

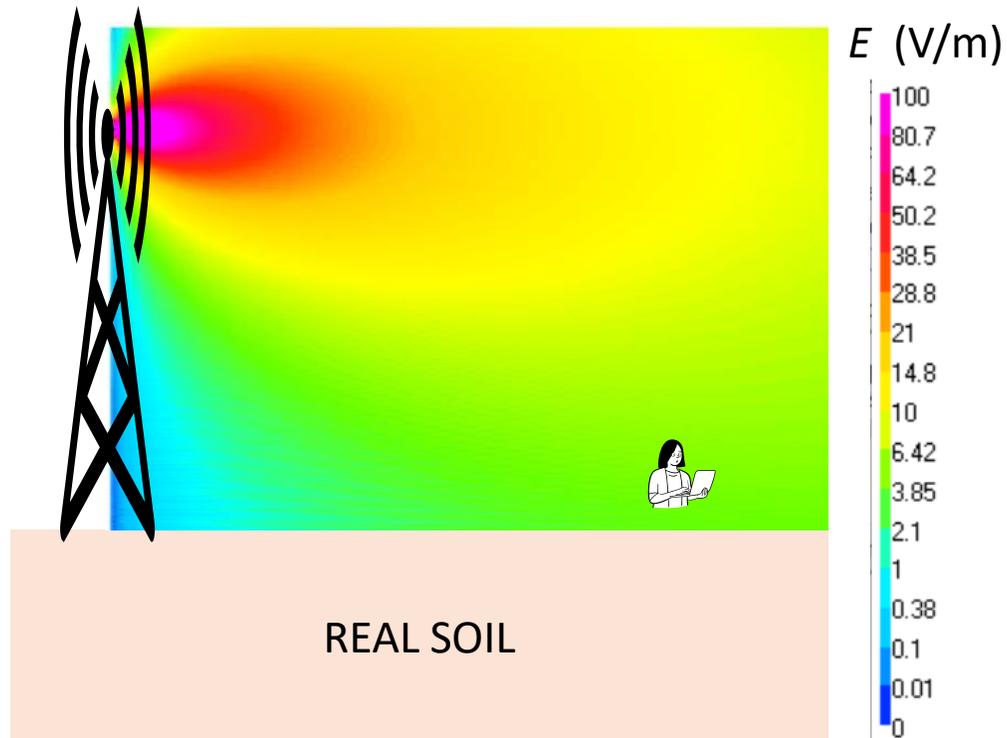
Channel Model of Line-of-Sight Radio Propagation by Reflection over Lossy Ground for Cellular Networks

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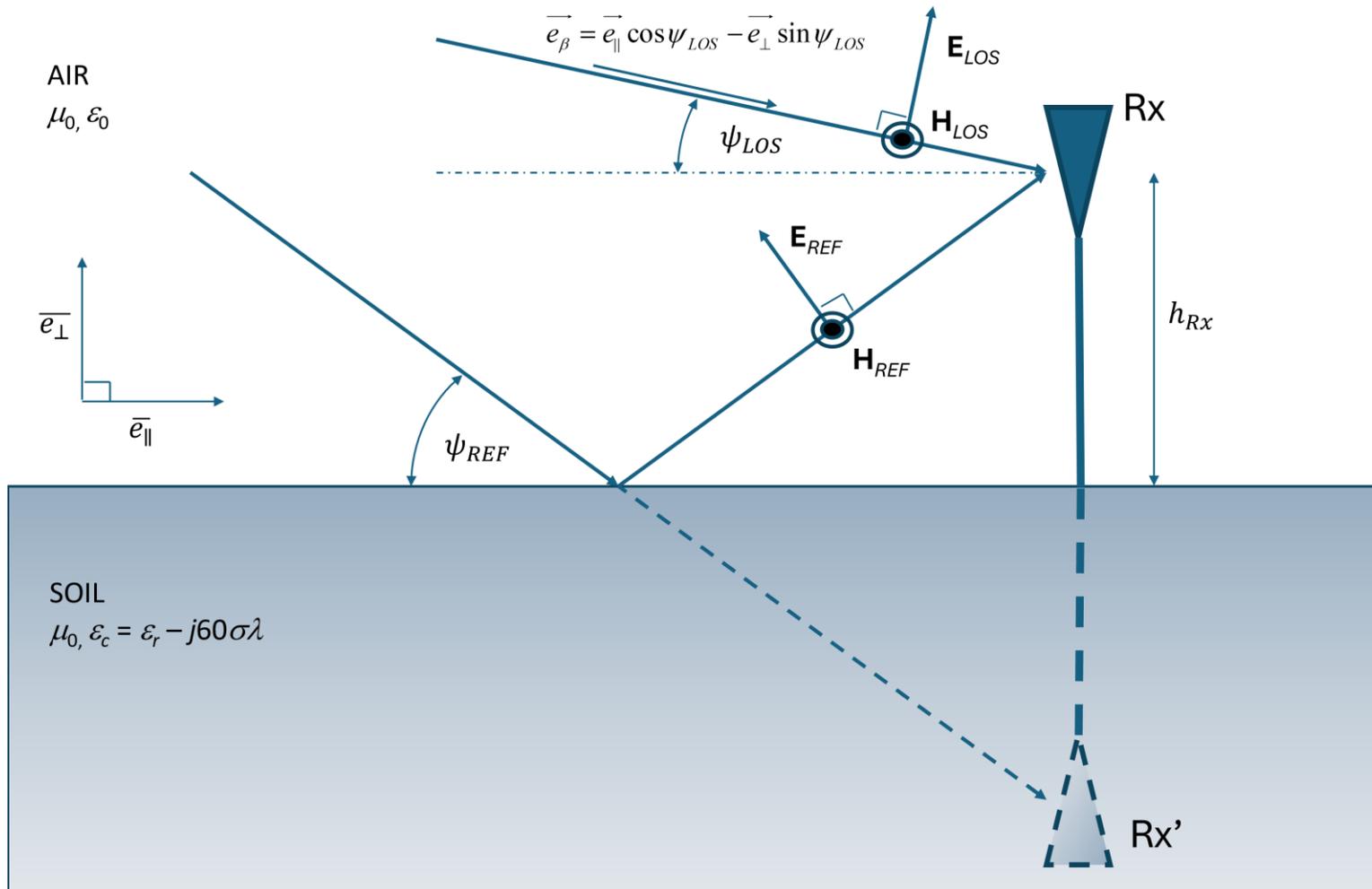
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Some basic issues in cellular networks



- What power could be expected by a user settled in the radiation near-field of the base station antenna, and how big is the propagation loss?
- How severe could the exposure issues be for the user?
- Can all these be predicted by analytical model with satisfactory accuracy?

Ray-tracing Analysis



Total E-field above ground:

$$\vec{E}_{Rx} = \vec{E}_{LOS} + \vec{E}_{REF} = \vec{E}(r_0) + \vec{E}(r_i)$$

Effective value of E-field in free space:

$$E(r) = \sqrt{\frac{Z_0 P_{Tx} G_{Tx}(\psi)}{4\pi}} \frac{1}{r}$$

Radio-path difference:

$$\Delta = r_i - r_0$$

Intrinsic impedance of free space is $Z_0 = 120\pi \Omega$.

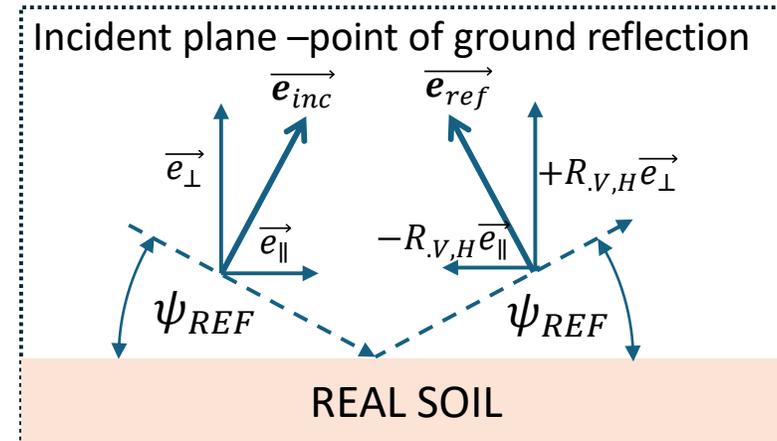
Modified Image Theory

- Vertically (parallel, or TM) polarized wave:

$$\vec{E}_{Rx} = \vec{e}_V E_{Rx}^V$$

- Horizontally (perpendicular, or TE) polarized wave:

$$\vec{H}_{Rx} = \vec{e}_H H_{Rx}^H$$



$$\vec{e}_{V,H} = \frac{1}{g_{\parallel}^{V,H}} \left[(\sin \psi_{LOS} - \kappa_{V,H} R_{V,H} e^{-j\beta\Delta} \sin \psi_{REF}) \vec{e}_{\parallel} + (\cos \psi_{LOS} - \kappa_{V,H} R_{V,H} e^{-j\beta\Delta} \cos \psi_{REF}) \vec{e}_{\perp} \right]$$

$$\kappa_{V,H} = \frac{r_0 G_{Tx}^{V,H}(\psi_{REF})}{r_i G_{Tx}^{V,H}(\psi_{LOS})} \quad g_{\parallel}^{V,H} = \sqrt{1 + 2\kappa_{V,H} \text{Re}(R_{V,H} e^{-j\beta\Delta}) \cos(\psi_{LOS} + \psi_{REF}) + \kappa_{V,H}^2 |R_{V,H}|^2}$$

Fresnel reflection coefficients:

$$R_V = \frac{\epsilon_c \sin \psi_{REF} - \sqrt{\epsilon_c - \cos^2 \psi_{REF}}}{\epsilon_c \sin \psi_{REF} + \sqrt{\epsilon_c - \cos^2 \psi_{REF}}} \quad R_H = \frac{\sin \psi_{REF} - \sqrt{\epsilon_c - \cos^2 \psi_{REF}}}{\sin \psi_{REF} + \sqrt{\epsilon_c - \cos^2 \psi_{REF}}}$$

EM Field Strength and Received Power

E-field at receiver point:

$$E_{Rx}^{V,H} = g_{\parallel,\perp}^{V,H} \sqrt{\frac{Z_0 P_{Tx} G_{Tx}^{V,H}(\psi_{LOS})}{4\pi}} \frac{1}{r_0}$$

H-field at receiver point:

$$H_{Rx}^{V,H} = g_{\perp,\parallel}^{V,H} \sqrt{\frac{P_{Tx} G_{Tx}^{V,H}(\psi_{LOS})}{4\pi Z_0}} \frac{1}{r_0}$$

EM power density at receiver point:

$$S^{V,H} = E_{Rx}^{V,H} H_{Rx}^{V,H} = g_{\parallel}^{V,H} g_{\perp}^{V,H} \frac{P_{Tx} G_{Tx}^{V,H}(\psi_{LOS})}{4\pi r_0^2}$$

Power absorbed by conjugate matched receiver:

$$P_{Rx}^{V,H} = \frac{\lambda^2}{4\pi} \sum_{\psi} G_{Rx}^{V,H}(\psi) S^{V,H}(\psi) = \gamma_{\parallel}^{V,H} \gamma_{\perp}^{V,H} \frac{P_{Tx} G_{Tx}^{V,H}(\psi_{LOS}) G_{Rx}^{V,H}(\psi_{LOS})}{4\pi r_0^2}$$

$$g_{\parallel}^{V,H} = \sqrt{1 + 2\kappa_{V,H} \text{Re}(R_{V,H} e^{-j\beta\Delta}) \cos(\psi_{LOS} + \psi_{REF}) + \kappa_{V,H}^2 |R_{V,H}|^2}$$

$$g_{\perp}^{V,H} = \sqrt{1 + 2\kappa_{V,H} \text{Re}(R_{V,H} e^{-j\beta\Delta}) + \kappa_{V,H}^2 |R_{V,H}|^2}$$

$$\kappa_{V,H} = \frac{r_0 G_{Tx}^{V,H}(\psi_{REF})}{r_i G_{Tx}^{V,H}(\psi_{LOS})}$$

$$\gamma_{\parallel}^{V,H} = \sqrt{1 + 2K_{V,H} \text{Re}(R_{V,H} e^{-j\beta\Delta}) \cos(\psi_{LOS} + \psi_{REF}) + K_{V,H}^2 |R_{V,H}|^2}$$

$$\gamma_{\perp}^{V,H} = \sqrt{1 + 2K_{V,H} \text{Re}(R_{V,H} e^{-j\beta\Delta}) + K_{V,H}^2 |R_{V,H}|^2}$$

$$K_{V,H} = \frac{r_0 G_{Tx}^{V,H}(\psi_{REF}) G_{Rx}^{V,H}(\psi_{REF})}{r_i G_{Tx}^{V,H}(\psi_{LOS}) G_{Rx}^{V,H}(\psi_{LOS})}$$

Path Gain

$$G^{V,H} = \frac{P_{Rx}^{V,H}}{P_{Tx}^{V,H}} = G_{FF}^{V,H} G_{FF}^{V,H} G_{FS} G_{Tx}^{V,H} G_{Rx}^{V,H} \quad G_{Tx,Rx}^{V,H} = G_{Tx,Rx}^{V,H} (\psi_{LOS})$$

$$G^{V,H}(dB) = G_{NF}^{V,H}(dB) + G_{FF}^{V,H}(dB) + G_{FS}(dB) + G_{Tx}^{V,H}(dB) + G_{Rx}^{V,H}(dB)$$

Free-space path-gain between two isotropic antennas:

$$G_{FS}(dB) = 20 \log \frac{\lambda}{4\pi r_0} = -32.45 - 20 \log f_{GHz} - 20 \log r_0$$

Ground-related propagation factors:

$$G_{FF}^{V,H}(dB) = 10 \log \left[1 + 2K_{V,H} \operatorname{Re}(R_{V,H} e^{-j\beta\Delta}) + K_{V,H}^2 |R_{V,H}|^2 \right]$$

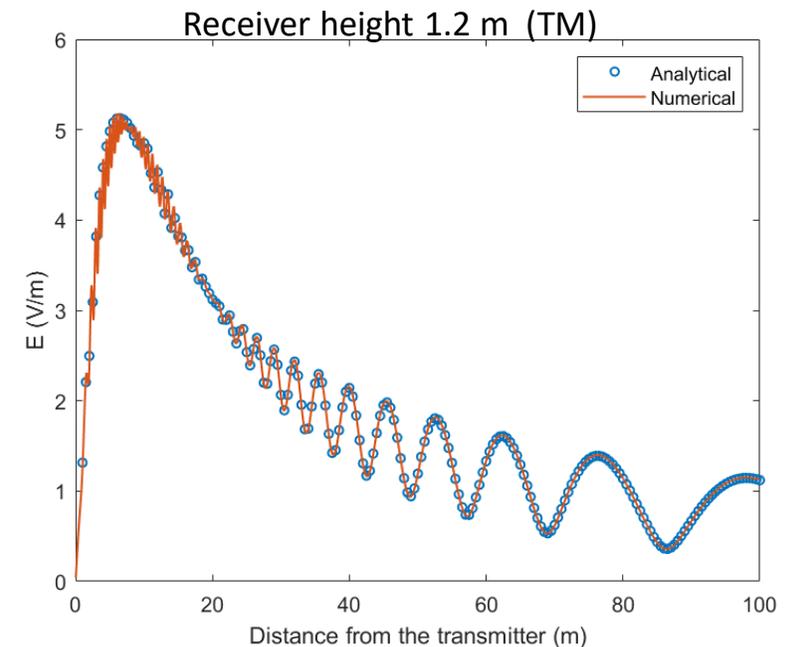
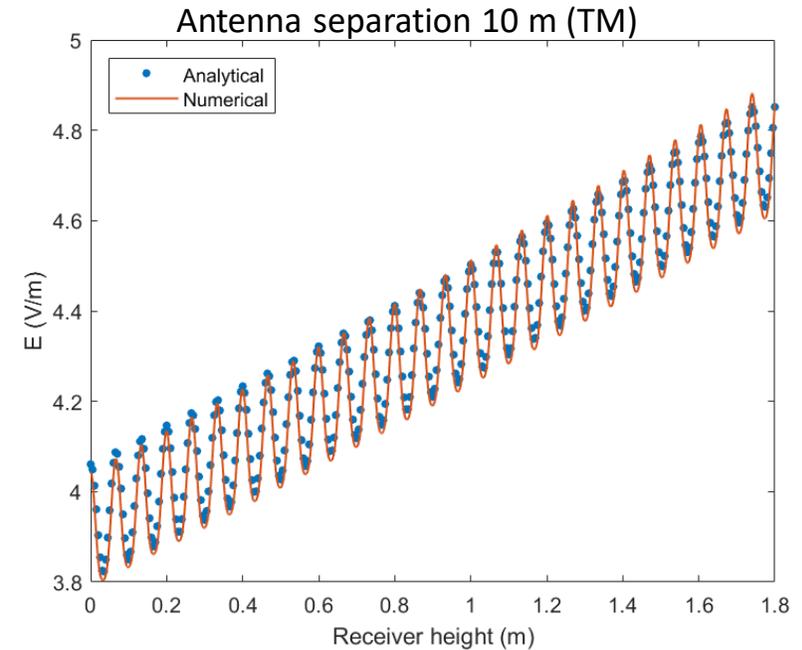
$$G_{NF}^{V,H}(dB) = 5 \log \left[1 - \frac{1 + 2K_{V,H} \operatorname{Re}(R_{V,H} e^{-j\beta\Delta}) [1 - \cos(\psi_{LOS} + \psi_{REF})]}{1 + 2K_{V,H} \operatorname{Re}(R_{V,H} e^{-j\beta\Delta}) + K_{V,H}^2 |R_{V,H}|^2} \right]$$

$$d > d_{max} \gg h_{Tx}, h_{Rx} \Rightarrow G_{FF}^{V,H} \approx \left(\frac{4\pi h_{Tx} h_{Rx}}{d\lambda} \right)^2 \quad \& \quad G_{NF}^{V,H} \approx 1 = 0 \text{ dB} \Rightarrow G^{V,H} \approx G_{Tx}^{V,H} G_{Rx}^{V,H} \left(\frac{h_{Tx} h_{Rx}}{d} \right)^2$$

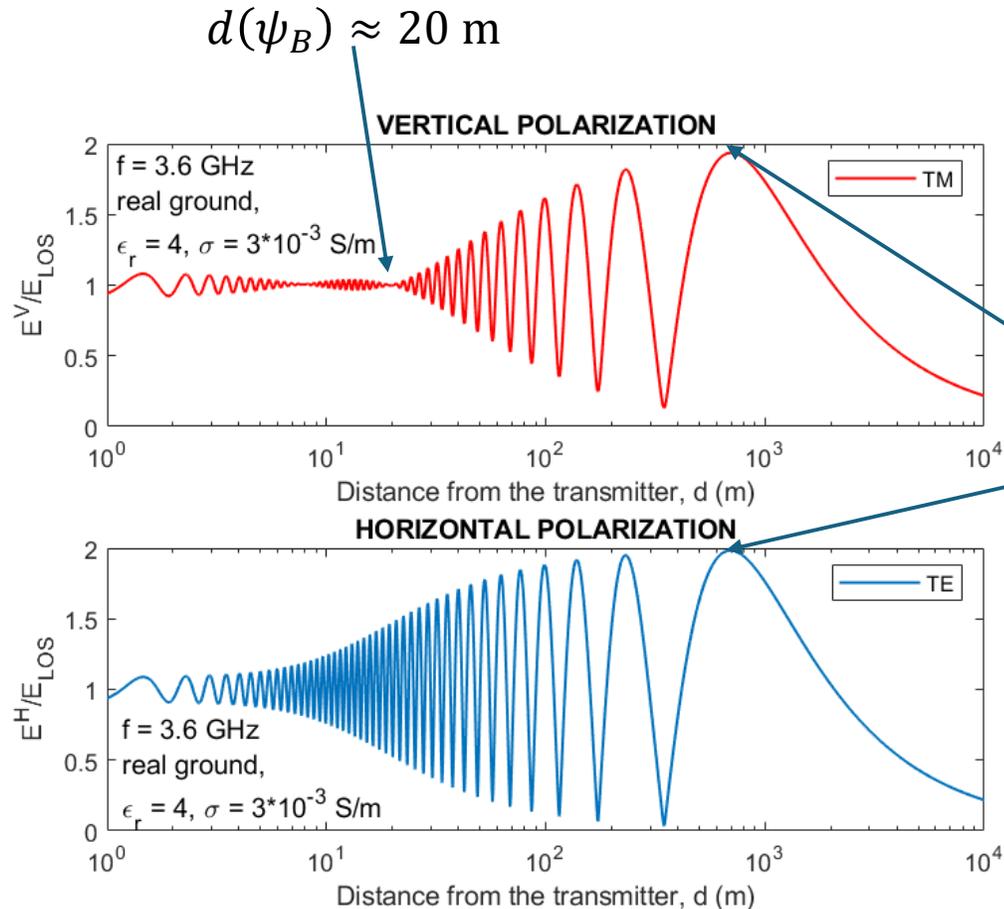
Example

- Vertical half-wave dipole (electric or magnetic) erected at eight meters above flat lossy ground
- Ground parameters: $\epsilon_r = 4$, $\sigma = 3 \cdot 10^{-3} \text{ Sm}^{-1}$
- Ground is a low-loss dielectric as: $\epsilon_r \gg 60 \sigma \lambda$
- Radiated power: $P_{TX} = 100 \text{ W}$ @ 3.6 GHz 5G-frequency
- Directive gain of half-wave dipole:

$$G_{Dipole}^{V,H} = 1.64 \frac{\cos^2\left(\frac{\pi}{2} \sin \psi\right)}{\cos^2 \psi}$$



Normalized electric field over ground vs. distance from the transmitter



Pseudo-Brewster angle:

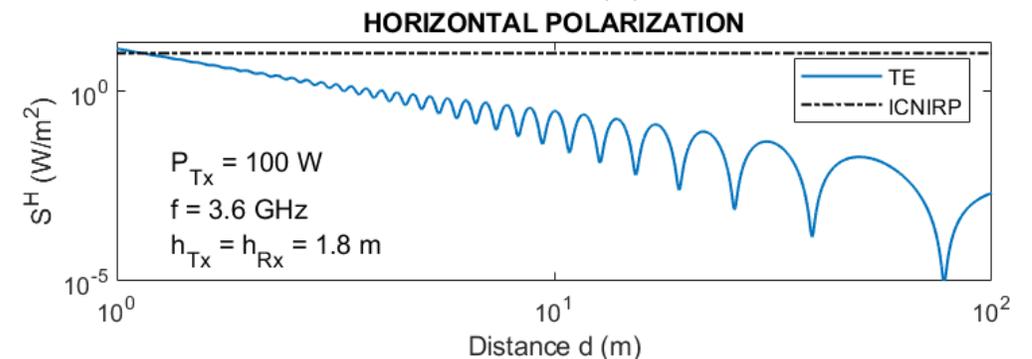
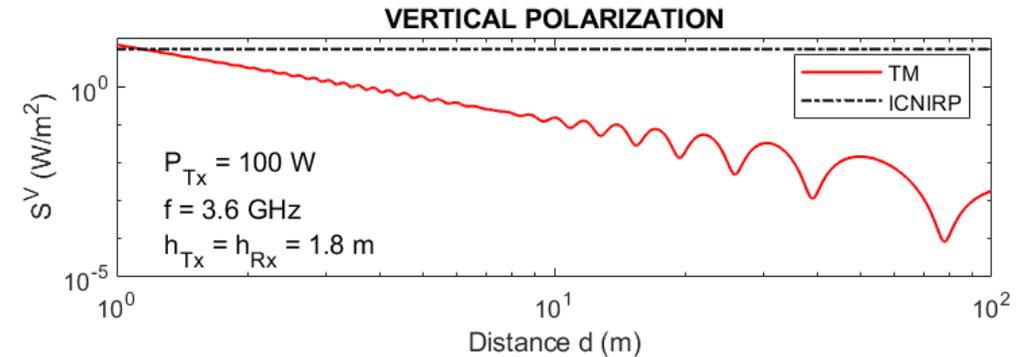
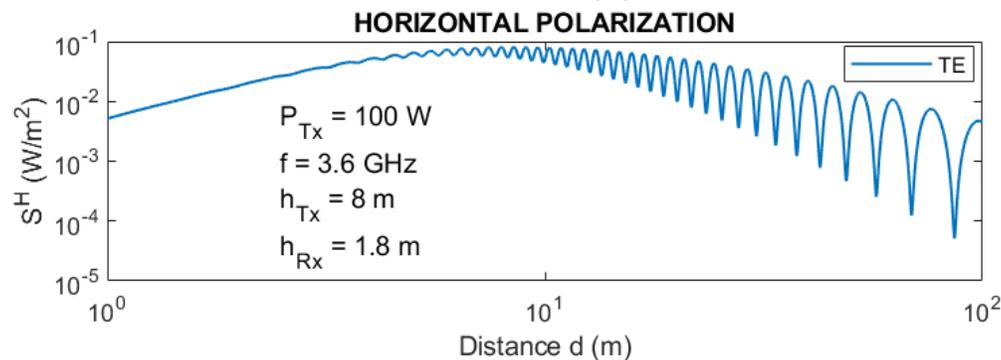
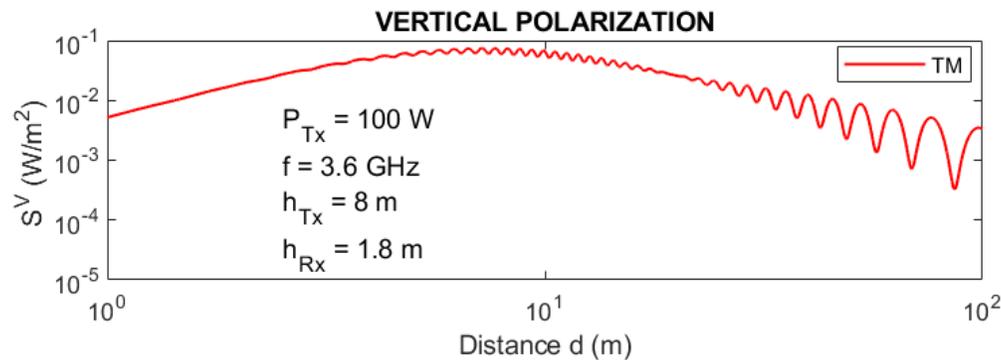
$$\psi_B = \sin^{-1} \frac{1}{\sqrt{1 + \epsilon_c}}$$

Far-field boundary:

$$d_{max} = \frac{4h_{Tx}h_{Rx}}{\lambda} = 692 \text{ m}$$

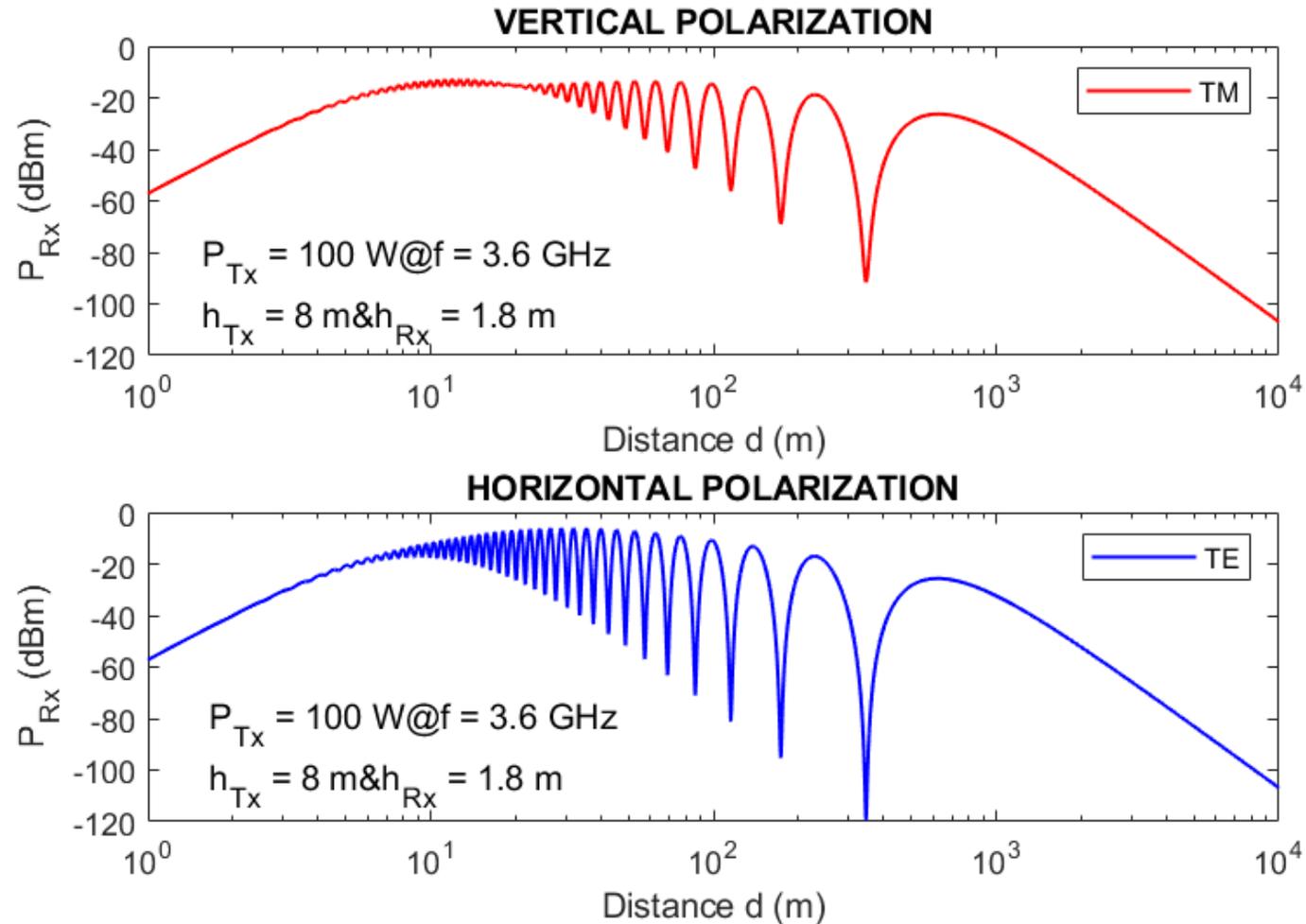
$$d > d_{max} \Rightarrow E_{Rx} \propto d^{-2} \Rightarrow P_{Rx} \propto d^{-4}$$

Incident power density vs. distance from the transmitter



ICNIRP: reference level for exposure to electromagnetic fields at $f > 2 \text{ GHz}$ averaged over 30 min and over the whole body is 10 W/m^2 for general population and 50 W/m^2 for occupational.

Power received by matched half-wave dipole receiver above real soil



Conclusion

- The analytical approach to model the LOS radio-propagation over realistic ground ensures reliable predictions of the channel parameters and dosimetry in all cases where the soil is out of the near-field region of the antennas.
- The proposed two-ray model can easily be upgraded by additional gain factors, such as rain attenuation or attenuation caused by water vapor and oxygen in the atmosphere. In addition, the radio-path lengths can be estimated allowing for tropospheric refraction. Also, the ground surface roughness can be included by using Rayleigh criterion for the reflection coefficients.
- As such, besides ground cellular networks, it can be easily applied to other radio networks for similar scenarios, e.g. to satellite ones.