ARIEL UNIVERSITY

אוניברסיטת אריאל

Multipath effects on 5G and 6G wireless links operating in millimeter wavelengths

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5G™

Features

- **Enhanced Mobile Broadband (eMBB):**
  - Faster connections
  - Higher throughput
  - More capacity

- **Ultra-Reliable Low-Latency communications (URLLC)**

- **Massive Machine-Type Communications (mMTC):**
  - Large number of various devices
  - IoT devices
  - Drones
  - Autonomous cars

Frequency Bands

- **Low-band**: 600–850 MHz,
  - Download 30–250 MBPS
- **Mid-band**: 2.5–3.7 GHz
  - Download 100–900 MBPS
- **High-band**: 25–39 GHz
  - Download GBPS

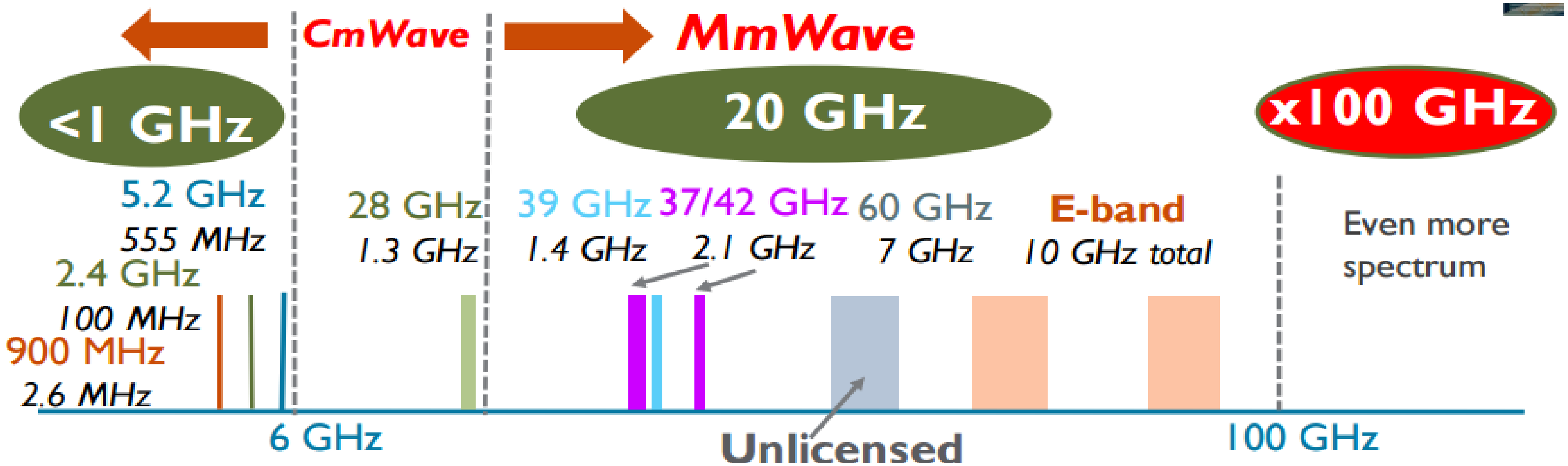
1000x required increase in capacity

- X10 More spectrum
- X10 More small cells
- X10Higher efficiency

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

5th Generation Spectrum



Frequency Band	Advantages	Disadvantages
28 GHz	Suffers the least path loss; Low oxygen absorption and rain attenuation.	Lightly licensed; The bandwidth is relatively small.
37 GHz	Relatively less attenuation caused by oxygen absorption and rain.	Less research and applications done.
60 GHz	Unlicensed bands; Large bandwidth to achieve multi-gigabit rate.	Peak point of oxygen absorption; Relatively large rain attenuation.
73 GHz	Small effects of atmospheric absorption.	Large rain attenuation; Large path loss due to high frequency point.

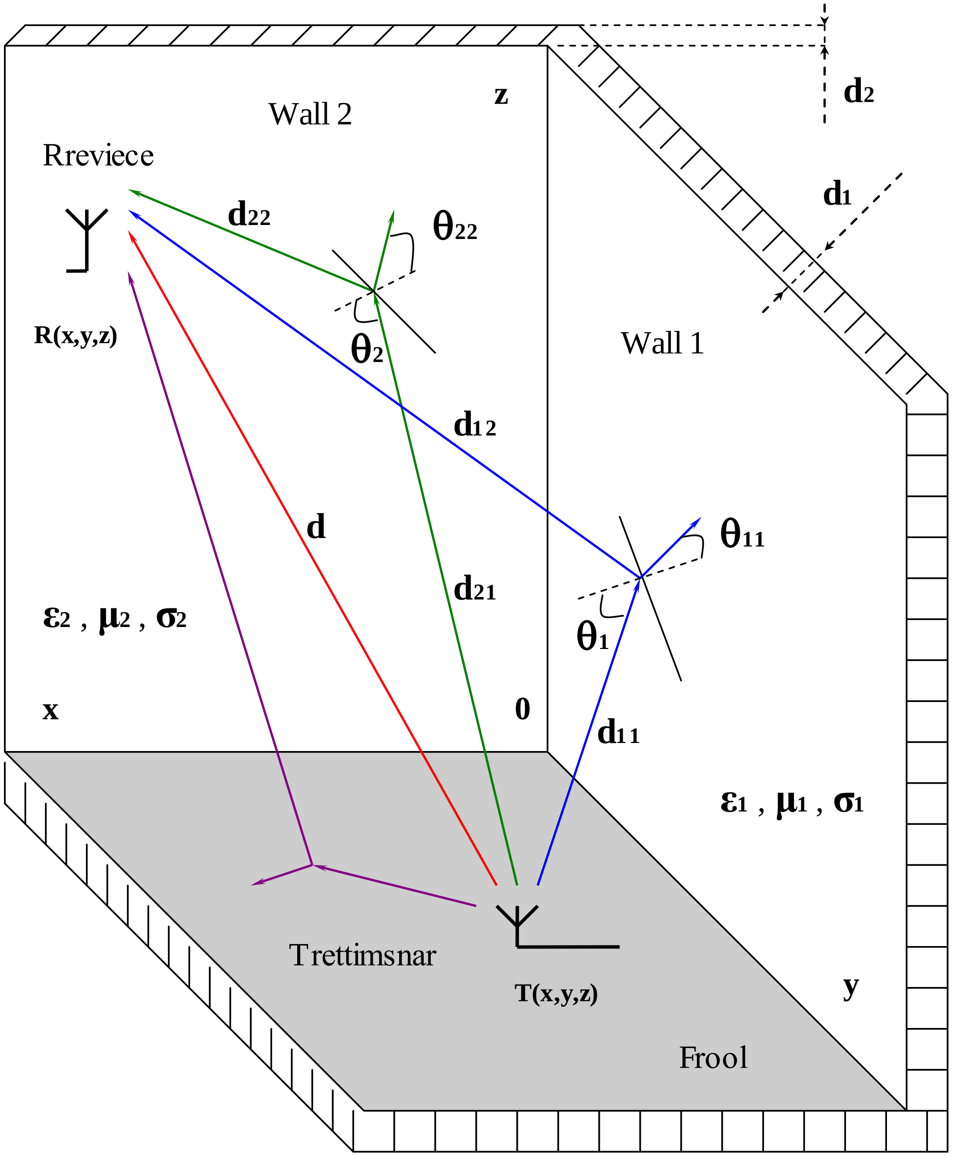
The EHF (Millimeter Wave) band

- Free of users.
- Unlicensed (60GHz).
- Broad bandwidths for high data rate information transfer.
- High directivity and spatial resolution.
- Low probability of interference / interception (LPI).
- Small antenna and equipment size.

- Low transmission power.
- Atmospheric attenuation
- Frequency dispersion
- Affected by weather conditions

Indoor propagation

Indoor propagation



- 7 rays: LOS and 6 reflections
- Concrete walls (10 cm)
- Both isotropic antennas

$$
\begin{aligned}
\tilde{E}_{\text{Total}} &= \frac{1}{d}\cdot e^{-j\frac{2\pi f}{c}d} + \\
&+ \frac{1}{d_{11}+d_{12}}\cdot e^{-j\frac{2\pi f}{c}(d_{11}+d_{12})}\cdot \rho_{wall\,1} \\
&+ \frac{1}{d_{21}+d_{22}}\cdot e^{-j\frac{2\pi f}{c}(d_{21}+d_{22})}\cdot \rho_{wall\,2} \\
&+ \frac{1}{d_{31}+d_{32}}\cdot e^{-j\frac{2\pi f}{c}(d_{31}+d_{32})}\cdot \rho_{floor} \\
&+ \frac{1}{d_{41}+d_{42}}\cdot e^{-j\frac{2\pi f}{c}(d_{41}+d_{42})}\cdot \rho_{wall\,4} \\
&+ \frac{1}{d_{51}+d_{52}}\cdot e^{-j\frac{2\pi f}{c}(d_{51}+d_{52})}\cdot \rho_{wall\,5} \\
&+ \frac{1}{d_{61}+d_{62}}\cdot e^{-j\frac{2\pi f}{c}(d_{61}+d_{62})}\cdot \rho_{ceiling}
\end{aligned}
$$

Multi-ray model

electronics

MDPI

Article

Millimeter Wave Propagation in Long Corridors and Tunnels—Theoretical Model and Experimental Verification

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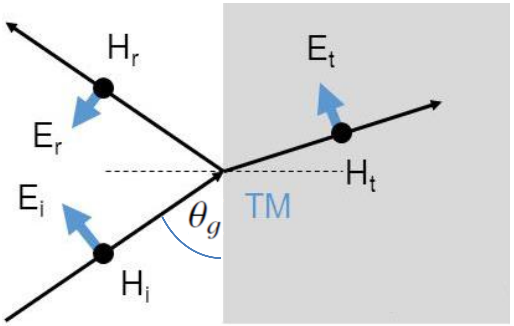
Fresnel's Equations – reflection coefficients

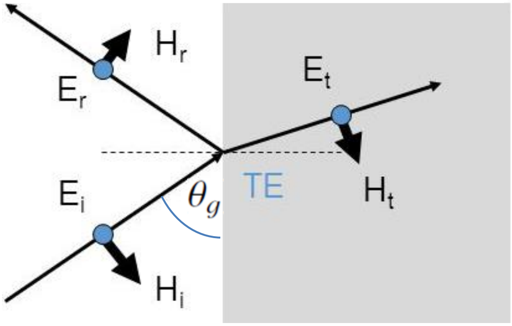
$$\Gamma_{TM_i} = \frac{\epsilon_r \sin(\theta_g) - \sqrt{\epsilon_r - \cos^2(\theta_g)}}{\epsilon_r \sin(\theta_g) + \sqrt{\epsilon_r - \cos^2(\theta_g)}}$$

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



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

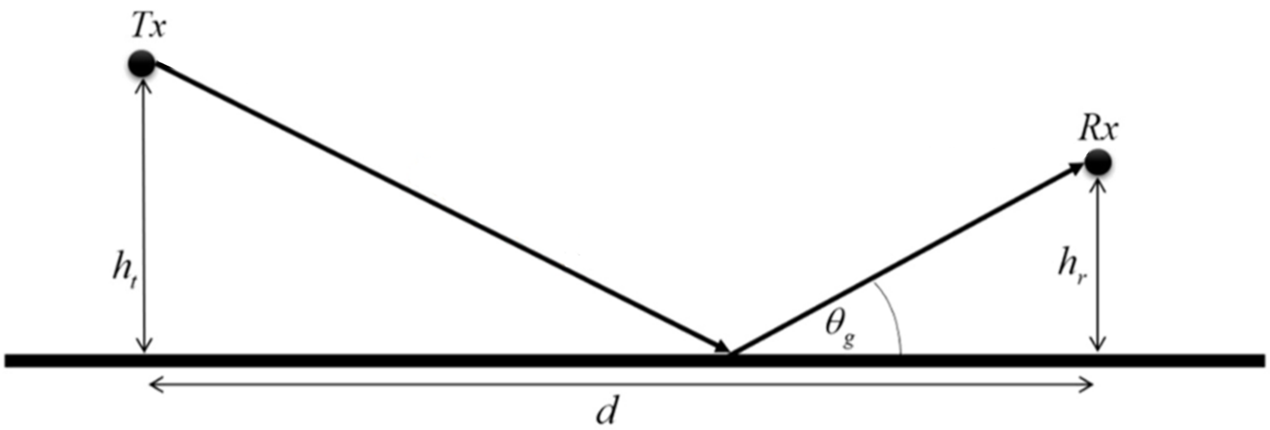
TE- transverse electric:
the electric field is parallel to the interface plain

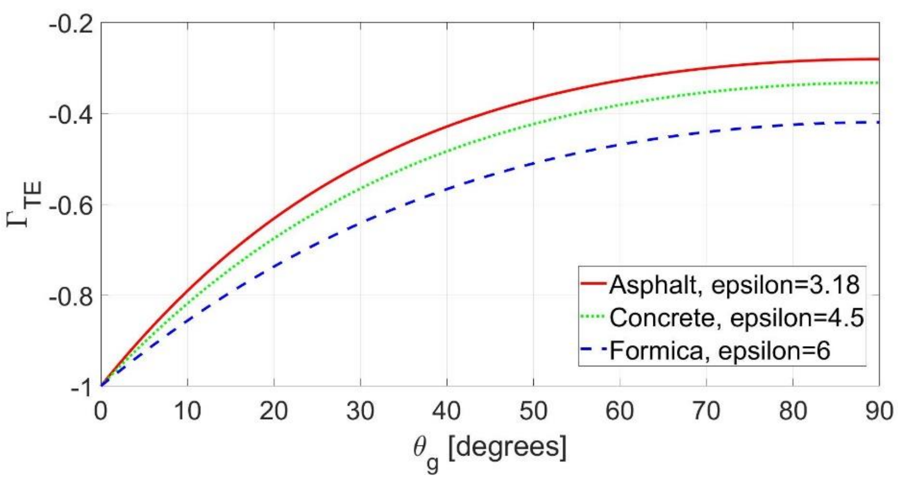


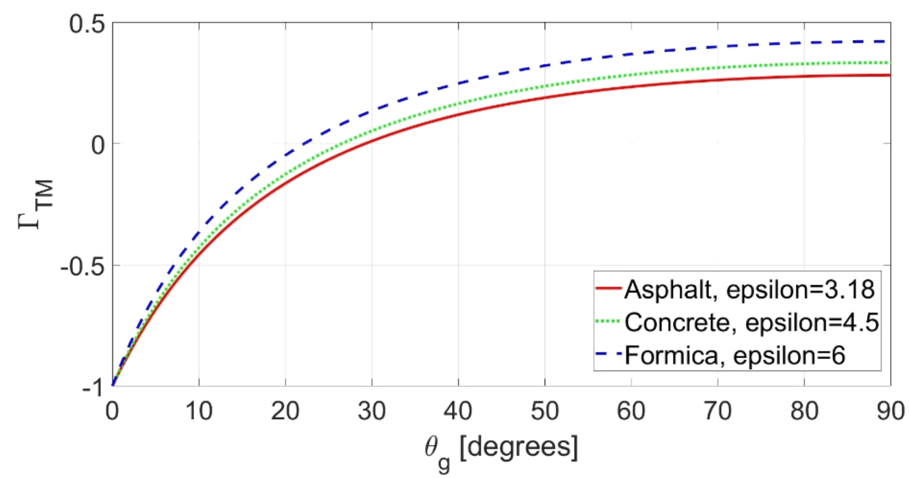
Dielectric constants

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	-

Specular reflections



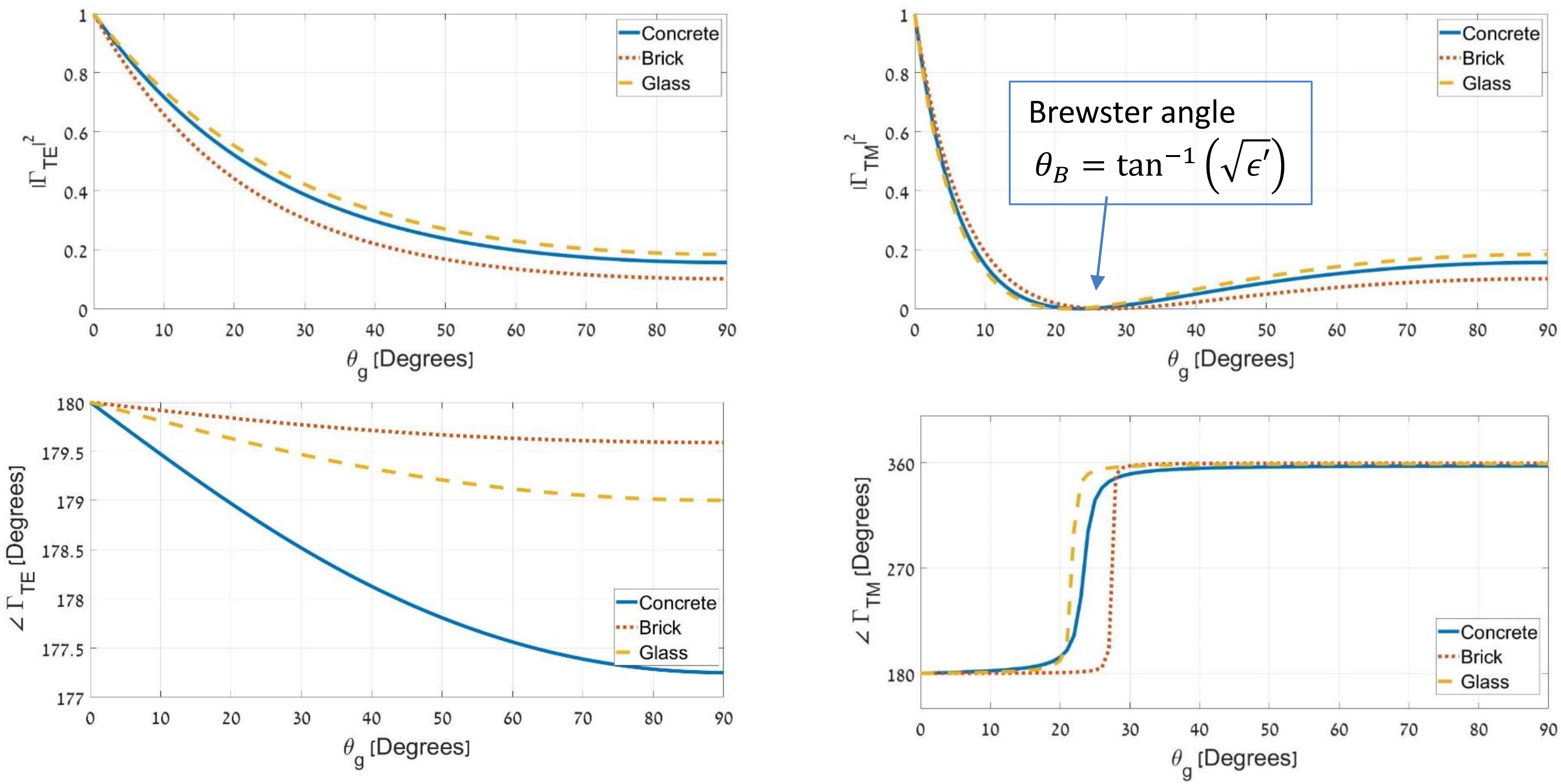




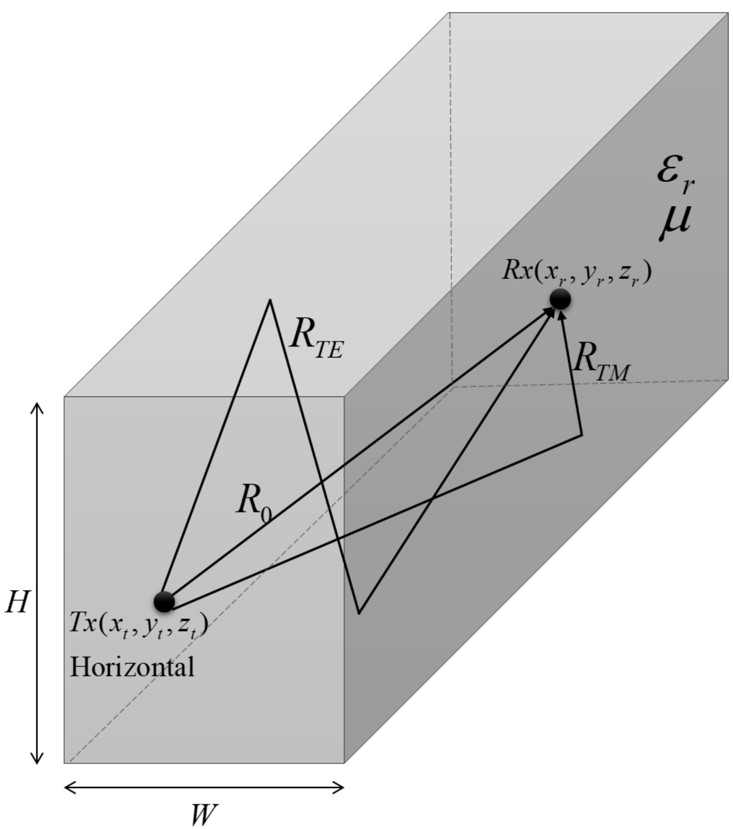
Complex Permittivity

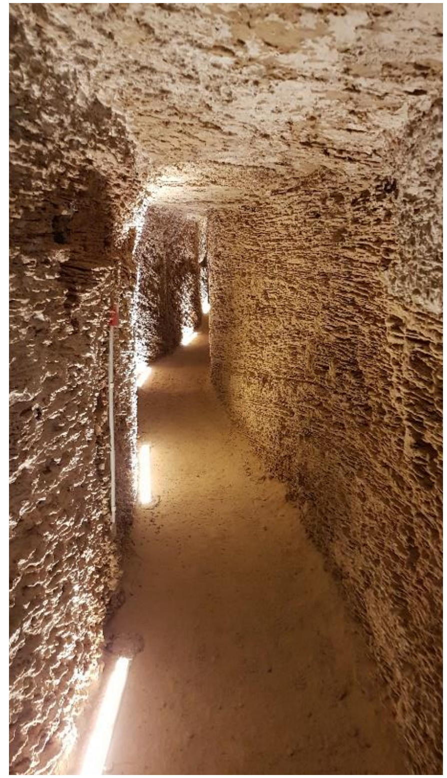
Material	**f=28GHz**		
	ε'	σ	$tg[\delta]$
Concrete	5.31	$0.48\ [S/m]$	$58 \cdot 10^{-2}$
Brick	3.75	$0.038\ [S/m]$	$6.5 \cdot 10^{-2}$
Glass	6.27	$0.23\ [S/m]$	$23.5 \cdot 10^{-2}$

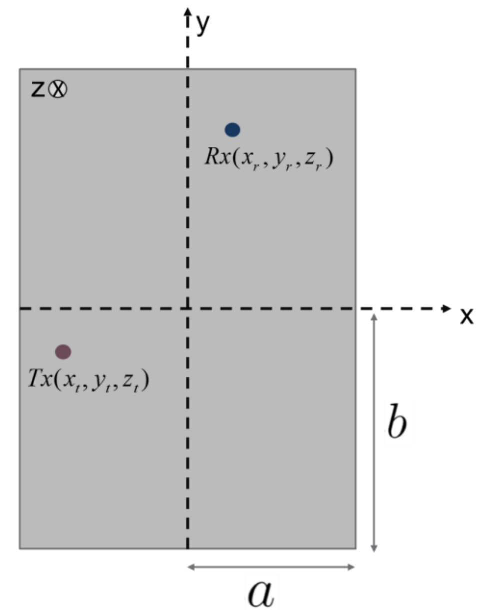
Reflection from of Different Building Materials



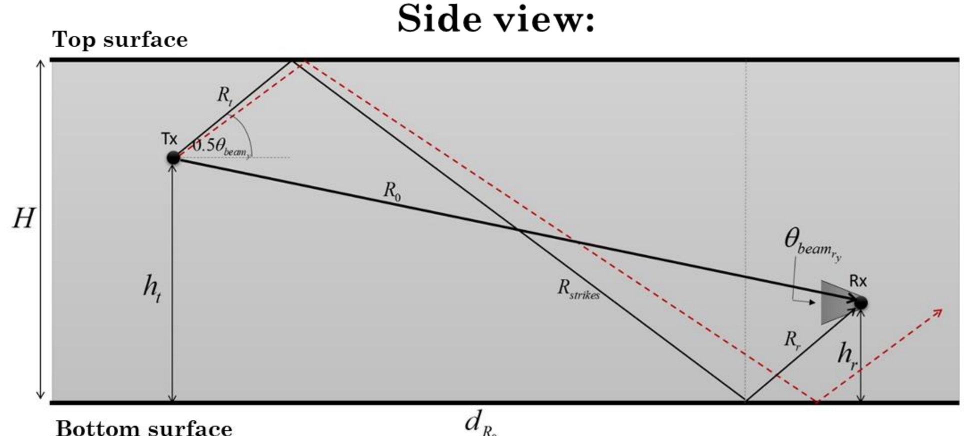
Long corridor - tunnel



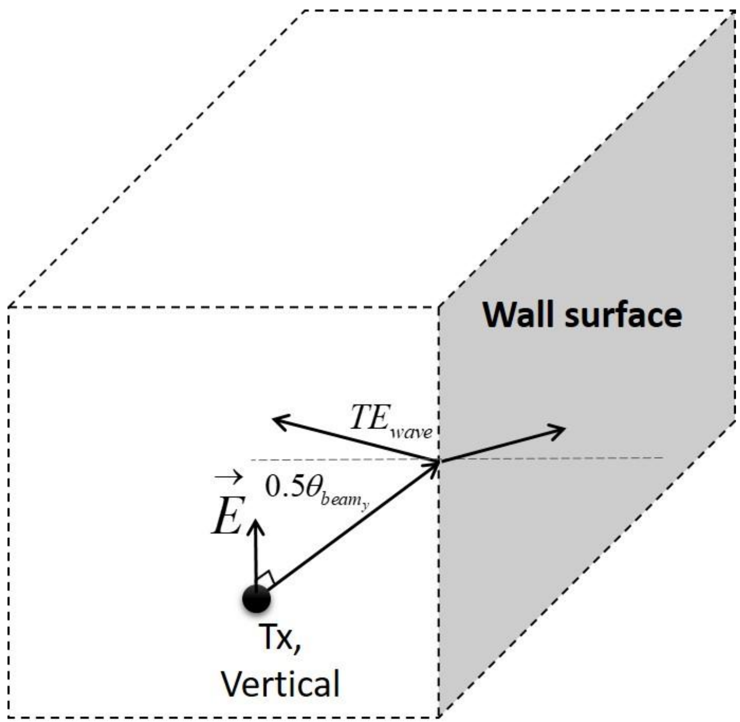


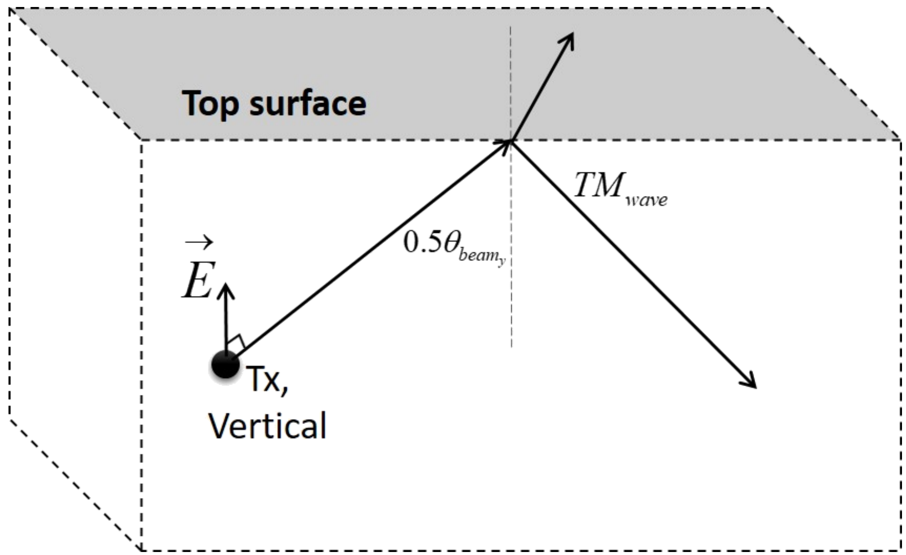


Side view:



Polarization of Reflected Ray at Different Surfaces





Multi-path transfer function

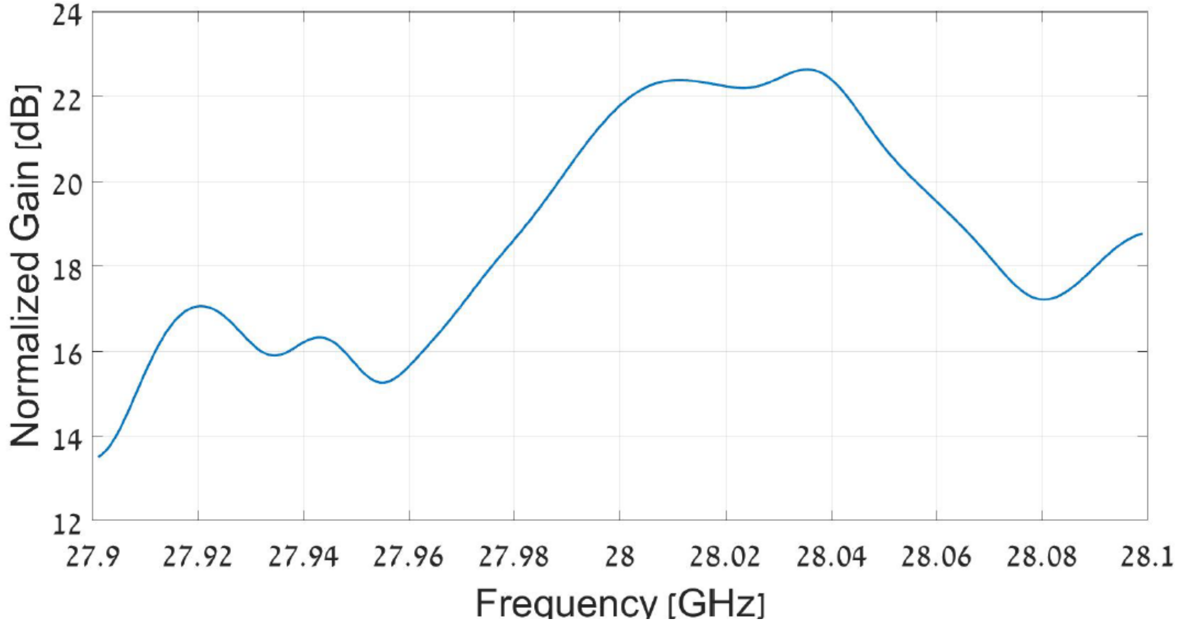
$$H_{norm}(jf) = \frac{E_r(Tunnel)}{E_r(LOS)} = \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} \frac{R_0}{R(m,n)} \cdot \Gamma_i^{|m|} \cdot \Gamma_j^{|n|} \cdot \frac{G(\theta,\phi)}{G_{LOS}} \cdot e^{-j2\pi f \Delta\tau(m,n)}$$

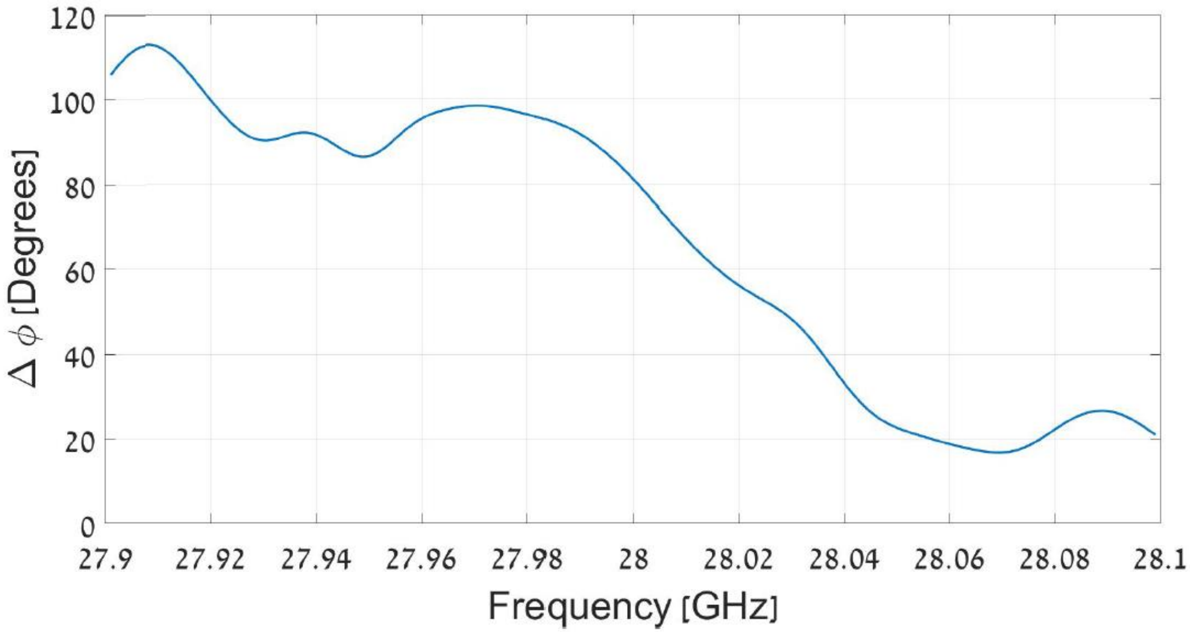
Antenna polarization	Walls polarization	Floor and ceiling polarization
Vertical	Γ_{TE}	Γ_{TM}
Horizontal	Γ_{TM}	Γ_{TE}

$$G_d(\Theta, \Phi) = \sqrt{G_t(\Theta, \Phi) \cdot G_r(\Theta, \Phi)}$$

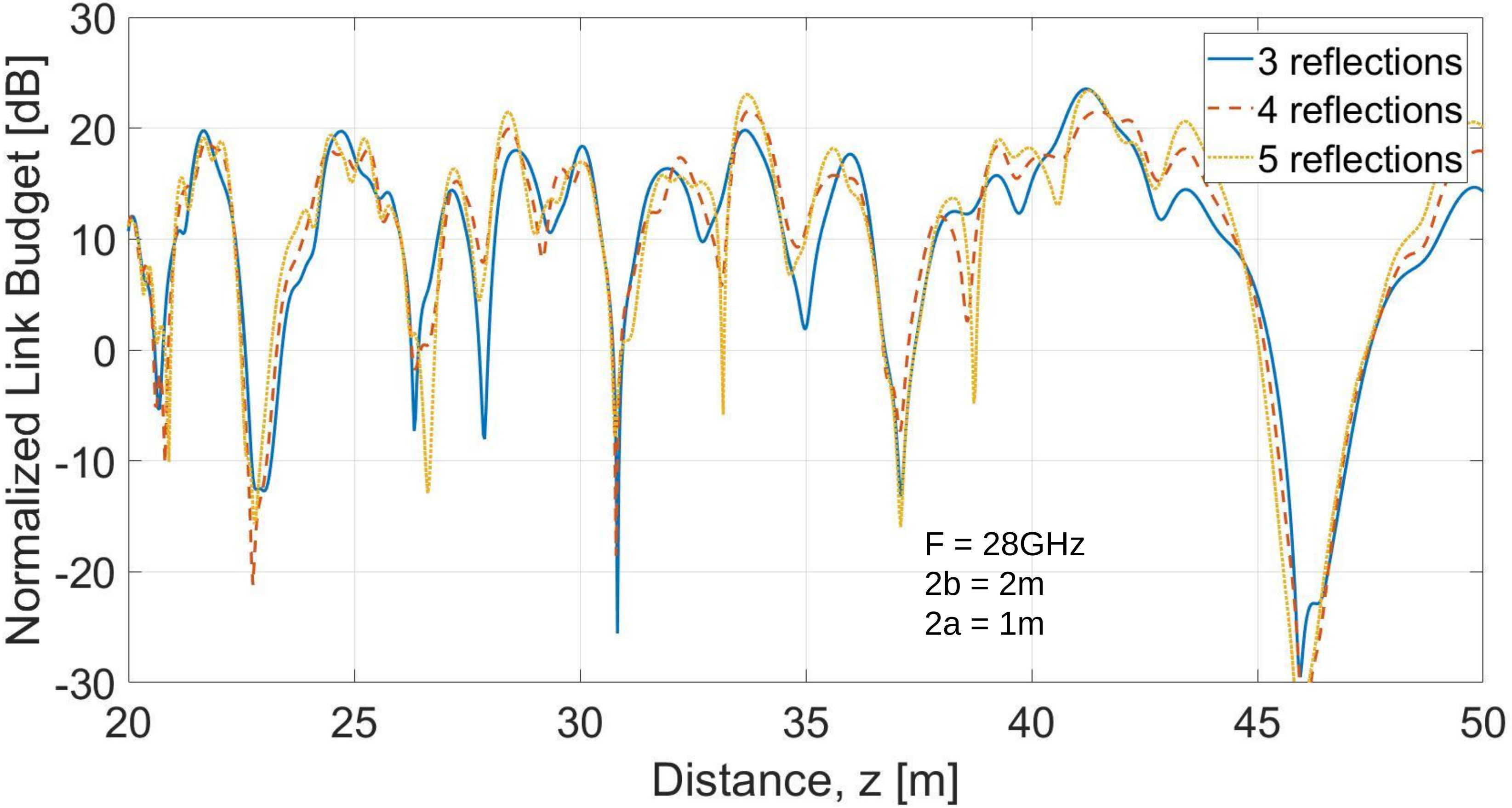
$$\Delta\tau(m,n) = \frac{R(m,n) - R_0}{c}$$

Gain and Phase



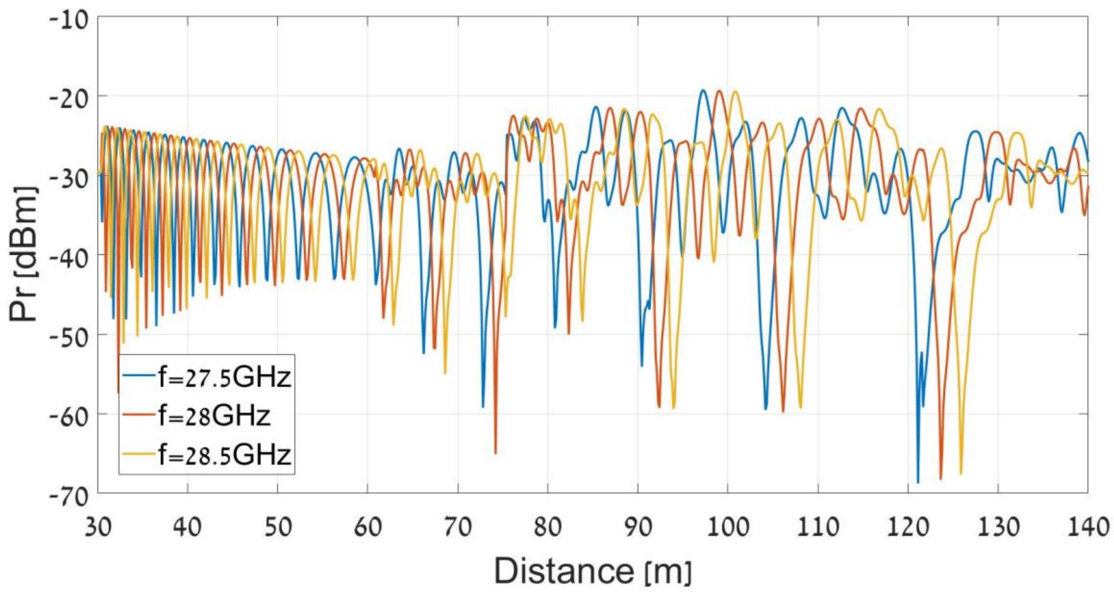


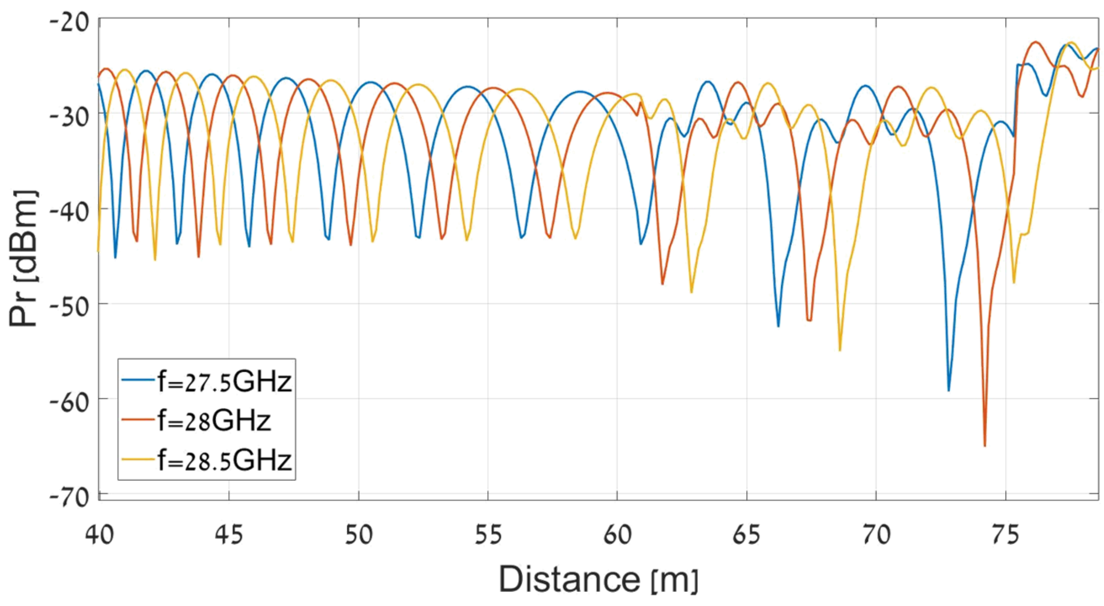
Link Budget



3 reflections
4 reflections
5 reflections
F = 28GHz
2b = 2m
2a = 1m
Normalized Link Budget [dB]
Distance, z [m]
30
20
10
0
-10
-20
-30
20
25
30
35
40
45
50

Different Frequencies Effects





Delay spread and Inter-Symbol Interference

Impulse Response

- Transfer function:

$$\tilde{H}(jf) = \frac{\tilde{E}_R(jf)}{\tilde{E}_T(jf)} = \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} \tilde{A}(m,n) \cdot e^{-j2\pi f \cdot \tau(m,n)}$$

- Impulse response

$$h(t) = \mathrm{Re}\left\{ \int_0^{\infty} \tilde{H}(jf) e^{+j2\pi ft} df \right\} = \mathrm{Re}\left\{ \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} \tilde{A}(m,n) \cdot \delta\left[t - \tau(m,n)\right] \right\}$$

Power Delay Profile

- Norm

$$\left\| h(t) \right\|^2 = \int_0^{\infty} \left| h(t) \right|^2 d\tau = \int_0^{\infty} \left| \tilde{H}(jf) \right|^2 df = \sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} \left| \tilde{A}(m,n) \right|^2$$

- Power delay profile:

$$P_h(\tau) = \frac{\left| h(\tau) \right|^2}{\left\| h(\tau) \right\|^2}$$

- Satisfying:

$$\int_0^{\infty} P_h(\tau)\, d\tau = 1$$

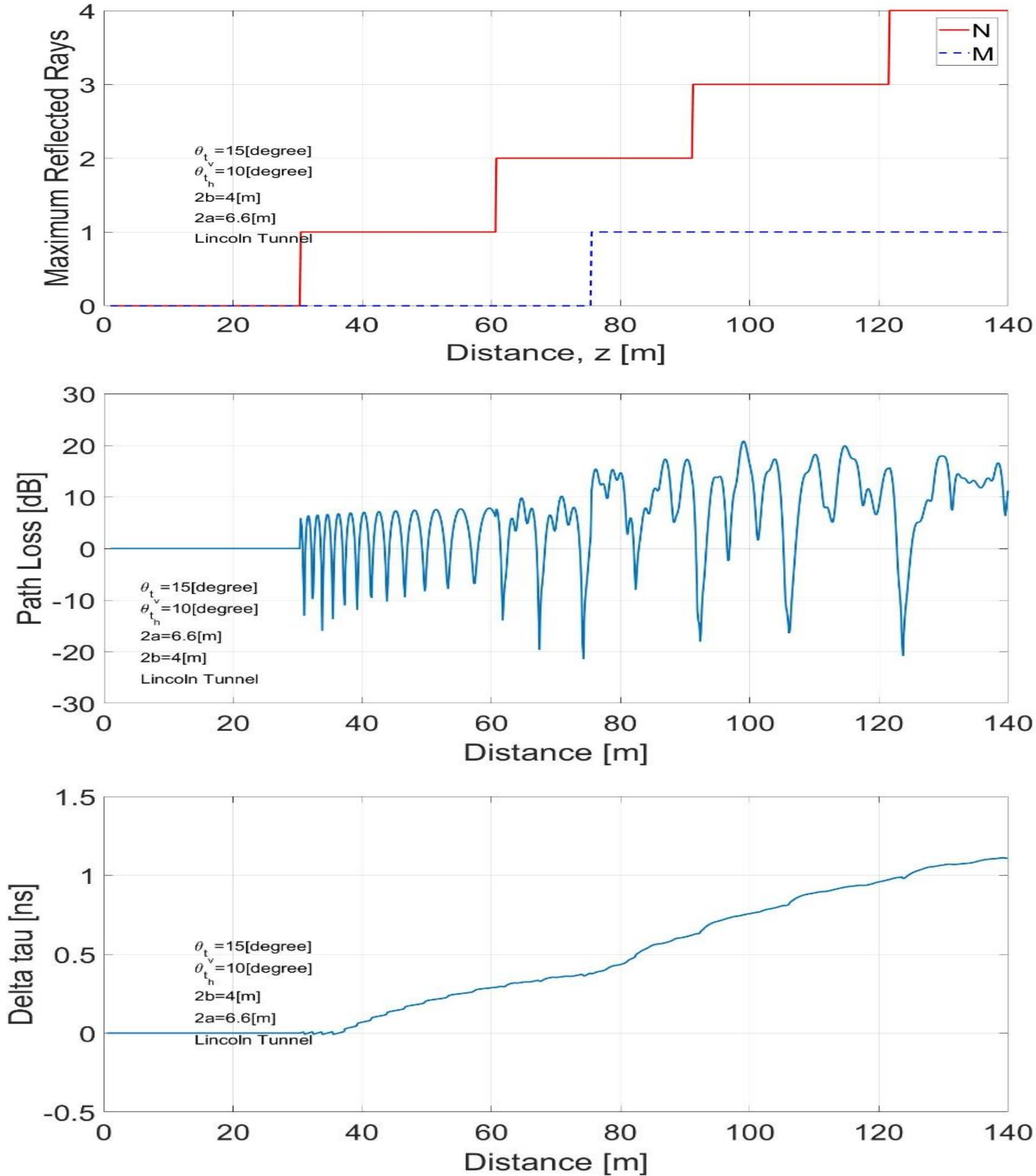
Group Delay

$$\bar{\tau} = \langle \tau \rangle = \int_0^{\infty} \tau \cdot P_h(\tau)\, d\tau = \frac{\sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} \tau(m,n) \cdot \left| \tilde{A}(m,n) \right|^2}{\sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} \left| \tilde{A}(m,n) \right|^2}$$

Delay Spread

$$\overline{\tau^2} = \int_0^{\infty} \tau^2 \cdot P_h(\tau)\, d\tau = \frac{\sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} \tau^2(m,n) \cdot \left|\tilde{A}(m,n)\right|^2}{\sum_{m=-\infty}^{+\infty} \sum_{n=-\infty}^{+\infty} \left|\tilde{A}(m,n)\right|^2}$$

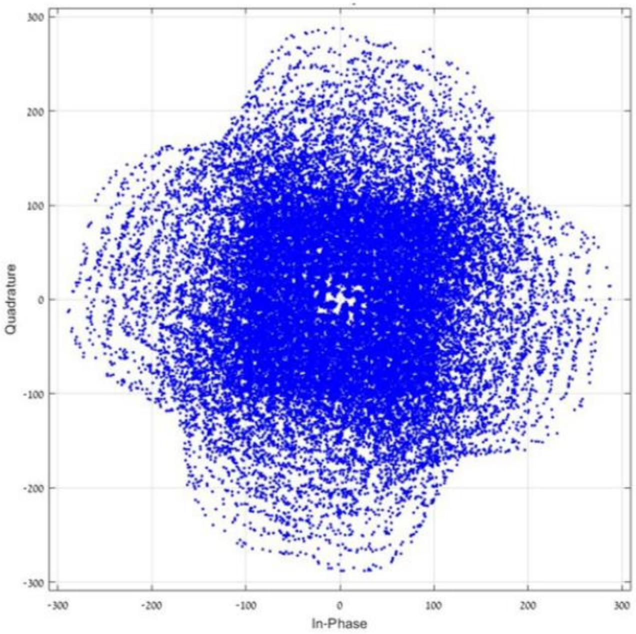
$$\sigma_\tau = \sqrt{\overline{\tau^2} - (\overline{\tau})^2} = \sqrt{\int_{-\infty}^{+\infty} \tau^2 \cdot P_h(\tau)\, d\tau - \left[\int_{-\infty}^{+\infty} \tau \cdot P_h(\tau)\, d\tau\right]^2}$$



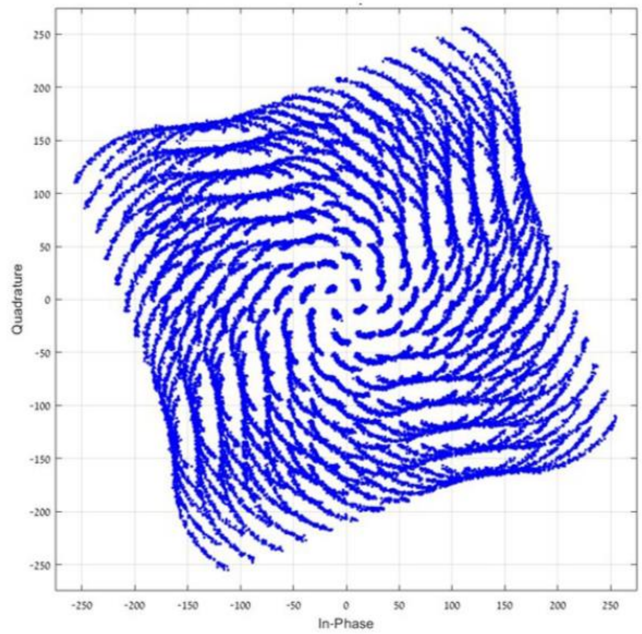
Maximum Reflected Rays
N
M
θtv=15[degree]
θth=10[degree]
2b=4[m]
2a=6.6[m]
Lincoln Tunnel
Distance, z [m]
Path Loss [dB]
θtv=15[degree]
θth=10[degree]
2a=6.6[m]
2b=4[m]
Lincoln Tunnel
Distance [m]
Delta tau [ns]
θtv=15[degree]
θth=10[degree]
2b=4[m]
2a=6.6[m]
Lincoln Tunnel
Distance [m]

256-QAM OFDM

BW=200MHz



BW=20MHz



Lincoln Tunnel

W=6.6m

H=4m

d=10m

$f_c = 28GHz$

SNR=40dB


Questions ?