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

1st Zoran Blažević
Dept. of Electronics and Computing
University of Split
Faculty of Electrical Engineering.
Mechanical Engineering and
Naval Architecture
Split, Croatia
zblaz@fesb.hr

2nd Maja Škiljo
Dept. of Electronics and Computing
University of Split
Faculty of Electrical Engineering.
Mechanical Engineering and
Naval Architecture
Split, Croatia
msekelja@fesb.hr

3rd Dragan Poljak
Dept. of Electronics and Computing
University of Split
Faculty of Electrical Engineering.
Mechanical Engineering and
Naval Architecture
Split, Croatia
dpoljak@fesb.hr

***Abstract*—In this paper, we propose radio-channel model for propagation over realistic ground. The formulas for electromagnetic field strength, power density, and the path-gain are derived. The results obtained by the proposed model in the case of transmitting half-wave dipole at a 5G frequency are first validated by full-wave model results and discussed upon. Also, the dosimetry parameters for the human exposure at a 5G frequency are inspected for radiated power of 100 W and different transmitter heights.**

***Index Terms*—radio-propagation over ground, incident field strength, incident power density, path-gain.**

I. Introduction

The contemporary development of cellular networks, aimed at satisfying an increasing number of services and users [1], places new demands on network planning and opens new issues in electromagnetic compatibility (EMC) and exposure dosimetry [2], [3]. In order to build a radio network that ensures good Quality-of-Service (QoS) and that, at the same time, obeys EMC and exposure limits, proper estimation and characterization of the received field strength and power are of the outermost importance. For that purpose, extensive measurements and complex simulation tools are commonly used.

As in the classic cellular networks the mobile receiver is usually in the radio shadow (of buildings, etc.), their physical layer is characterized statistically, as in [4], with the possibility to estimate the mean power and path-loss law analytically as in [5]. Examples of the radio-channel characterization in new generations of the networks can be found in, e.g., [6], [1].

However, new generations of mobile networks (5G/6G) will also result in a larger number of base station antennas erected at lower or moderate heights serving nearby users with a clear Line-of-Sight (LOS) path to their devices. In such scenarios, the received field pattern is shaped mostly by the energy arriving via the LOS path and the ground-reflected path, whereas the diffuse multipath component can be expected to be rather small. Then, a quite accurate prediction of the received signal strengths is possible to obtain analytically.

However, the often used classic far-field model for radio-propagation over ground from [7] (Eq. (3.37)) may not be fully adequate for the purpose. On the other hand, the influence of the ground cannot be neglected by relying solely on the Fris formula for the free-space propagation [8]. Furthermore, although it respects the impact of the antenna radiation patterns on the direct and ground-reflected field, the enhanced model of [9], [10] does not take into account their different angles-of-arrival to the receiving point.

Therefore, in this paper, we propose an analytical approach to the analysis of the LOS radio propagation over ground based on ray-tracing method, including the scenarios where the antennas' heights are comparable to their mutual separation. This analytical model can provide a quick assessment of the received field strength and other dosimetry parameters, for various situations using different frequencies, polarization, radiated power, antennas' heights and radiation patterns. Besides antenna characteristics and propagation geometry, the proposed two-path model takes into account the properties of soil through Fresnel's reflection coefficients, resulting in an excellent agreement with the numerical results calculated by 4nec2 software.

II. Electromagnetic Field of Dipole Above Ground

The strength of the electric field (in volts per meter) in free space at a distance r far from the transmitter with the gain pattern G_{Tx} that radiates the power P_{Tx} (in watts) is given by [7]:

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

This work was supported by the Croatian Science Foundation under the project number HRZZ-IPS-2024-02-7779.

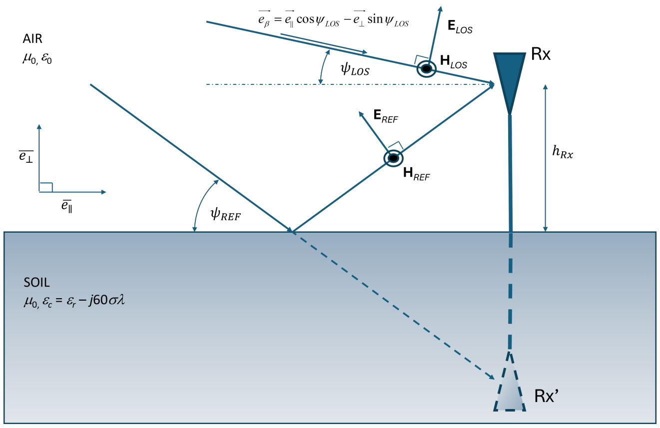

Fig. 1. Vertically (TM) polarized EM field incidence above lossy ground.

where $Z_0 = 120\pi\ \Omega$ is the free-space impedance. The magnetic field strength in the far zone of the transmitter is simply $H = \frac{E}{Z_0}$. The fields propagate through space as $\boldsymbol{E}, \boldsymbol{H} \propto e^{-j\beta r}$, $\beta = \frac{2\pi}{\lambda} = \frac{2\pi f}{c}$, c being the velocity of light and λ is the wavelength.

Let us now consider radiation in the far-field at a frequency f of a matched dipole settled at a height $h_{Tx} >> \lambda$ above infinite real soil of permittivity ϵ_r and conductivity σ. Following Fig. 1, the incident field at the observed point T in the upper space is the sum of two components:

$$\vec{\boldsymbol{E}}\left(T\right) = \vec{\boldsymbol{E}}_{LOS}\left(T\right) + \vec{\boldsymbol{E}}_{REF}\left(T\right) \tag{2}$$

where, applying (1), $\vec{\boldsymbol{E}}_{LOS}\left(T\right) = \vec{\boldsymbol{E}}\left(\vec{r_0}\right)$ is the direct wave component and $\vec{\boldsymbol{E}}_{REF}\left(T\right) = \vec{\boldsymbol{E}}\left(\vec{r_i}\right)$ is the reflected wave component. Here, r_0 and r_i are the radio-path lengths of direct and reflected wave, respectively.

The reflected field can be calculated applying modified image theory and Fresnel reflection coefficients R_H and R_V for perpendicular (horizontal or transverse electric (TE)) polarization and for parallel (vertical or transverse magnetic (TM)) polarization, respectively. In the case of flat smooth ground, they can be expressed as:

$$R_H = \frac{\sin\psi_{REF} - \sqrt{\epsilon_c - \cos^2\psi_{REF}}}{\sin\psi_{REF} + \sqrt{\epsilon_c - \cos^2\psi_{REF}}} \tag{3}$$

$$R_V = \frac{\epsilon_c\sin\psi_{REF} - \sqrt{\epsilon_c - \cos^2\psi_{REF}}}{\epsilon_c\sin\psi_{REF} + \sqrt{\epsilon_c - \cos^2\psi_{REF}}} \tag{4}$$

where $\epsilon_c = \epsilon_r - j60\sigma\lambda$ is the complex permittivity of soil. The roughness and curvature of the ground surface can also be included in the calculation, according to the Rayleigh criterion and applying the divergence factor, respectively [7] .

A. Vertically polarized wave

Accounting for the field components parallel to the ground and the perpendicular ones while applying (2), the strength of the vertically polarized total electric field above ground can be expressed as:

$$E_{Rx}^{V} = g_{\parallel}^{V}\sqrt{\frac{Z_0 P_{Tx} G_{Tx}\left(\psi_{LOS}\right)}{4\pi}}\frac{1}{r_0} \tag{5}$$

where, in the case of parallel polarization, the influence of the ground on the total electric field is expressed by the parameter:

$$g_{\parallel}^{V} = \sqrt{1 + 2\kappa Re\left(R_V e^{-j\beta\Delta}\right)\cos\left(\psi_{LOS} + \psi_{REF}\right) + \kappa^2|R_V|^2} \tag{6}$$

in which $\Delta = r_i - r_0$, and:

$$\kappa = \frac{r_0 G_{Tx}\left(\psi_{REF}\right)}{r_i G_{Tx}\left(\psi_{LOS}\right)} \tag{7}$$

where, in this case, G_{Tx} refers to the vertically polarized antenna radiation pattern. In a sense, the parameter κ weights the contribution of the field component reflected from the soil to the total field relative to the antenna radiation pattern and the receiver height.

Applying (2), the total electric field at the observed point above ground is found to be oriented in the direction of the complex unit vector:

$$\begin{aligned}\vec{e}_V = \frac{1}{g_{\parallel}^{V}}\{&\left[\sin\psi_{LOS} - \kappa R_V\sin\psi_{REF}e^{-j\beta\Delta}\right]\vec{e}_{\parallel}\\ &+ \left[\cos\psi_{LOS} + \kappa R_V\cos\psi_{REF}e^{-j\beta\Delta}\right]\vec{e}_{\perp}\}\end{aligned} \tag{8}$$

At the same time, the total magnetic field at the observation point is perpendicular to the incident plane (in direction of ort vector $\vec{n} = \vec{e}_{\parallel} \times \vec{e}_{\perp}$) and its strength can be expressed as:

$$H_{Rx}^{V} = g_{\perp}^{V}\sqrt{\frac{P_{Tx} G_{Tx}\left(\psi_{LOS}\right)}{4\pi Z_0}}\frac{1}{r_0} \tag{9}$$

where, in the case of parallel polarization, the influence of the ground on the total magnetic field is expressed by the parameter:

$$g_{\perp}^{V} = \sqrt{1 + 2\kappa Re\left(R_V e^{-j\beta\Delta}\right) + \kappa^2|R_V|^2} \tag{10}$$

Considering that the electric and magnetic fields are mutually perpendicular, the power density at the observed point can be expressed as:

$$S^V = E_{Rx}^{V} H_{Rx}^{V} = G_G^V \frac{P_{Tx} G_{Tx}\left(\psi_{LOS}\right)}{4\pi r_0^2} \tag{11}$$

where $G_G^V = g_{\parallel}^{V} g_{\perp}^{V}$.

B. Horizontally polarized wave

The analysis for the case of horizontal polarization follows the same procedure as for the vertical one. The horizontally polarized electric field is in the direction of the ort vector $-\vec{n}$, and its strength is:

$$E_{Rx}^{H} = g_{\perp}^{H}\sqrt{\frac{Z_0 P_{Tx} G_{Tx}\left(\psi_{LOS}\right)}{4\pi}}\frac{1}{r_0} \tag{12}$$

where:

$$g_\perp^H = \sqrt{1 + 2\kappa Re\left(R_H e^{-j\beta\Delta}\right) + \kappa^2 |R_H|^2} \tag{13}$$

Here, G_{Tx} refers to the horizontally polarized antenna radiation pattern.

The total magnetic field is in the direction of the unit vector:

$$\begin{aligned} \vec{e}_H = \frac{1}{g_\parallel^H}\{&\left[\sin\psi_{LOS} - \kappa R_H \sin\psi_{REF} e^{-j\beta\Delta}\right]\vec{e}_\parallel \\ &+ \left[\cos\psi_{LOS} + \kappa R_H \cos\psi_{REF} e^{-j\beta\Delta}\right]\vec{e}_\perp\} \end{aligned} \tag{14}$$

where:

$$g_\parallel^H = \sqrt{1 + 2\kappa Re\left(R_H e^{-j\beta\Delta}\right)\cos\left(\psi_{LOS} + \psi_{REF}\right) + \kappa^2 |R_H|^2} \tag{15}$$

As the magnetic field strength can be expressed as:

$$H_{Rx}^H = g_\parallel^H \sqrt{\frac{P_{Tx} G_{Tx}\left(\psi_{LOS}\right)}{4\pi Z_0}}\frac{1}{r_0} \tag{16}$$

the power density of the horizontally polarized wave is given by:

$$S^H = E_{Rx}^H H_{Rx}^H = G_G^H \frac{P_{Tx} G_{Tx}\left(\psi_{LOS}\right)}{4\pi r_0^2} \tag{17}$$

where $G_G^H = g_\perp^H g_\parallel^H$.

C. Path gain

With knowledge about the incident power density, the power absorbed by the receiver antenna can be calculated as:

$$P_{Rx}^{V,H} = \frac{\lambda^2}{4\pi} G_{Rx}^{V,H}\left(\psi_{EM}\right) S^{V,H} \tag{18}$$

where G_{Rx} is the gain pattern of the receiving antenna, and where indices V and H refer to vertical (parallel) and horizontal (perpendicular) polarization, respectively.

Depending on polarization, the arrival angle ψ_{EM} of the power at the receiving antenna is determined by the unit vector:

$$\vec{e}_S^{V,M} = \vec{e}_{V,M} \times \vec{n} \tag{19}$$

and the total path gain for radio channels over ground can be expressed as:

$$\begin{aligned} G^{V,H} &= \frac{P_{Rx}^{V,H}}{P_{Tx}^{V,H}} \\ &= G_{FS} G_G^{V,H} G_{Tx}^{V,H}\left(\psi_{LOS}\right) G_{Rx}^{V,H}\left(\psi_{EM}\right) \end{aligned} \tag{20}$$

where G_{FS} is the free-space path gain.

In decibels, denoting $G_{Tx} = G_{Tx}^{V,H}\left(\psi_{LOS}\right)$, $G_{Rx} = G_{Rx}^{V,H}\left(\psi_{EM}\right)$, and expressing $G_G = G_{FF} G_{NF}$, it is given by:

$$\begin{aligned} G^{V,H}(dB) = G_{FS}(dB) + G_{FF}(dB) + G_{NF}(dB) \\ + G_{Tx}(dB) + G_{Rx}(dB) \end{aligned} \tag{21}$$

where:

$$\begin{aligned} G_{FS}(dB) &= 20\log\frac{\lambda}{4\pi r_0} \\ &= -32.45 - 20\log f_{GHz} - 20\log r_0 \end{aligned} \tag{22}$$

is the Fris equation where f_{GHz} is frequency in gigahertz,

$$G_{FF}^{V,H}(dB) = 10\log\left[1 + 2\kappa Re\left(R_{V,H} e^{-j\beta\Delta}\right) + \kappa^2 |R_{V,H}|^2\right] \tag{23}$$

$$G_{NF}^{V,H}(dB) = 5\log \left[1 - \frac{2\kappa Re\left(R_{V,H} e^{-j\beta\Delta}\right)\left[1 - \cos\left(\psi_{LOS} + \psi_{REF}\right)\right]}{1 + 2\kappa Re\left(R_{V,H} e^{-j\beta\Delta}\right) + \kappa^2 |R_{V,H}|^2}\right] \tag{24}$$

The factor G_{FF} dominates at long distances and depicts the radio propagation of the far field. On the other hand, G_{NF} models the impact on the radiation near field of the antenna above ground where the antenna separations are comparable to their heights, and it vanishes at large distances from the transmitter where $d >> h_{Tx}, h_{Rx}$.

If necessary, in addition to introducing ground roughness in (3), (4), the proposed model can be easily upgraded by additional gain factors in (20), i.e. in (21), such as rain attenuation or attenuation caused by water vapor and oxygen in the atmosphere. Also, the radio-path lengths r_0 and r_i can be estimated allowing the tropospheric refraction [7].

D. Vertical electric dipole above ground

Let us now take a typical example of a vertical half-wave electric dipole radiating the power $P_{Tx} = 100$ W at a 5G frequency of $f = 3.6$ GHz. It is erected at a height $h_{Tx} = 8$ m above flat lossy ground. Its directive gain pattern can be expressed as:

$$G_{Tx} = 1.64\frac{\cos^2\left(\frac{\pi}{2}\sin\psi\right)}{\cos^2\psi} \tag{25}$$

where the launch angle ψ is measured relative to the line perpendicular to the antenna axis, which is parallel to the ground and in the direction of maximum radiation.

The soil permittivity at the selected frequency is taken to be $\epsilon_r = 4$, and the conductivity $\sigma = 3 \cdot 10^{-3}$ S/m. As $\epsilon_r >> 60\sigma\lambda$, the soil behaves as a low-loss dielectric.

First, in order to validate the proposed analytical model for radio-propagation over ground, we verify the results of the received electric field strength at a distance of 10 m calculated by (5) with the results of the full-wave model obtained by 4nec2 using the Method of Moments in Fig. 2. In 4nec2, a 4.15 cm long straight wire with a radius of 0.1 mm fed at the center is used to simulate the transmitter. There is excellent agreement between the analytical and numerical results. The field strength varies in an oscillatory manner with the receiver height showing a quasi-linear trend of increasing as the antenna separation becomes less.

The received electric field normalized to the strength of electric field in free-space versus distance from the transmitter is given in Fig. 3, and compared to the case of the half-wave magnetic dipole (with equal radiation pattern). The oscillations

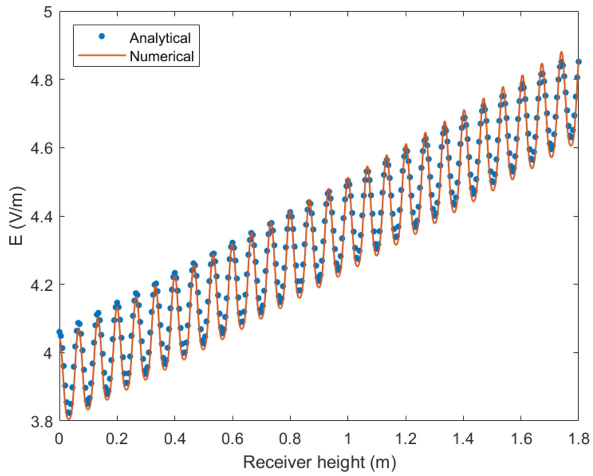

Fig. 2. Comparison between analytical and numerical results for the received electric field above ground 10 meters from the dipole (vertical polarization)

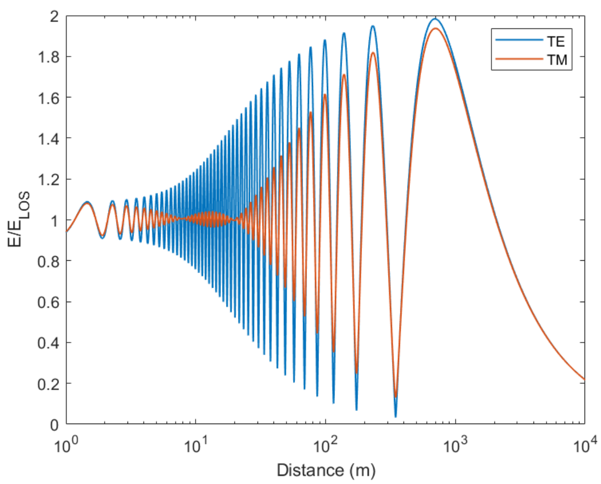

Fig. 3. Normalized electric field over ground vs. distance from the transmitter

of the field strength are more emphasized for horizontal polarization, which is caused by difference in the reflection coefficients. The position of the farthest (last) maximum is equal in both cases (as expected), showing that the 3,6-GHz far field of the dipole erected eight meters over ground begins at roughly 700 m away.

Aside for the network optimization, accurate predictions of the incident field strength are also very important for reliable EM dosimetry. Besides the incident field is one of the dosimetry parameters itself [11], it is an input parameter for the calculation of other exposure parameters such like the incident power density (see (11), (17)), the in-body induced electric field, etc. [2]. However, following ICNIRP [11], it is not applicable to the selected 5G frequency. An applicable one is the incident power density, for which the reference level for exposure to electromagnetic fields at $f > 2$ GHz averaged over 30 min and over the whole body is 10 W/m^2 for general

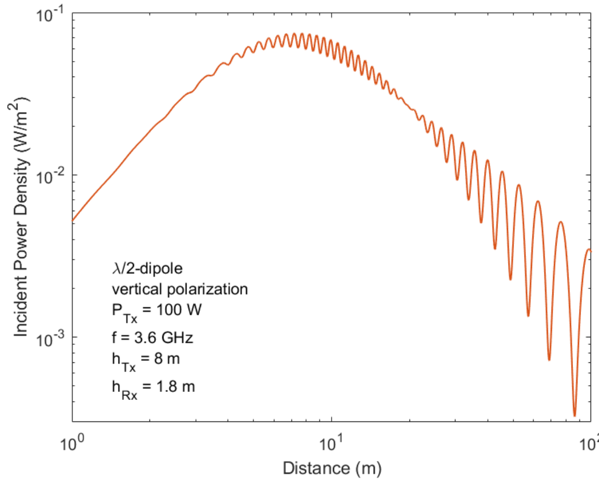

Fig. 4. Incident power density vs. height over ground for the transmitter height of 8 m

population and 50 W/m^2 for occupational.

The incident power density against the distance from the transmitter calculated by (11) for the selected scenario is given in Fig. 4. Besides on the distance, it is vividly governed by the properties of ground and antenna radiation pattern. The maximum power density is at roughly eight meters away from the transmitter, exhibiting more oscillatory behavior as the distance increases. The obtained values are found to be well below the exposure limits.

To assess the impact of the antenna radiation pattern in combination with the transmitter height, we checked the same scenario, but of the dipole at height $h_{Tx} = h_{Rx} = 1.8$ m where $G_{Tx} = 1.64 = 2.15$ dB. The results are shown in Fig. 5. In this case, however, the power density has a continuous trend of decreasing with distance, and the exposure limit for general public is exceeded in the antenna vicinity, up to more than a meter from.

III. Conclusion

The proposed channel model for 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, and it can be easily upgraded by additional gain factors if needed. As such, it can be well applied to the characterization of LOS radio channels in cellular and radio networks of other types in similar scenarios. With some caution necessary due to the Fresnel approximation for the Sommerfeld reflection coefficients, it could also be tested for the transmitter in greater proximity to the ground. However, we are leaving this matter for future considerations.

Acknowledgment

This work was supported by the Croatian Science Foundation under the project number HRZZ-IPS-2024-02-7779.

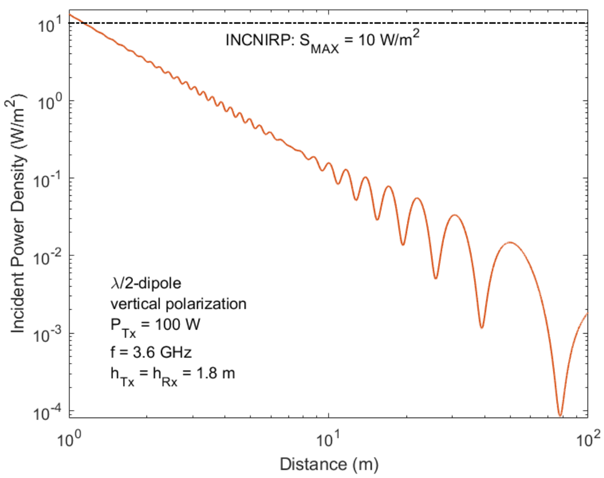

Fig. 5. Incident power density vs. height over ground for the transmitter height of 1.8 m

References

[1] T. S. Rappaport, S. Sun, R. Mayzus, H. Zhao, Y. Azar, K. Wang, G. N. Wong, J. K. Schulz, M. Samimi, and F. Gutierrez, "Millimeter wave mobile communications for 5g cellular: It will work!" *IEEE Access*, vol. 1, pp. 335–349, 2013.

[2] L. Chiaraviglio, A. Elzanaty, and M.-S. Alouini, "Health risks associated with 5g exposure: A view from the communications engineering perspective," *IEEE Open Journal of the Communications Society*, vol. 2, pp. 2131–2179, 2021.

[3] W. H. Bailey, B. R. T. Cotts, and P. J. Dopart, "Wireless 5g radiofrequency technology — an overview of small cell exposures, standards and science," *IEEE Access*, vol. 8, pp. 140 792–140 797, 2020.

[4] H. Suzuki, "A statistical model for urban radio propogation," *IEEE Transactions on Communications*, vol. 25, no. 7, pp. 673–680, 1977.

[5] D. Chizhik and J. Ling, "Propagation over clutter: Physical stochastic model," *IEEE Transactions on Antennas and Propagation*, vol. 56, no. 4, pp. 1071–1077, 2008.

[6] V. R. F. Guijarro, J. D. Vega Sánchez, M. C. P. Paredes, F. G. Arévalo, and D. P. M. Osorio, "Comparative evaluation of radio network planning for different 5g-nr channel models on urban macro environments in quito city," *IEEE Access*, vol. 12, pp. 5708–5730, 2024.

[7] L. Boithias, *Radio Wave Propagation*. North Oxford Academic, 1987. [Online]. Available: https://books.google.hr/books?id=H62lQAAACAAJ

[8] T. K. Sarkar, S. Burintramart, N. Yilmazer, S. Hwang, Y. Zhang, A. De, and M. Salazar-Palma, "A discussion about some of the principles/practices of wireless communication under a maxwellian framework," *IEEE Transactions on Antennas and Propagation*, vol. 54, no. 12, pp. 3727–3745, 2006.

[9] S. Loyka and A. Kouki, "Using two ray multipath model for microwave link budget analysis," *IEEE Antennas and Propagation Magazine*, vol. 43, no. 5, pp. 31–36, 2001.

[10] S. Loyka, A. Kouki, and F. Gagnon, "Fading prediction on microwave links for airborne communications," in *IEEE 54th Vehicular Technology Conference. VTC Fall 2001. Proceedings (Cat. No.01CH37211)*, vol. 4, 2001, pp. 1960–1964 vol.4.

[11] ICNIRP, "Guidelines for limiting exposure to electromagnetic fields (100 khz to 300 ghz)," *Health Physics*, vol. 5, no. 118, pp. 483–524, May 2020.