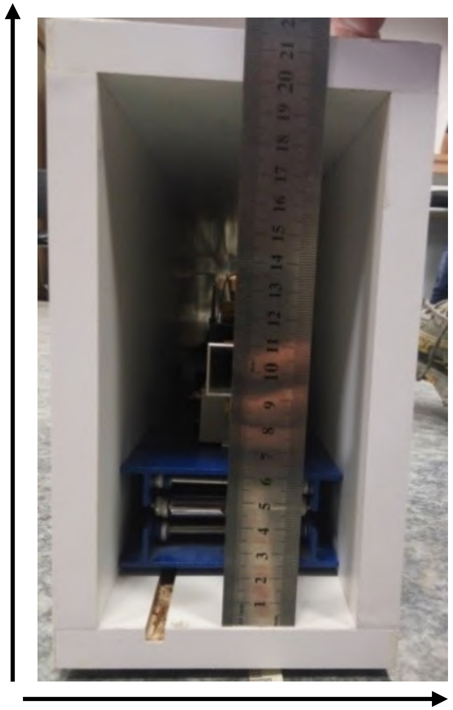
Effects of Different Building Materials







Scaling



Parameter	Full Scale	Subscale
Length	L	$L' = L/S$
Wavelength	λ	$\lambda' = \lambda/S$
Frequency	f	$f' = Sf$
Permittivity	ϵ	$\epsilon' = \epsilon$
Permeability	μ	$\mu' = \mu$
Conductivity	σ	$\sigma' = S\sigma$

The Rayleigh Criterion for Roughness

Rayleigh Criterion: $$\Delta\varphi < \frac{\pi}{2}$$

Below this value the surface reflection behavior can be described like a mirror

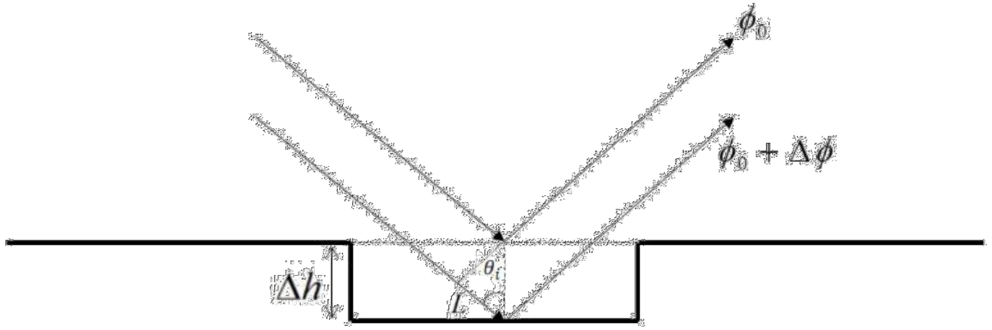
$$\Delta\varphi = k\Delta L = \frac{2\pi}{\lambda}\Delta L$$

$$\Delta L = 2L = 2\Delta h \cos\theta_i = 2\Delta h \sin\theta_g$$

$$\Downarrow$$

$$\Delta\varphi = \frac{2\pi}{\lambda}\cdot 2\Delta h \sin\theta_g$$

$$\Rightarrow \quad \boxed{\Delta h < \frac{\lambda}{8\sin\theta_g}}$$



Example:

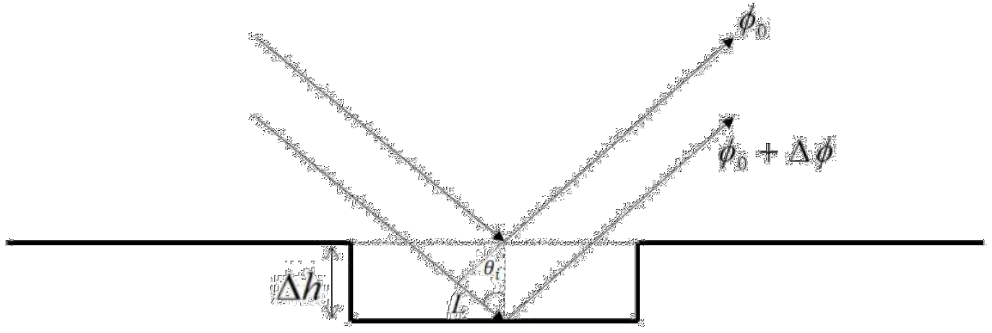
$$f = 30GHz$$

$$\theta_g = 10^{\circ}$$

$$\Downarrow$$

$$\boxed{\Delta h < 0.72cm}$$

$$\boxed{\Delta h < \frac{\lambda}{8 \sin \theta_g}}$$



Example (2):

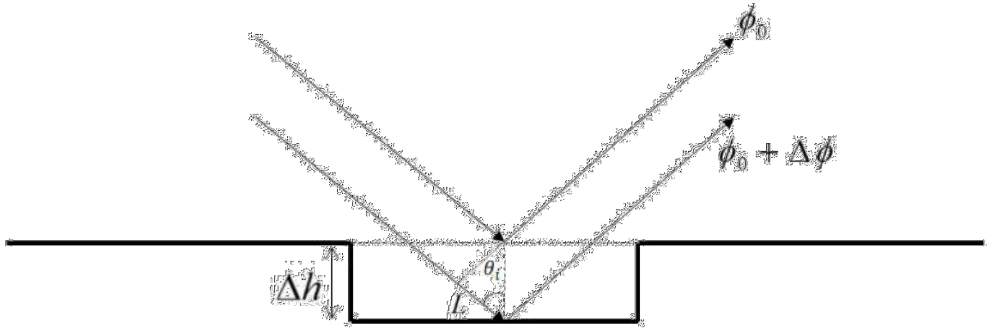
$$f = 94GHz$$

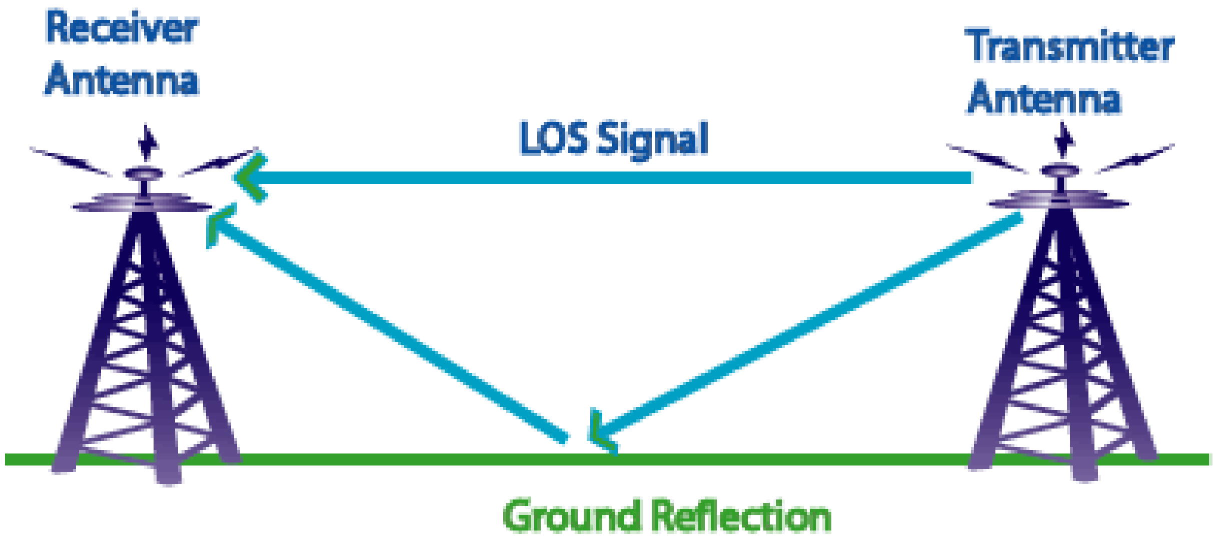
$$\theta_g = 10^{\circ}$$

$$\Downarrow$$

$$\boxed{\Delta h < 0.23cm}$$

$$\boxed{\Delta h < \frac{\lambda}{8 \sin \theta_g}}$$



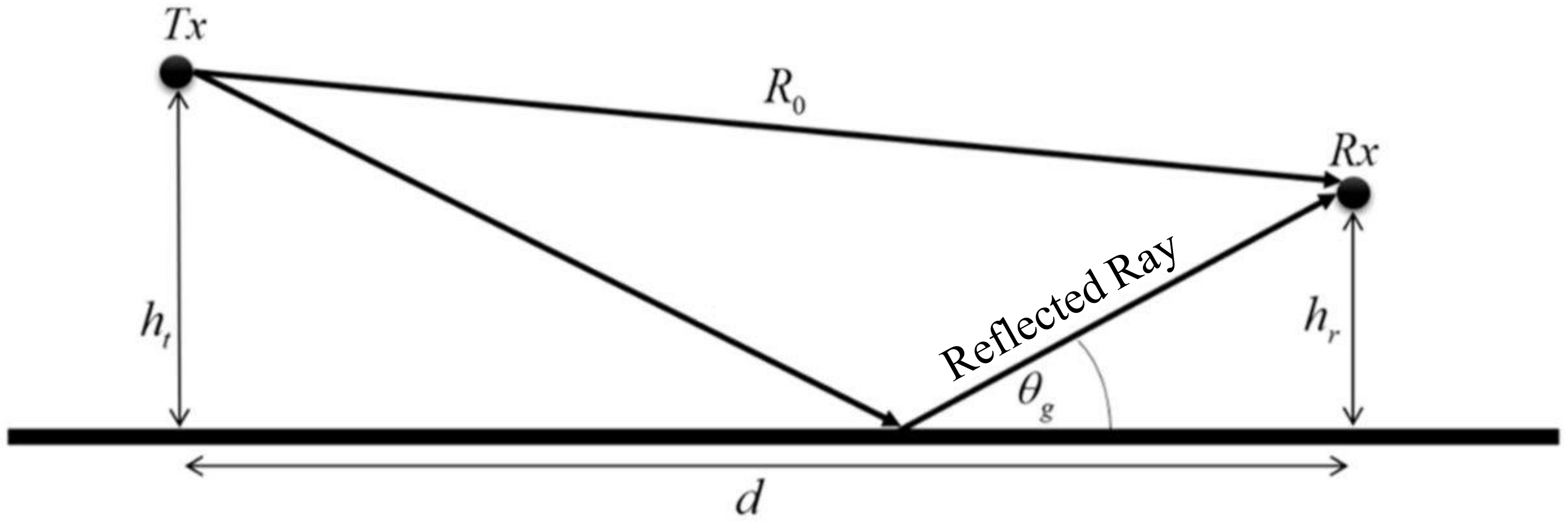


Two Rays Model

Friis equation for LOS free space communication:

$$P_r = G_r \left(\frac{\lambda}{4\pi R_0} \right)^2 G_t P_t$$

In the two-ray model, the received power is a result of coherent field summation of the LOS ray and the reflected ray



$$\frac{P_r}{P_t} = \left(\frac{\lambda}{4\pi}\right)^2 \cdot \left| \underbrace{\frac{G_d(\theta_0)e^{-jkR_0}}{R_0}}_{\text{LOS}} + \underbrace{\frac{G_d(\theta_g)\Gamma_0 e^{-jkR_p}}{R_p}}_{\text{reflected}} \right|^2$$

P_t: Transmitter power

P_r: Received power

λ: Wavelength

R_0: LOS path length between T_x and R_x

R_p: Reflected ray path length between T_x and R_x

k: Wavenumber, $k = 2\pi/\lambda$

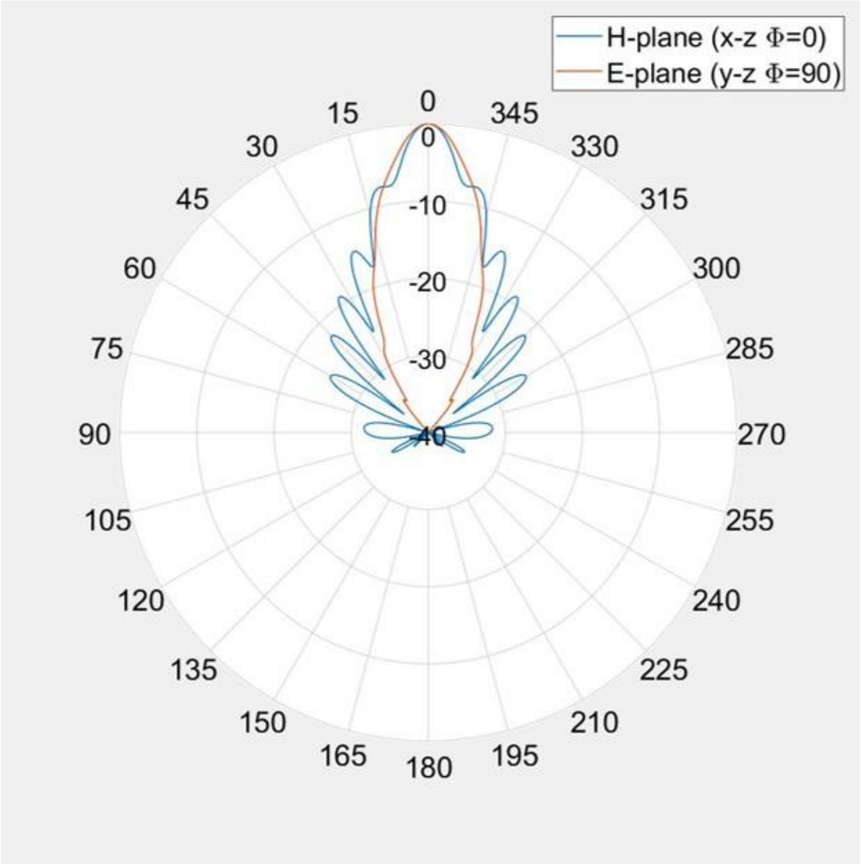
G_t, G_r: Gain of T_x and R_x antennas

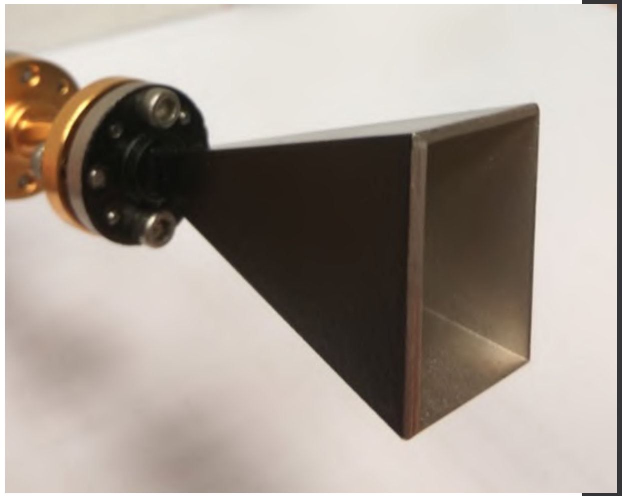
$G_d(\theta_g) = \sqrt{G_t(\theta) \cdot G_r(\theta)}$: Geometric mean of T_x and R_x antenna gains at θ_g angle

Γ_0= Reflection coefficient

Radiation Pattern - G(θ)

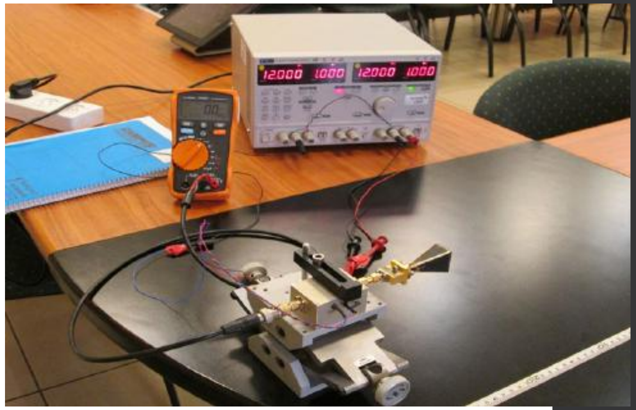
- Horn antenna
- 94GHz
- Gain of 24 dBi



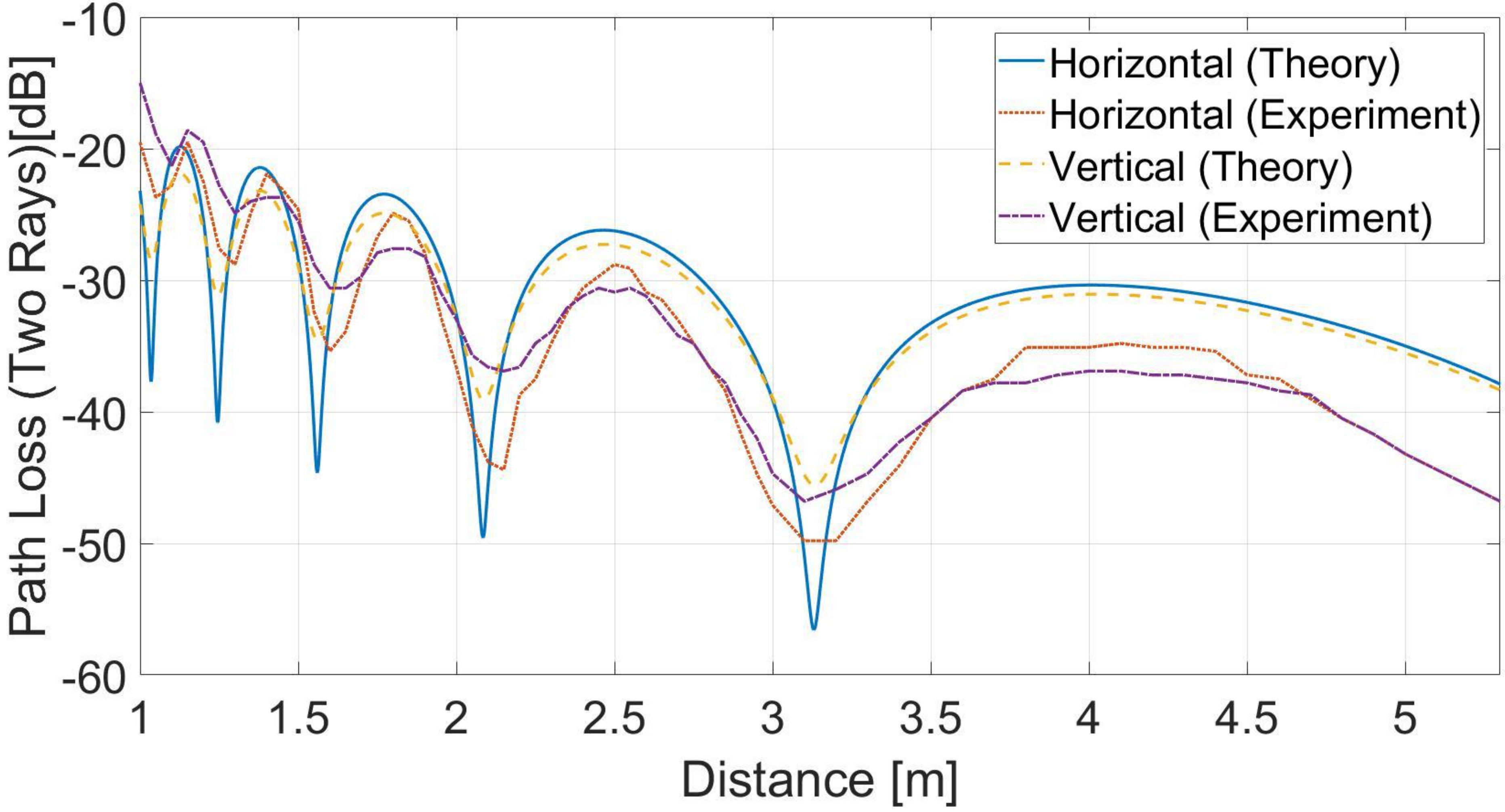


Experimental setup

- Formica coat - epsilon=4
- Frequency - 94GHz
- Pt - 17dBm
- Distance - 4.5m
- Tx/Rx height- 10cm



Experiments Results



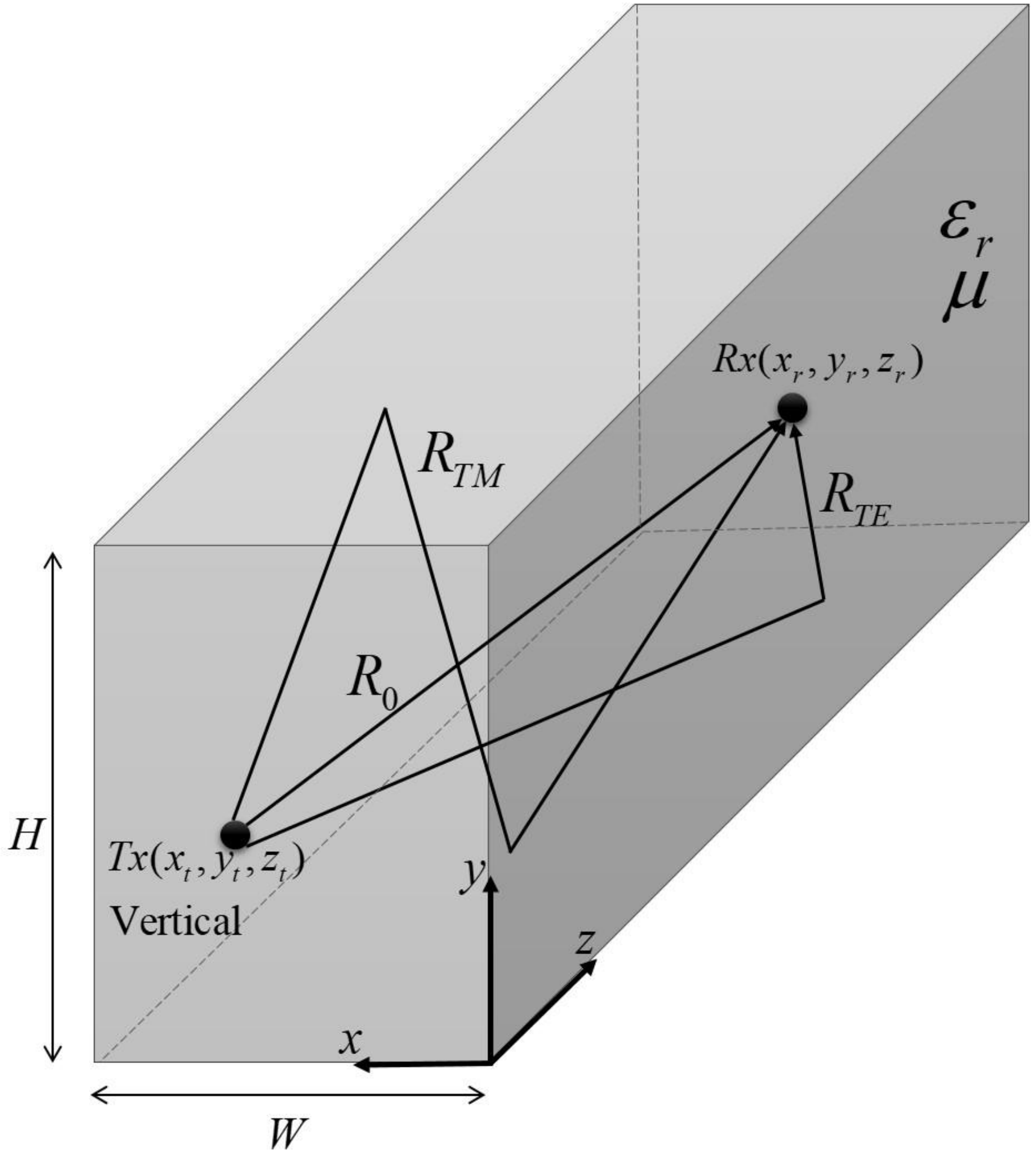
Propagation in Tunnels

Ray Tracing Model

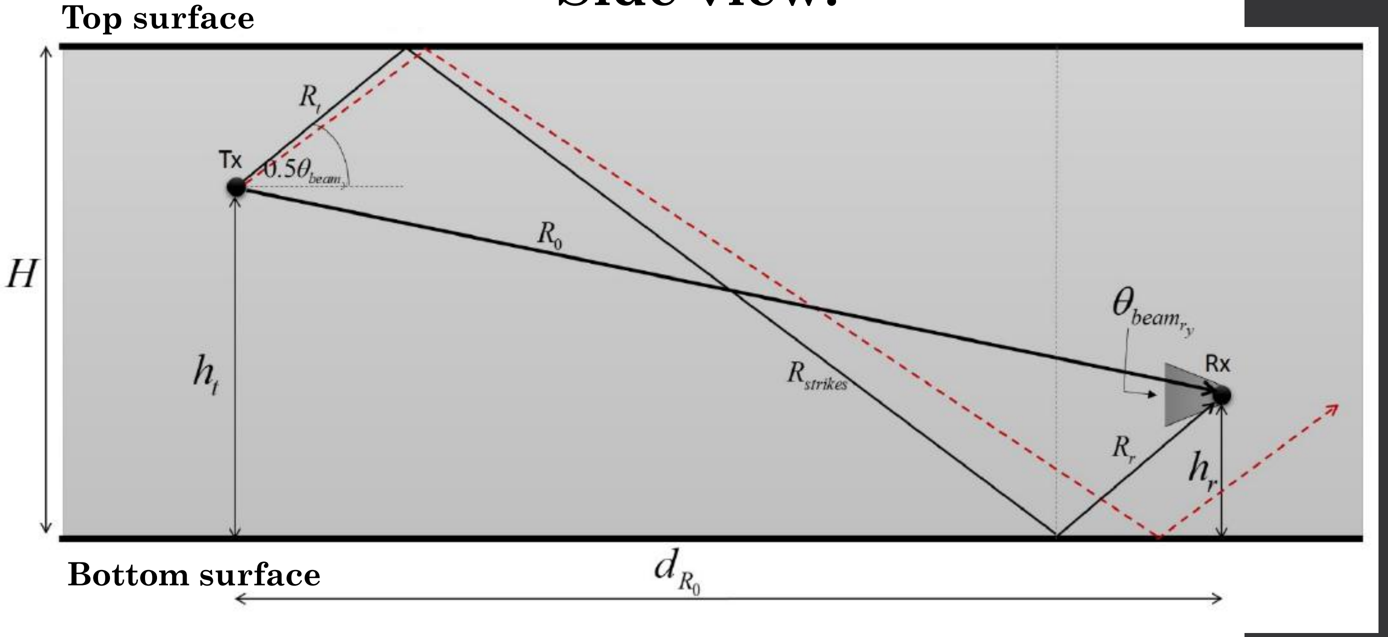
- Sum of LOS field with all reflected fields
- The reflected ray intensity is calculated using Fresnel

  equation
- Path length of each reflected ray is calculated using geometrical optics and image method
- Number of reflections is determined by the beam-width of the antenna (antenna gain)

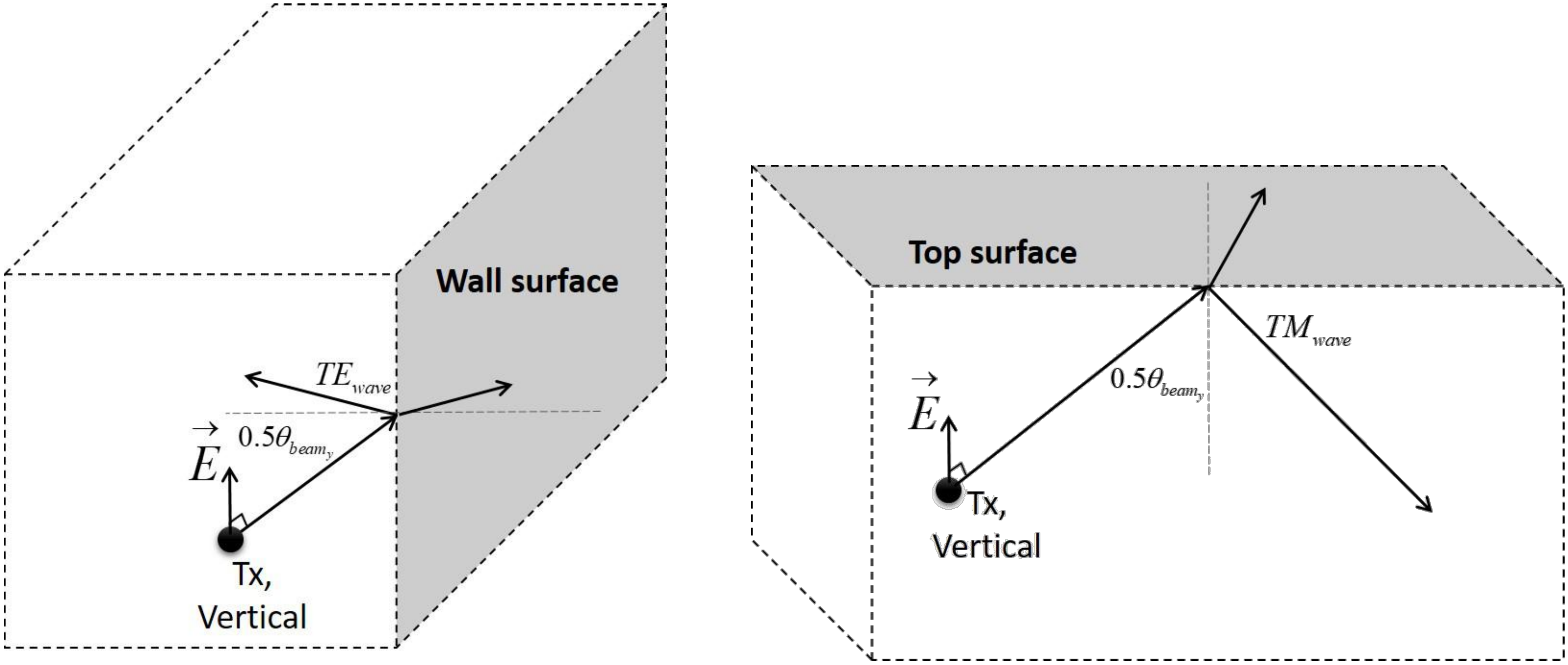
Reflections From Walls



Side view:



Polarization of Reflected Ray at Each Surface



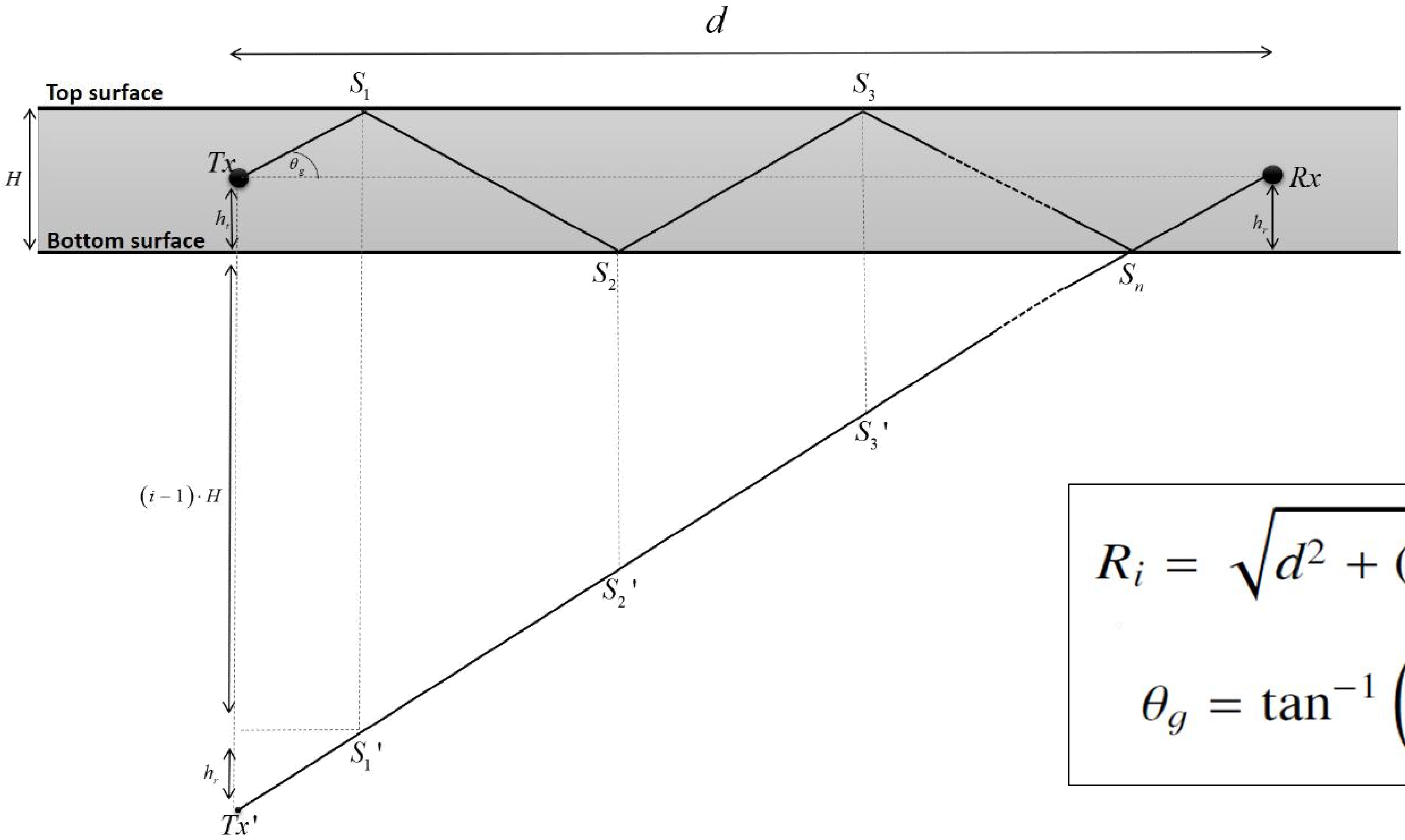
Multi-ray Summation

Symmetric scenario – Tx and Rx are located at the center of the tunnel cross section

$$\frac{P_r}{P_t} = \left(\frac{\lambda}{4\pi}\right)^2 \cdot \left| \frac{G_d e^{-jkR_0}}{R_0} + 2\sum_{i=1}^{n_v} \frac{G_d(\theta)\,(\Gamma_i)^i\, e^{-jkR_i}}{R_i} + 2\sum_{i=1}^{n_h} \frac{G_d(\theta)\,(\Gamma_i)^i\, e^{-jkR_i}}{R_i} \right|^2$$

Antenna polarization	Walls polarization	Floor and ceiling polarization
Vertical	Γ_{TE}	Γ_{TM}
Horizontal	Γ_{TM}	Γ_{TE}

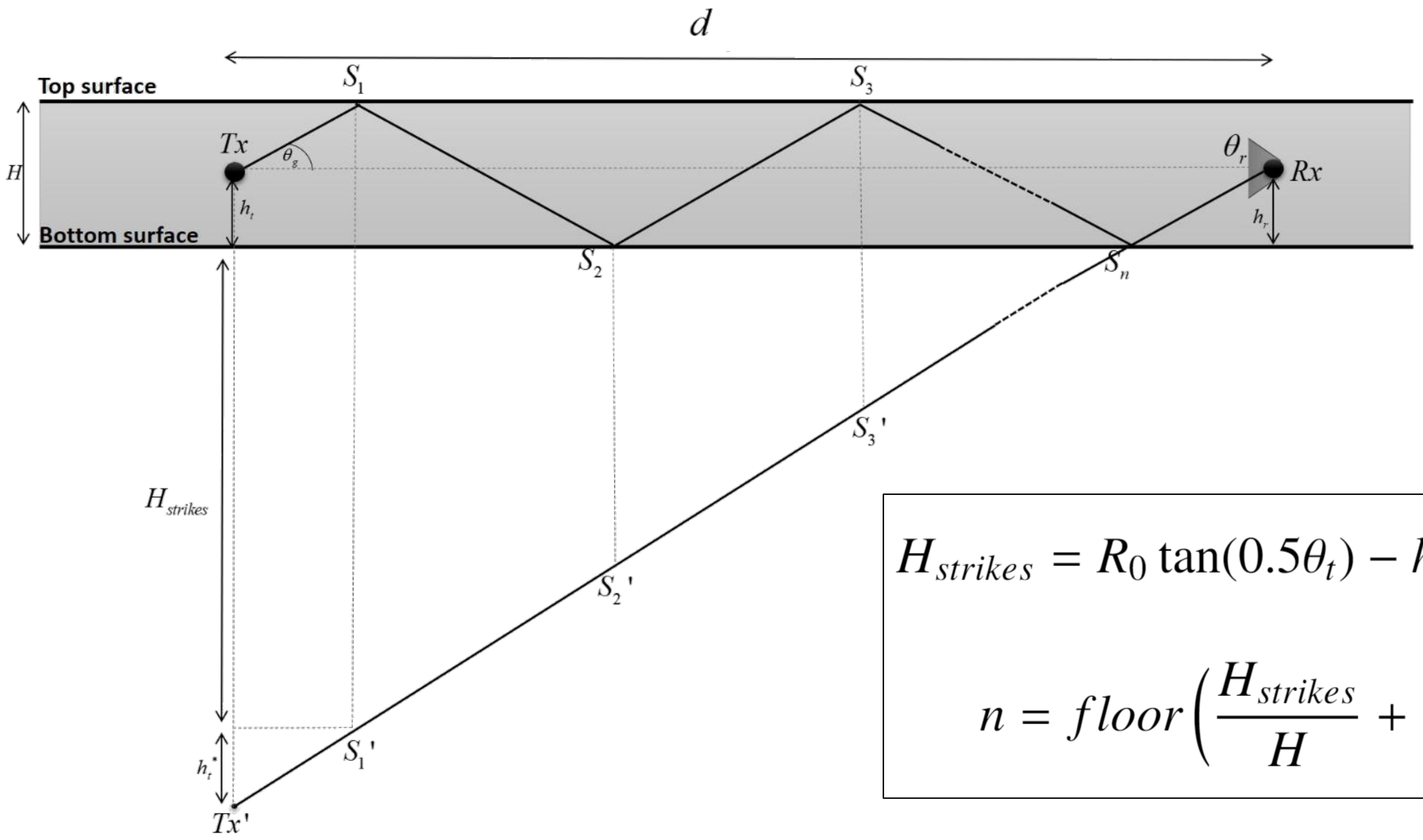
Image Method (GO)



$$R_i = \sqrt{d^2 + (iH)^2}$$

$$\theta_g = \tan^{-1}\left(\frac{iH}{d}\right)$$

Number of Reflected Rays



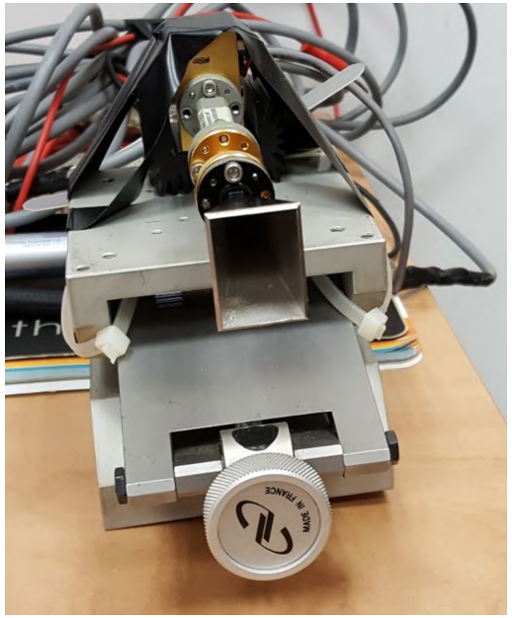
$$H_{strikes} = R_0 \tan(0.5\theta_t) - h_t - h_r$$

$$n = floor\left(\frac{H_{strikes}}{H} + 1\right)$$

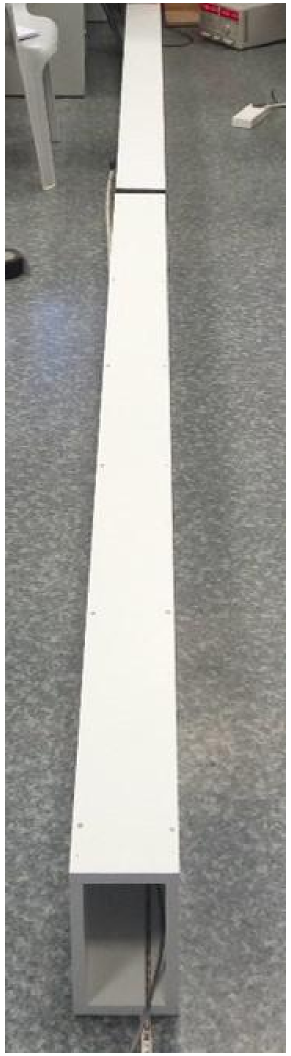
Experiments and Results

Experimental setup

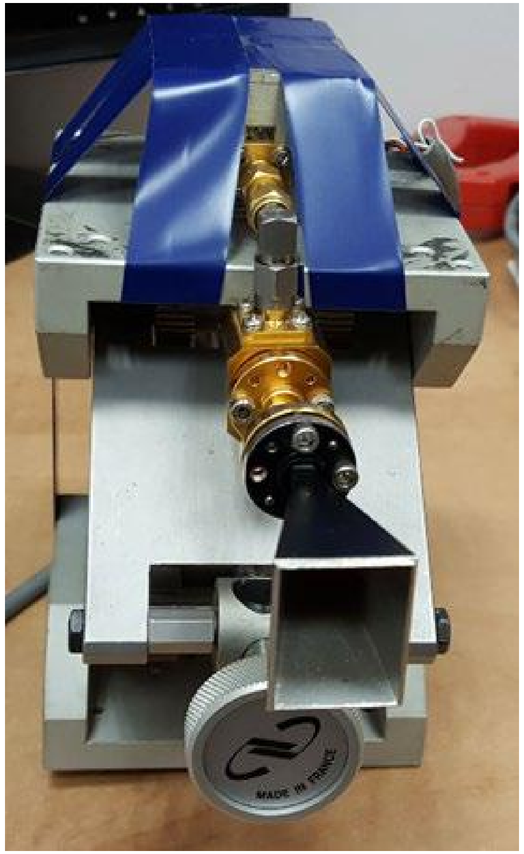
- Radiation Pattern - G(θ)
- Frequency: 94GHz
- Distance: 6 meters



Transmitter

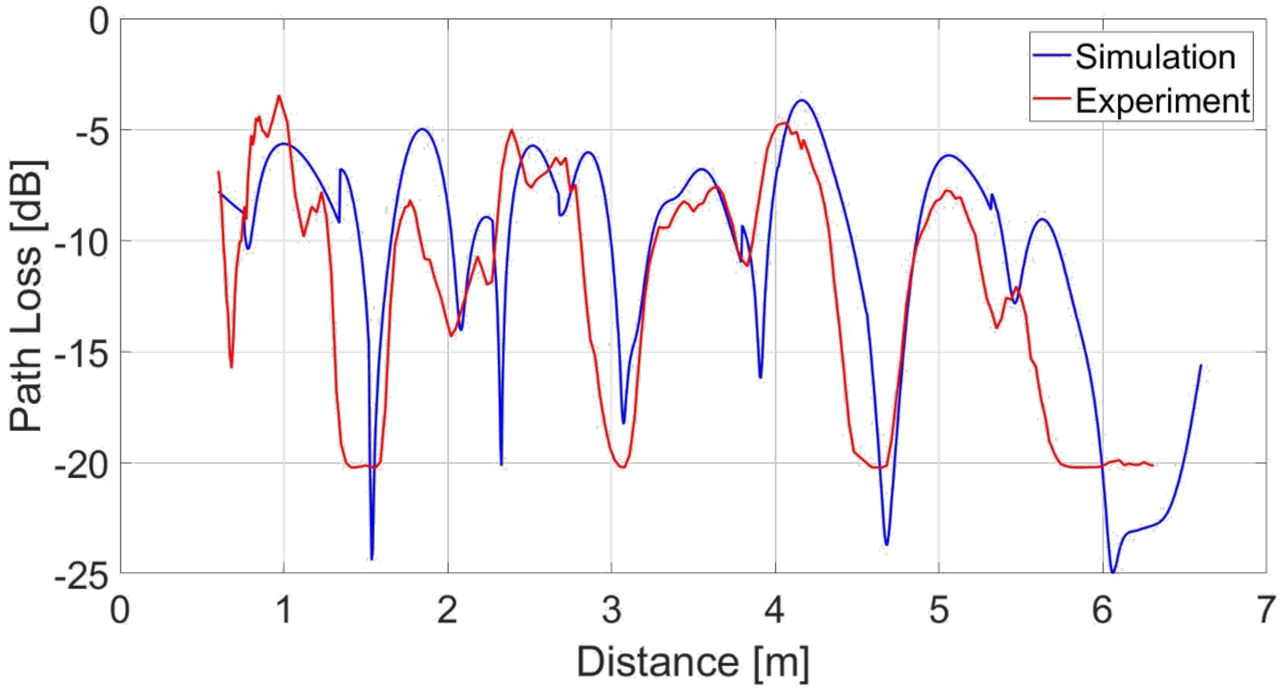


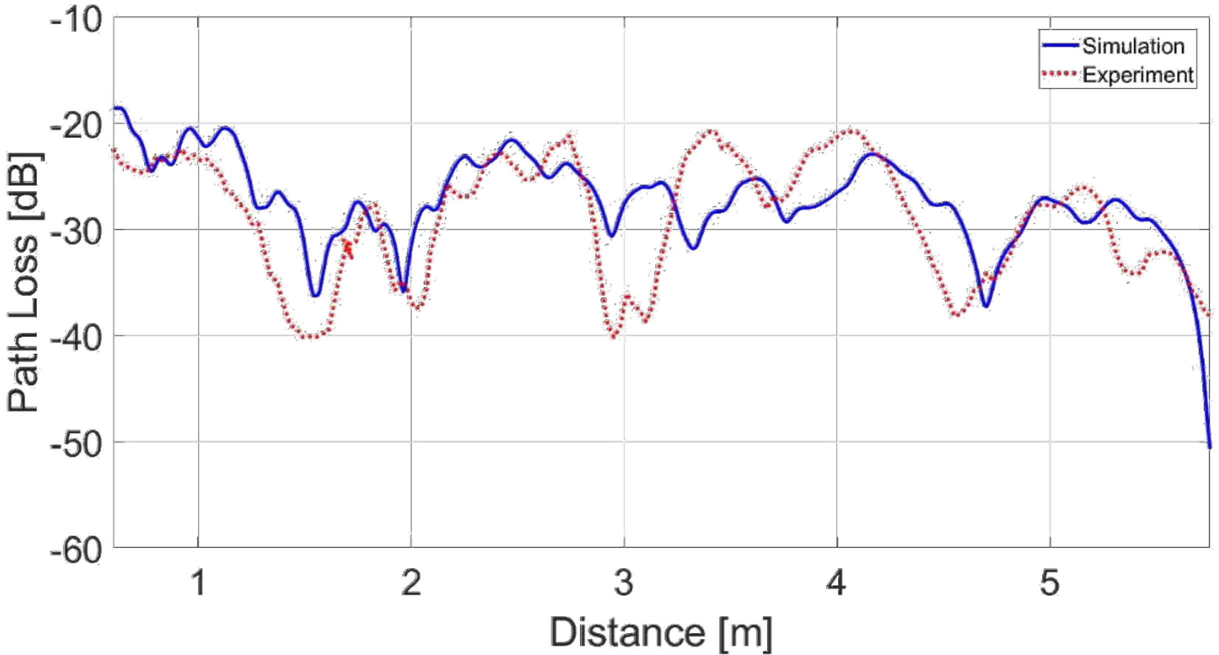
Sub-scale tunnel



Detector with

Antenna polarization- vertical (left), horizontal (right)





Summary

- MMW communication contains new challenges:
  - Atmospheric effects
  - Weather conditions like fog and rain
  - Reflections

- Multiple reflection at indoor environment
  - Reflection affects the received signal
  - At some scenarios it can help to preserve the link
- We improve our models and adjust to more complex challenges

Thank you for listening!