On the Use of Efficient Methods for the Assessment of Radiated Field from Radio Base Station Antennas and Related Legal Issues Pertaining to Human Exposure to Nonionizing Radiation
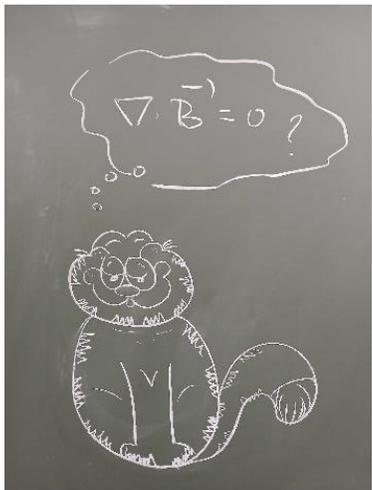
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mipro 2025

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JUNE 02 - 06, 2025 OPATIJA, CROATIA
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INTRODUCTION

- Contemporary wireless communication systems operating in the GHz frequency range must provide a high quality of service (QoS) and meet the necessary safety aspects regarding human exposure to radiation from such systems.

- EM-thermal dosimetry includes the assessment of:

    - external fields generated by EMI sources via calculation and/or measuremens.

    - internal fields

    - related local temperature increase in tissues,

- As configurations of base station antenna systems are often too complex the calculations in the far-field zone are carried out by using:

    - simplified procedures

    - semi-empirical formulas

- The rigorous *full-wave model* is applied mostly in some relatively rare cases involving calculations in the near-field region.

INTRODUCTION

- The paper reviews some models used by the authors for the determination of the field levels due to radiation of base station antennas.

- Some efficient analytical/numerical methods are outlined and number of illustrative computational examples for realistic scenarios of the human exposure to radio base station antennas are given.

- Certain measurement procedures are also outlined and measured field values results are presented for typical exposure scenarios.

- The state-of-the art regarding corresponding international and national legal issues are given in the paper, as well.

ASSESSMENT OF FIELDS RADIATED BY BASE STATION ANTENNA SYSTEMS

- Base station antenna system mounted on free standing tower radiating above a lossy half-space is considered as a source of EMI.

- Incident and reflected field, respectively, can be taken into account while the lower half space can be considered as PEC ground, homogeneous or multilayered lossy half space.
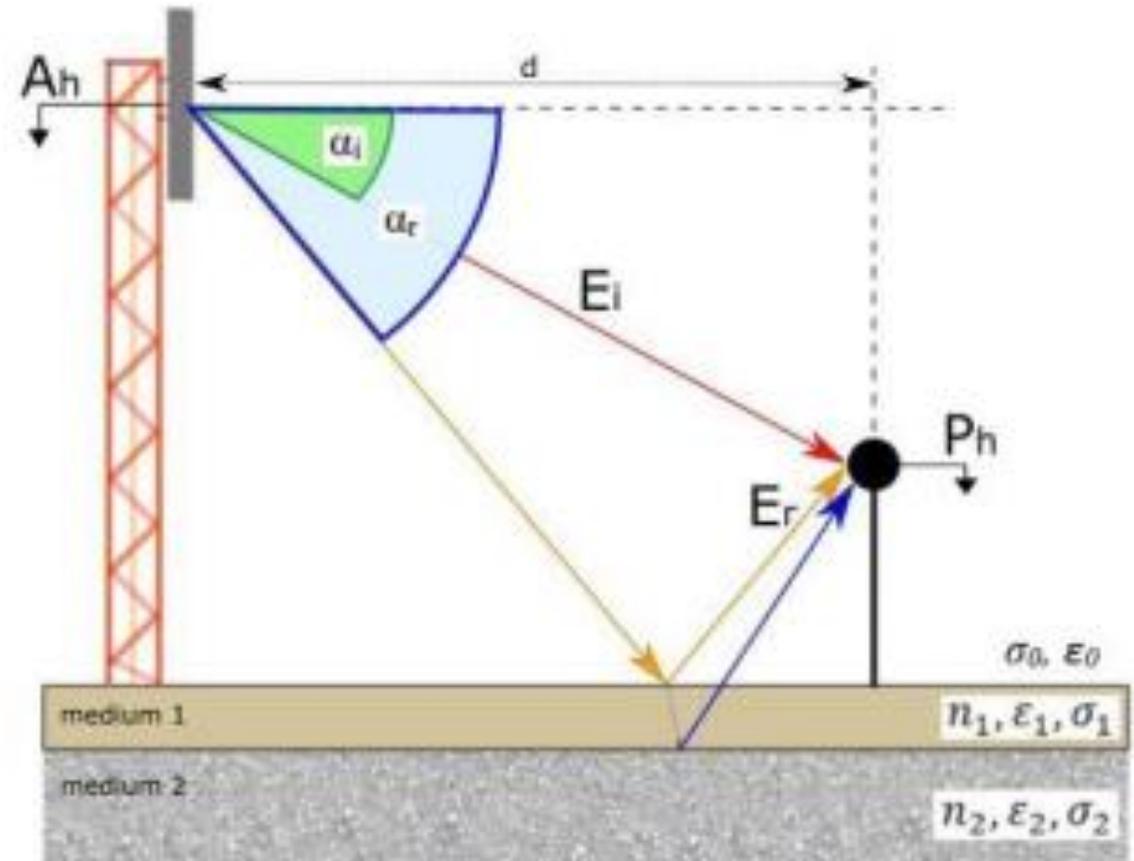

Figure 1. Radiation from base station antenna system

Rigorous Integro-Differential Equation Approach

- Base station antenna system mounted on free standing tower radiating above a lossy half-space is considered as EMI source.

- Models used to analyze radiation of base station antennas of 2G/3G/4G generation are based on the set of coupled Pocklington IDEs .

- Provided the currents along the wires are determined it is possible to calculate the related radiated field by using corresponding integral expressions.

- A general geometry of an arbitrary wire and its image, respectively is shown in Fig 2.

Figure 2. Curved wire configuration and its image

ASSESSMENT OF FIELDS RADIATED BY BASE STATION ANTENNA SYSTEMS

- The corresponding integro-differential equation set is given by

$$E_{sm}^{exc}(s) = \frac{j}{4\pi\omega\varepsilon_0}\sum_{n=1}^{N_w}\int_0^{L_n}\left\{\left[k^2\,\vec{e}_{s_m}\vec{e}_{s_n'} - \frac{\partial^2}{\partial s_m\partial s_n'}\right]g_{0n}(s_m,s_n') + R^{tot}\left[k^2\,\vec{e}_{s_m}\vec{e}_{s_n^*} - \frac{\partial^2}{\partial s_m\partial s_n^*}\right]g_{in}(s_m,s_n^*)\right\}I(s_n')ds'$$

$$g_{0mn}(s_m,s_n') = \frac{e^{-jk\,R_{1mn}}}{R_{1mn}}\ ,\ g_{imn}(s_m,s_n') = \frac{e^{-jk\,R_{2mn}}}{R_{2mn}} \qquad \varepsilon_{effm,n} = \varepsilon_{rm,n} - j\frac{\sigma_{m,n}}{\omega}$$

while the total reflection coefficient to account for the reflection between air and layered lower medium, arising from the extended use of the modified image theory is

$$R^{tot} = \frac{R_{12}+R_{23}e^{-2\gamma_2 d}}{1+R_{12}R_{23}e^{-2\gamma_2 d}} \qquad\qquad R_{mn} = \frac{\varepsilon_{eff,m}-\varepsilon_{eff,n}}{\varepsilon_{eff,m}+\varepsilon_{eff,n}}$$

ASSESSMENT OF FIELDS RADIATED BY BASE STATION ANTENNA SYSTEMS

- The total electric and magnetic fields irradiated by a configuration of multiple wires of arbitrary shape are given by

$$\vec{E} = \sum_{n=1}^{N_w} \left[\vec{E}_{0n} + R^{tot} \cdot \vec{E}_{in} \right]$$

$$\vec{H} = \sum_{n=1}^{N_w} \left[\vec{H}_{Sn} + R^{tot} \cdot \vec{H}_{In} \right]$$

$$\vec{E}_{0n} = \frac{1}{j4\pi\omega\varepsilon_0} \left[k_1^2 \int_0^{L_n} \vec{e}_{s_n} \cdot I(s_n') g_{0n}(\vec{r},\vec{r}')ds_n' + \int_0^L \frac{\partial I(s_n')}{\partial s_n'} \nabla g_{0n}(\vec{r},\vec{r}')ds_n' \right] \qquad \vec{H}_{Sn} = -\frac{1}{4\pi} \int_0^{L_n} I(s_n') \vec{e}_{s} \times \nabla g_{0n}(\vec{r},\vec{r}')ds'$$

$$\vec{E}_{in} = \frac{1}{j4\pi\omega\varepsilon_0} \left[k_1^2 \int_0^{L_n} \vec{e}_{s_n} \cdot I(s'_n) g_{in}(\vec{r},\vec{r}*)dw' - \int_0^{L_n} \frac{\partial I(s*)}{\partial s_n*} \nabla g_{in}(\vec{r},\vec{r}*)ds' \right] \qquad \vec{H}_{In} = -\frac{1}{4\pi} \int_0^{L_n} I(s_n') \vec{e}_{s*} \times \nabla g_{in}(\vec{r},\vec{r}*)ds'$$

NUMERICAL SOLUTION

- The Set of Pocklington integro-differential equations is solved via the Galerkin-Bubnov scheme of the Indirect Boundary Element Method (GB-IBEM).

$$\sum_{n=1}^{M}\sum_{i=1}^{N_n}[Z]_{ji}^{e}\{I\}_{i}^{e}=\{V\}_{j}^{e}$$

$$[Z]_{ij}^{e} = -\int_{-1}^{1}\int_{-1}^{1}\{D\}_j\{D'\}_i^T\, g_{0nm}(s_n,s_m')\frac{ds_m'}{d\xi'}d\xi'\frac{ds_n}{d\xi}d\xi + k_1^2\bar{e}_{s_n}\bar{e}_{s_m}\int_{-1}^{1}\int_{-1}^{1}\{f\}_j\{f'\}_i^T\, g_{0nm}(s_n,s_m')\frac{ds_m'}{d\xi'}d\xi'\frac{ds_n}{d\xi}d\xi -$$

$$-R_{TM}\int_{-1}^{1}\int_{-1}^{1}\{D\}_j\{D'\}_i^T\, g_{inm}(s_n,s_m^*)\frac{ds_m'}{d\xi'}d\xi'\frac{ds_n}{d\xi}d\xi + R^{tot}\cdot k_1^2\bar{e}_{s_n}\bar{e}_{s_m^*}\int_{-1}^{1}\int_{-1}^{1}\{f\}_j\{f'\}_i^T\, g_{inm}(s_n,s_m^*)\frac{ds_m'}{d\xi'}d\xi'\frac{ds_n}{d\xi}d\xi$$

$$\{V\}_j^n = -j4\pi\omega\varepsilon_0\int_{-1}^{1}E_{s_n}^{exc}(s_n)f_{jn}(s_n)\frac{ds_n}{d\xi}d\xi_n$$

Numerical Solution

- Once the current distribution is obtained, the radiated electric and magnetic field can be obtained applying the similar BEM formalism:

$$\vec{E} = \sum_{k=1}^{N}\left[\vec{E}^e_{Sk} + R^{tot}\cdot\vec{E}^e_{Ik}\right]$$

$$\vec{E}^e_{Sk} = \frac{1}{j4\pi\omega\varepsilon_0}\sum_{i=1}^{n}\left[k^2\int_{-1}^{1}\vec{e}_{ks}I^e_{ik}f_i(\xi)g_{0k}(\vec{r},\vec{r}')\frac{ds_k'}{d\xi}d\xi + \int_{-1}^{1}I^e_{ik}\frac{\partial f_i(\xi)}{\partial\xi}\nabla g_{0k}(\vec{r},\vec{r}')\frac{ds_k'}{d\xi}d\xi\right]$$

$$\vec{E}^e_{I} = \frac{1}{j4\pi\omega\varepsilon_0}\sum_{i=1}^{n}\left[k^2\int_{-1}^{1}\vec{e}_{ks*}I^e_{ik}f_i(\xi)g_{ik}(\vec{r},\vec{r}*)\frac{ds_k'}{d\xi}d\xi - \int_{-1}^{1}I^e_{ik}\frac{\partial f_i(\xi)}{\partial\xi'}\nabla g_{ik}(\vec{r},\vec{r}*)\frac{ds_k'}{d\xi}d\xi\right]$$

$$\vec{H} = \sum_{k=1}^{N}\left[\vec{H}^e_{Sk} + R^{tot}\cdot\vec{H}^e_{Ik}\right]$$

$$\vec{H}^e_{Sk} = -\frac{1}{4\pi}\sum_{i=1}^{n}\int_{-1}^{1}I_{ik}f_i(\xi)\vec{e}_{s_k'}\times\nabla g_{0k}(\vec{r},\vec{r}')\frac{ds_k'}{d\xi}d\xi$$

$$\vec{H}^e_{Ik} = -\frac{1}{4\pi}\sum_{i=1}^{n}\int_{-1}^{1}I^e_{ik}f_i(\xi)\vec{e}_{ks*}\times\nabla g_{ik}(\vec{r},\vec{r}*)\frac{ds_k'}{d\xi}d\xi$$

ASSESSMENT OF FIELDS RADIATED BY BASE STATION ANTENNA SYSTEMS

Ray Tracing Approximation

- Ray tracing approach has been widely used to estimate radiated field from 2G/3G/4G antenna systems.

- According to this approximation a relatively simple formula for the assessment of the electric field radiated from a base station antenna is given by

$$E = (1 + |\Gamma|) \cdot \frac{\sqrt{30 \cdot P_t \cdot G(\theta, \emptyset)}}{r}$$

where:

- P_t and $G(\phi, \Theta)$ is the antenna input power and gain

- r is the distance from antenna to the observation point

- Γ is the corresponding reflection coefficient

ASSESSMENT OF FIELDS RADIATED BY BASE STATION ANTENNA SYSTEMS

Inclusion of Duty Cycle for 5G Systems

- The measurement of field levels in 2G to 5G technologies pertain to the signal emitted with a constant power (so-called *pilot signal* – PS, or *reference element* - RE) and then the exposure projection under maximum load (maximum traffic conditions) is carried out through extrapolation.

- Generally, the maximal electric field level is estimated according to the relation

$$E^{max} = \sqrt{A} \cdot E_{PS/RE}^{max}$$

where A stands for the product of all applied extrapolation factors, and $E_{PS/RE}^{max}$ denotes the highest measured field level of the pilot signal.

ASSESSMENT OF FIELDS RADIATED BY BASE STATION ANTENNA SYSTEMS

Inclusion of Duty Cycle for 5G Systems

- The value of $E_{PS/RE}^{max}$ is related with the power at the measurement equipment connector, $P_{PS/RE}^{max}$, to which the antenna factor AF, characteristic impedance Z_{in}, and cable attenuation G_c are added

$$E_{PS/RE}^{max} = \sqrt{\frac{P_{PS/RE}^{max} \cdot Z_{in}}{G_c}} \cdot AF$$

- The exposure level at measurement point reaches the highest value for the maximum base station load, i.e. when the entire time frame is loaded with downlink data.

- In that case the base station has the highest gain (G_{max}) in the direction of the measurement point.

ASSESSMENT OF FIELDS RADIATED BY BASE STATION ANTENNA SYSTEMS

Inclusion of Duty Cycle for 5G Systems

- If the power of the reference element (E_{RE}^{max}) is measured, the extrapolation of the results is given by

$$E_{5G}^{max} = \sqrt{N_{RE}} \cdot E_{RE}^{max}$$

where N_{RE} is the total number of subcarriers

$$N_{RE} = 12 \cdot N_{RB} \leq 3300$$

and N_{RB} stands for total number of resource blocks.

ASSESSMENT OF FIELDS RADIATED BY BASE STATION ANTENNA SYSTEMS

Inclusion of Duty Cycle for 5G Systems

- In the case of an active antenna system, the antenna gain in downlink (G_{max}) is higher compared to SSB antenna gain (G_{SSB}).

- Therefore, to calculate the maximum exposure level it is necessary to add extrapolation factor F_{beam}

$$F_{beam} = \frac{G_{max}}{G_{SSB}}$$

- F_{beam} can be determined either using the SSB and traffic radiation pattern diagrams or by measuring the field levels in the time domain, where initiating data traffic is required.

Assessment of Fields Radiated by Base Station Antenna Systems

Inclusion of Duty Cycle for 5G Systems

- Therefore, it follows

$$E_{5G}^{max} = \sqrt{N_{RE} \cdot F_{beam}} \cdot E_{RE}^{max}$$

- Note that 5GNR can operate in either *TDD* (*Time Division Duplex*) or *FDD* (*Frequency Division Duplex*) mode which refers to a split frequency spectrum for the uplink and downlink connections.

- The implementation of the *TDD* mode is more common in 5G technology, where equal frequency bands are assigned for both uplink and downlink with a single connection active at a given time period.

Assessment of Fields Radiated by Base Station Antenna Systems

Inclusion of Duty Cycle for 5G Systems

- Therefore, it follows The uplink and downlink connections share the same frequencies, but they are separated in time, Fig. 3.
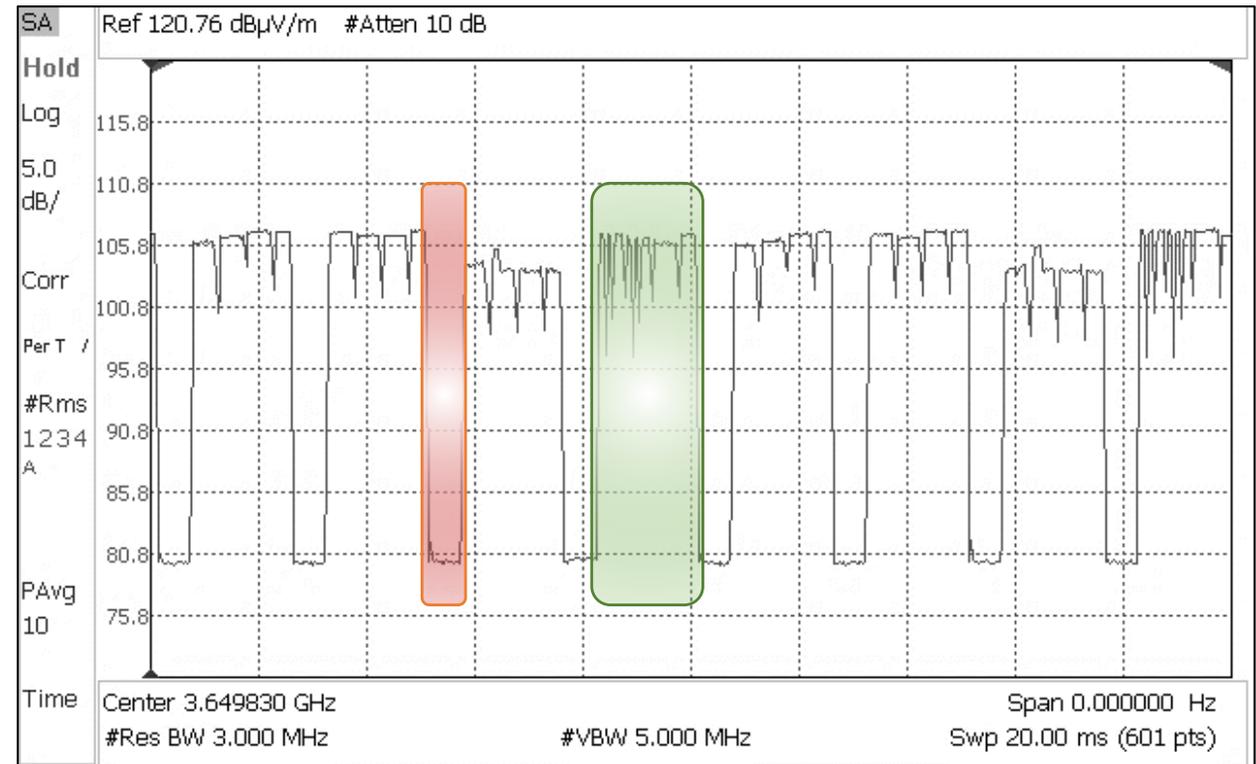

Figure 3.   The distribution of downlink (green) and uplink (red) in 5GNR TDD operation mode

ASSESSMENT OF FIELDS RADIATED BY BASE STATION ANTENNA SYSTEMS

Inclusion of Duty Cycle for 5G Systems

- When extrapolating the measured results, duty cycle factor F_{TDD} is included.

- In *TDD* mode, the highest exposure level is proportional to the portion of time with the downlink active in relation to the total time

$$F_{TDD} = \frac{\frac{DL}{UL}}{\frac{DL}{UL} + 1}$$

where *DL/UL* is the ratio of downlink transmission time to uplink transmission time.

- Additionally, the duty cycle factor can also be obtained from

$$F_{TDD} = \frac{N_{DL}}{N_T}$$

where:

    - N_{DL} is the number of pixels assigned to the downlink,

    - N_T is the total number of pixels on the analyzer screen.

ASSESSMENT OF FIELDS RADIATED BY BASE STATION ANTENNA SYSTEMS

Inclusion of Duty Cycle for 5G Systems

- Finally, in the case of the *TDD* mode, the extrapolated field level is

$$E_{5G}^{max} = \sqrt{N_{RE} \cdot F_{beam} \cdot F_{TDD}} \cdot E_{RE}^{max}$$

- Some 5G base stations are capable of limiting radiated power ensuring the average radiated power not to exceed a certain level within a specific time period.

- Thus, the total extrapolated field level can be reduced by a factor F_{PR}, which typically ranges from 0.2 to 1.

$$E_{5G}^{max} = k \cdot \sqrt{N_{RE}} \cdot E_{RE}^{max} \qquad k = \sqrt{F_{beam} \cdot F_{TDD} \cdot F_{PR}}$$

ASSESSMENT OF FIELDS RADIATED BY BASE STATION ANTENNA SYSTEMS

Inclusion of Duty Cycle for 5G Systems

- As in measurement procedures, the same extrapolation factors are used for the calculation of the field level , i.e. one has

$$E_{5G}^{max} = k \cdot (1 + |\Gamma|) \cdot \frac{\sqrt{30 \cdot EIRP_{max} \cdot G_{\theta,\vartheta}}}{r}$$

where:

- $EIRP_{max}$ is the maximal effective isotropic radiated power of the antenna
- $G_{\theta,\vartheta}$ is numerical antenna gain due to the azimuth and elevation, respectively.

ILLUSTRATIVE EXAMPLES

Rigorous approach

- Numerous calculated results are presented using different models.

- The obtained results are validated by comparison against the results obtained via NEC (Numerical Electromagnetic Code) package.

- The radiation source is $\lambda/2$ dipole placed vertically at height $h = 20$ m above the lossy ground ($\sigma = 0.001$ S/m and $\varepsilon_r = 10$).

- The dipole is excited by 1V voltage source.

- Electric field is calculated at points 1.5 m above ground for distances ranging from 20 m to 200 m perpendicular to the antenna.

ILLUSTRATIVE EXAMPLES

Rigorous approach

- Figure 4 shows the results obtained by using GB-IBEM, NEC package and Ray Tracing approach for the operating frequency $f = 900$ MHz.

- The results obtained by GB-IBEM and NEC appear to be in an excellent agreement.

- Ray tracing approximation does not take into account a phase of the direct and reflected signals, thus neglecting the oscillations in the signal amplitude for lower distances from the EMI source.
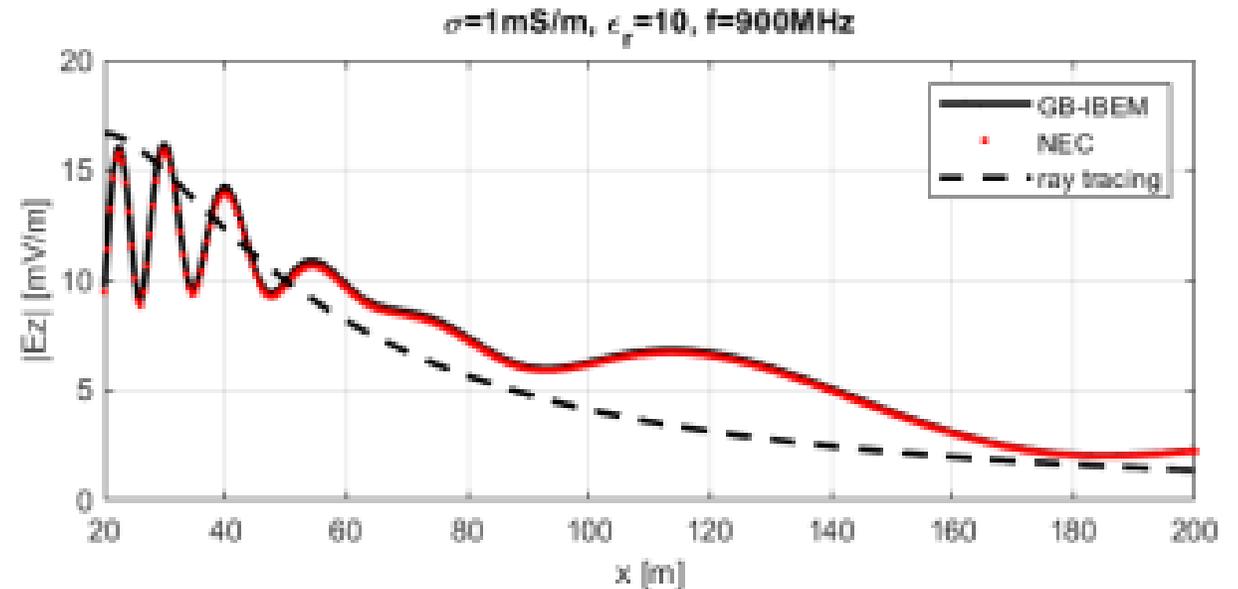

Figure 4. E_z component of the radiated field at $z=1.5$m for different methods

ILLUSTRATIVE EXAMPLES

Rigorous approach

- Electric field distribution over the real ground, for LTE (1.8GHz) and 5G (3.5GHz), is shown in Figs 5 and 6.

- While the amplitudes remain the same, the appearance of the peaks is related to the corresponding wavelengths.
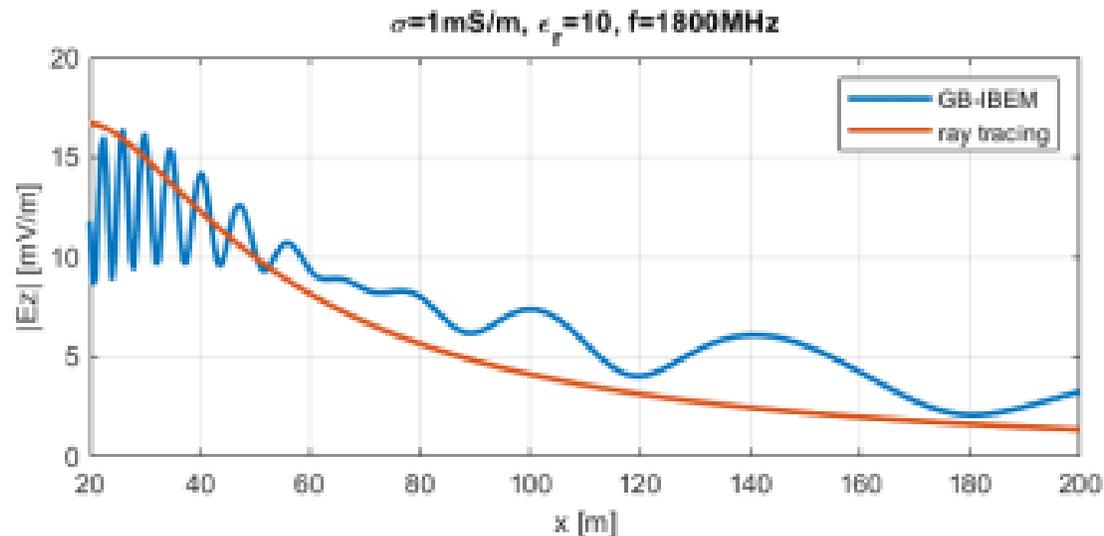

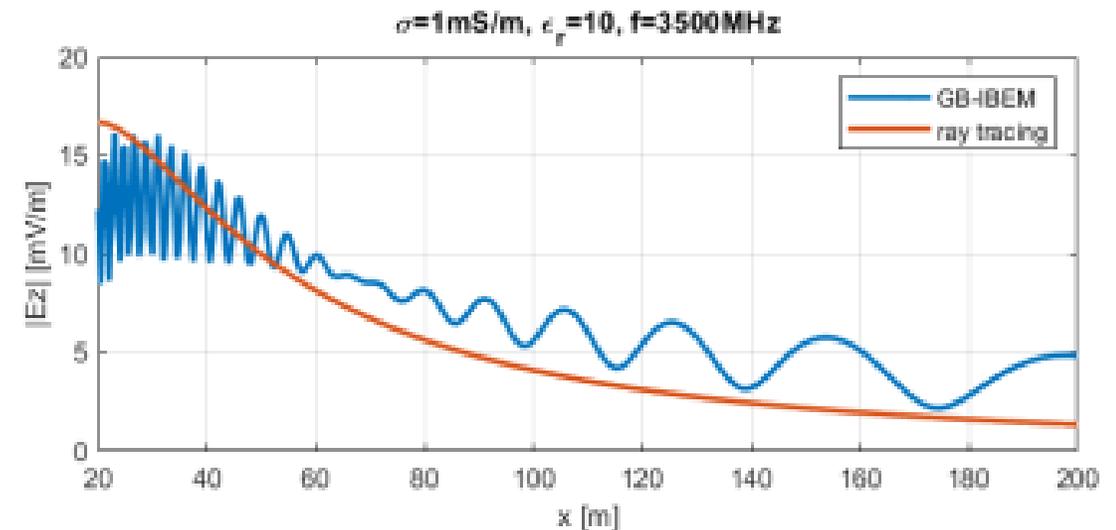Figure 5. E_z component of the radiated field at z=1.5m for operating frequency f=1.8GHz

Figure 6. E_z component of the radiated field at z=1.5m for operating frequency f=3.5GHz

ILLUSTRATIVE EXAMPLES

Ray tracing approach

- Figure 7 shows the electric field calculated via ray tracing approach for the case of free space approximation (FS), perfect ground (PG), Modified Image theory (MIT) approach and lossy half-space scenario (Fresnel Reflection Coefficient Method - FRM).

- EMI source is 3G panel antenna (8 dipoles with metal grid) placed vertically at height 20 m above the ground.

- The input power is 100 W and the operating frequency is 936.8 MHz.

ILLUSTRATIVE EXAMPLES

Ray tracing approach

- The obtained results via Ray Tracing Approach are found to be comparable with the results obtained via NEC.

- However, different field values may be expected depending on the calculation procedure at specific points, in particular in terms of local minima and maxima.
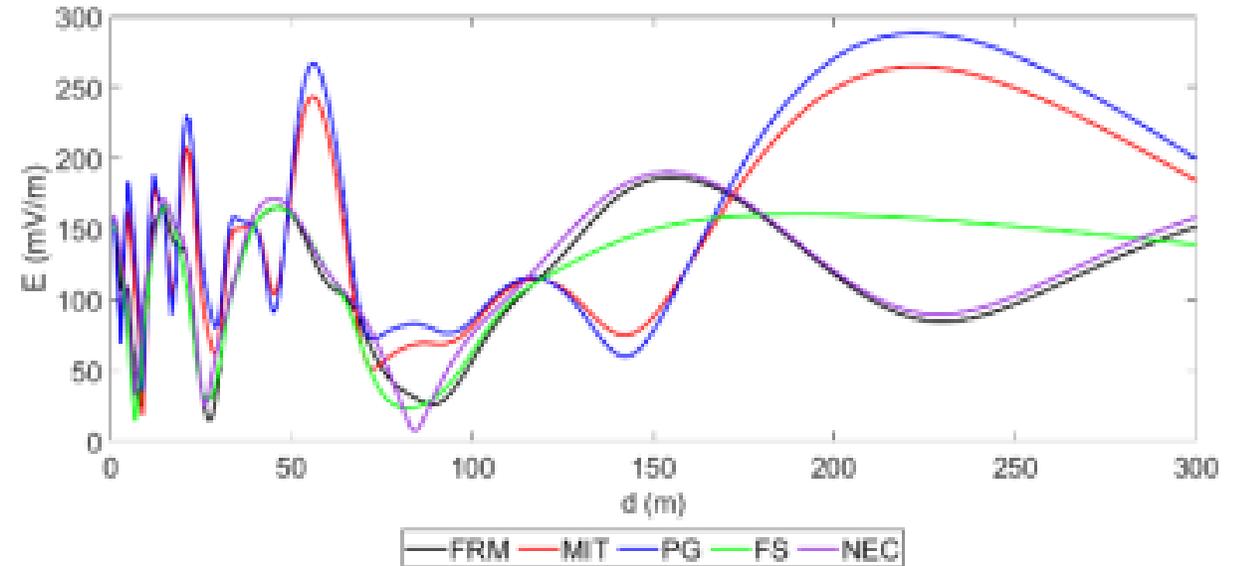

Figure 7. Radiated field vs distance using Ray Tracing method and NEC ($\varepsilon_1 = 10$, $\sigma_1 = 0,01$ S/m, i $A_h = 20$ m)

ILLUSTRATIVE EXAMPLES

Fields from 5G Antenna Systems

- Next set of computational examples deals with the calculated and measured results for the fields radiated from 5G antenna system.

- First example deals with the calculated results obtained by means of the relations outlined in Section II.

- The full set of input parameters is shown in Table I.

TABLE I.   INPUT DATA SET FOR THE CALCULATION OF FIELD RADIATED BY 5G-NR35 TECHNOLOGY

Frequency range	NR 3500 (3400 MHz - 3800 MHz)
Antenna type	AIR 3268
MIMO configuration	32x32
EIRP (dBm)	56,00
Mechanical tilt (°)	0
Electrical tilt (°)	0
F_{TDD}	1 and 0,75

- Note that the number of transmitter carriers is $T_X = 32$, while *EIRP* is determined with duty cycle $F_{TDD} = 1$ and $F_{TDD} = 0.75$, respectively.

ILLUSTRATIVE EXAMPLES

Fields from 5G Antenna Systems

- The corresponding field curves are shown in Fig.8.

- Note that the difference between the results for two duty cycles is roughly 13%.

- Next example deals with comparison of calculated and measured results.

- The parameters are shown in Table II and III, while Table III shows distances and azimuth of observation points from the antenna system and the reflection coefficient is Γ=0.6.
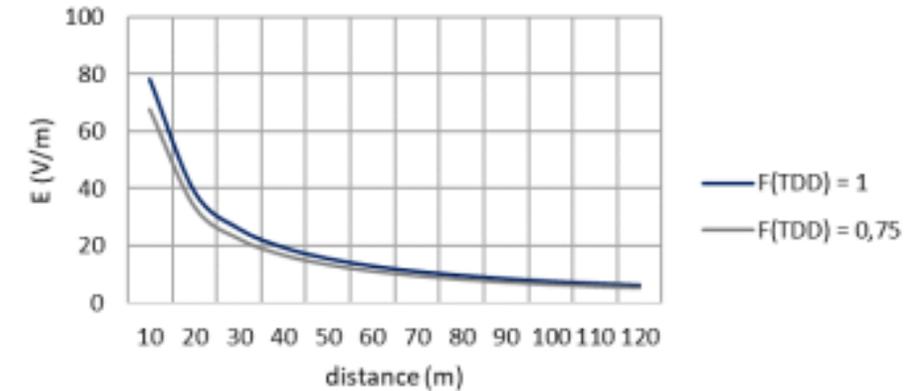

Figure 8. Radiated field vs distance

TABLE II.   INPUT DATA SET FOR THE CALCULATION OF FIELD RADIATED BY 5G-NR35 TECHNOLOGY

Frequency range	NR 3500 (3400 MHz – 3800 MHz)
Azimut (º)	155, 235
Antenna type	AIR 3268
Number of channels	1
MIMO configuration	32T32
EIRP (dBm)	54,61
F_{TDD}	0,75
Mechanical tilt (º)	5
Electrical tilt (º)	0

TABLE III.   DISTANCES AND AZIMUTH OF OBSERVATION POINTS

Observation points	r (m)	θ (º)
t1	33	149
t2	34	187
t3	90	223
t4	120	242
t5	75	146
t6	51	132

ILLUSTRATIVE EXAMPLES

Fields from 5G Antenna Systems

• Figure 9 shows the comparison of calculated and measured results at a given location for 6 observation points.

• Though the results are generally comparable in some observation points there are higher values for the calculated values and vice versa.

• The calculated field levels can vary significantly depending on the calculation procedure and can also be lower from the measured values (t1 and t6 from Fig. 9).
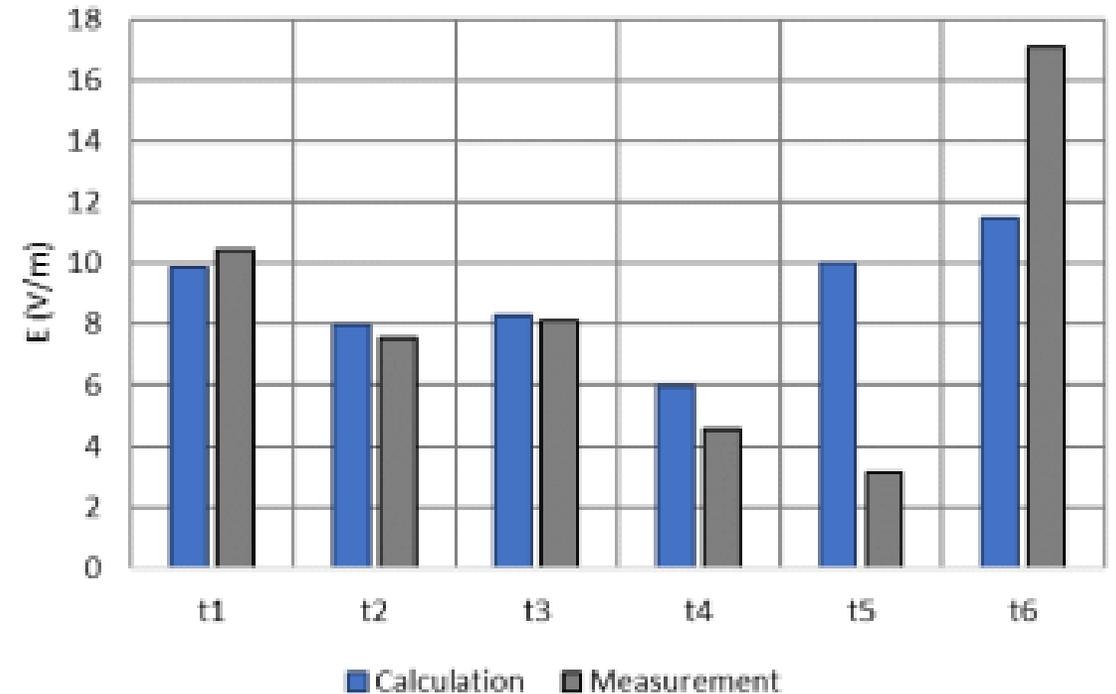
Figure 9. Comparison of calculated with measured results

ILLUSTRATIVE EXAMPLES

Fields from 5G Antenna Systems

- Therefore, a corresponding statistical approach to the field calculation is of interest aiming to obtain corresponding confidence interval pertaining to the several uncertainties that are likely to arise within the given assessment method.

- It is worth emphasizing that all calculated and measured results are obtained by the authors of this paper.

A NOTE ON LEGAL ISSUES

Regulatory challenges pertaining to the non-ionizing EMF radiation

- It is important to note that EU has implemented Directive (EU) 2018/1972 of the European Parliament and of the Council of 11 December 2018.

- The directive aims to harmonize the application of EMF exposure levels in a way that refers to their implementations of the precautionary approach from Recommendation No. 1999/519/EC.

- Some of the EU member states have adopted exposure limits determined by basic restrictions recommended in the ICNIRP guidelines, while some others have established higher or lower exposure limits than those recommended in the ICNIRP guidelines, respectively.

A NOTE ON LEGAL ISSUES

*Regulatory challenges pertaining to the non-ionizing EMF radiation*

- Among other countries worldwide, Croatia applies the 1998 ICNIRP guidelines.
- Croatia, as a Member State, has determined through the Regulation, by applying the precautionary principle that the limit values of reference quantities are reduced in relation to their corresponding basic restrictions and Ministry of health is responsible for setting exposure limits.
- The legislation currently in force has not changed since 2014, or rather, since 2018.
- Due to technology capacities for the 5G and for the following generation 6G, thorough revision legal frame of non-ionizing EMF radiation should be undertaken and are expected to be carried out in near future.

CONCLUDING REMARKS

- The paper deals with for the determination of the field levels radiated by base station antennas to which humans could be exposed.

- Some efficient analytical/numerical methods, used by the authors, are reviewed and outlined followed by a number of illustrative computational examples for realistic scenarios of the human exposure to radio base station antennas.

- Certain measurement procedures and related results pertaining to radiated field from 5G base stations are also outlined and measurement results are presented for typical exposure scenarios.

- Some remarks on corresponding international and national legal issues pertaining to human exposure to HF radiation are given.

Thank you for your attention!
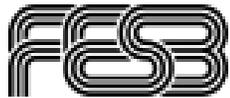
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