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Investigation of EMF Exposure Level for Uplink and Downlink of 5G Network Using Ray Tracing Approach

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Abstract. To provide enhanced mobile services, the 5G system is expected to further densify its network infrastructure and scale up the deployment of massive antenna arrays that emit high-energy beams using the millimeter wave spectrum. These radically new features will significantly impact the EMF exposure level in the 5G networks. In this paper, EMF exposure for 5G mobile networks in a dense urban environment is investigated using a raytracing approach for the uplink (UL) and downlink (DL). A massive multi-input multi-output antenna with multiuser beamforming capability is considered for the 5G base station. For DL, the maximum rate transmission (MRT) technique is used to direct the beams toward all the active users, and total power density (PD) is used to evaluate the EMF exposure level. On the other hand, EMF exposure due to UL is investigated using electric field strength and specific absorption rate (SAR). The proposed ray-tracing based EMF evaluation framework exploits detailed information of the scenarios, including 3D building geometry, EM characteristics, multipath propagation, user locations and beamforming radiation pattern, to effectively evaluate the EMF's spatial variation levels. Following this evaluation procedure, the impact of different user densities and distributions is analyzed in terms of PD and SAR. Results show that for DL, the peak PD increases from 6.65 to 24.92 dBm/m^2 when the number of active users in the area increases from a single user to 100%. Considering the worst-case scenario, the PD exposure reaches 62% of the ICNIRP's limit. Saturation of the spatial EMF distribution occurs when the number of active DL beams is above 25%. For UL, within 5m radius of the user's location, the average E-field may increase from 2.40 to 3.98 V/m. (increment of 66%) if the number of active users in the area increases from 25% to 100%. Moreover, when 100% of the users are actively transmitting, there is only a 10% probability that the SAR may exceed 0.06 W/kg (or 3% of the ICNIRP's limit).

Keywords: Dense urban environment; EMF exposure; Multiuser beamforming; Power density; Specific absorption rate

1. Introduction

In order to support the demands for higher throughput and improved quality-of-service (QoS) specified in the 5G and beyond standards, new features such as beamforming

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antenna array, millimeter wave (mm-wave) technology, denser network, large-scale distributed antenna system, and large-scale carrier aggregation will be implemented in the upgraded networks. However, these new features may pose a health risk as they are expected to cause higher levels of human electromagnetic field (EMF) radiation exposure. For instance, the high-gain directional beamforming antenna arrays can form narrow beams with high concentrations of electromagnetic energy to aid signal transmission. The densification of networks will further reduce the cell size so that more base stations/access points (BSs/APs) can be deployed closer to the users to improve the connection quality. The mobile users will be closer to one or more BSs/Aps, causing an increased level of EMF radiation exposure. In (Nasim, 2019), the author investigated human EMF exposure in indoor and outdoor environments from 5G downlink communications and compared its impacts with the other cellular technologies considering the features that the 5G will likely adopt. The simulation results reveal that the EMF exposure may exceed the regulatory limits for a very short separation distance between BSs and user equipment (UE). In the news, there are growing public concerns about the risk of higher radiation exposure introduced by mobile networks (Kathy, 2019; Reality Check Team, 2019). In 2011, the International Agency for Research on Cancer (IARC) classified RF EMF as possibly carcinogenic to humans (Group 2B), based on an increased risk for glioma, a malignant type of brain cancer associated with wireless phone use (IARC, 2013). Recognizing the potential health risk of EMF radiation exposure, most of the countries in the world have set up their own national standards for exposure limits to EMF. The majority of these national standards draw on the guidelines set by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) (ICNIRP, 2020). So far, it is well accepted by the research community that exposure levels from 5G BS is safe as long as it complies with the EMF regulations (Bushberg et al., 2020). Nevertheless, 5G is radically different from legacy pre-5G standards due to the utilization of large antennas MIMO arrays, beamforming techniques, and mm-wave spectrum. Therefore, further work is needed to understand the EMF impact by integrating these 5G features into a proper EMF evaluation framework so that useful conclusions and new insights can be drawn from the results.

1.1. Related Works

This section discusses previous works relevant to EMF exposure evaluation of beamforming. In (Chiaraviglio et al., 2018), the authors analyzed the EMF levels of realistic pre-5G scenarios using ray tracing. However, only standard fixed beam BS antenna and frequency less than 3 GHz are considered. In (Chiaraviglio et al., 2021), the authors investigated the EMF impacts of the pencil beamforming technique of 5G BS in terms of power density (PD). However, the proposed EMF evaluation procedure is only applicable for localization-based beamforming using the standard 3GPP propagation model (ETSI, 2019). Downlink EMF exposure generated by 5G beamforming antennas is investigated in (Noé & Gaudaire, 2021) using ray-tracing. The authors compared the influence of different beamforming approaches on electric field exposure levels in urban environments. However, the frequency used is not specified. EMF exposure evaluation methodology can be found in international standards such as IEC 62232 (IEC, 2017) and ITU K.91 (ITU, 2020) for assessing the EMF level from individual base stations and base station sites based either on calculations or measurements. These evaluation guidelines' primary purpose is to assess EMF compliance boundaries of cellular BS and devices. Hence, highly simplified models such as the free-space formula and time-averaged antenna patterns are usually used for calculating exclusion zones. This methodology is unsuitable for accurate spatial mapping of EMF level for the entire site area. Field measurement using live commercial 5G site is another way for evaluating the EMF exposure (Aerts et al., 2021; Colombi et al., 2020).

However, this approach has some key challenges such as the availability of site and equipment, detailed BS and device parameters, dynamic traffic and multiuser conditions (Adda et al., 2020). Moreover, fine-grained analysis for the entire site area is not feasible via measurement. It is well known that mm-wave transmission is very sensitive to terrain irregularity and buildings or obstacles geometry. As a result, the variability in EMF levels from one location to another in an urban scenario can be very significant. In these conditions, a deterministic technique such as ray-tracing is very promising for effective evaluation of the EMF exposure. However, the EMF evaluation framework based on ray-tracing is still not well defined, and considering the different exposure modes of 5G compared to legacy systems, further work is required to provide a precise spatial characterization of the EMF impact. Specifically, the impacts of practical mm-wave beamforming abnormalities such as dual main beam and the combined effects of multiuser beams in a realistic 3D environment on the EMF level are still less understood. A lack of study also considers the total uplink exposure in a realistic densely populated urban scenario. In contrast to the existing works, the following key novelties are introduced in this work: 1) we design a framework based on ray-tracing that allows 3D scenarios definition and synthesis of mm-wave massive MIMO beams according to the UE's multipath channel characteristics; and 2) we characterize the spatial EMF distribution with different variation of user distribution, user density as well as average and worst case conditions.

2. System Model & Proposed Framework

5G will employ a set of radically new technologies, such as large-scale MIMO antenna arrays, precise beamforming, and mm-wave communications. These new features will substantially change the radio access part of 5G networks compared to the legacy pre-5G standards. Therefore, new radio access models integrating these 5G features must be developed for EMF exposure evaluation. Figure 1 shows the flowchart of the proposed EMF evaluation framework based on ray-tracing.

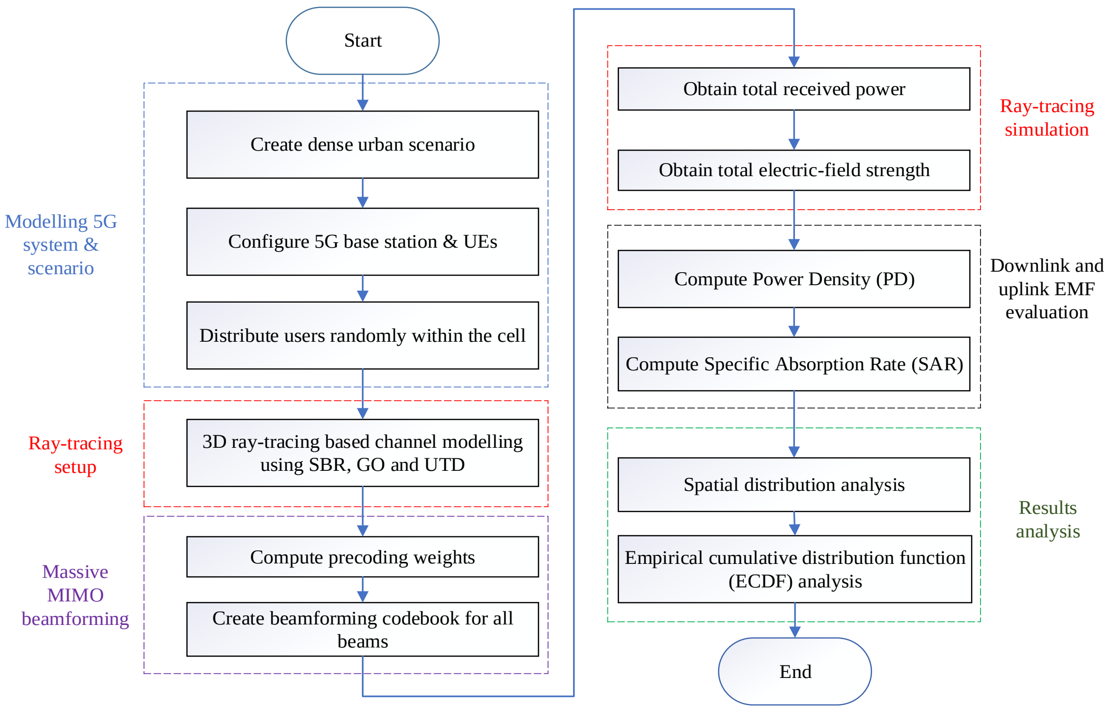


Figure 1 Flowchart of the proposed EMF evaluation framework

The details of the proposed evaluation framework are described in the following subsections:

2.1. Modelling 5G System and Scenario

A 3D map is needed to create a dense urban environment for ray-tracing simulation. For example, as shown in Figure 2a, a small cell scenario in the urban city of Rosslyn, Virginia, is considered. The size of the area considered is 0.09 km2. Based on (Ibraiwish et al., 2022), for a dense urban environment, the expected population size in this area is 123 people. By randomly distributing the users' locations, 93 users are found to be located outdoors, and 30 users are located within the buildings (or indoor). In this work, only outdoor users are considered for EMF exposure evaluation. Figure 2a shows the 5G base station (green dot) positioned on the top of a lamp post on a road divider in a major traffic intersection. The users (red dots) are randomly distributed within the cell. The EM properties of the materials such as building, and vegetation are defined according to the recommendation of previous works in the literature.

We consider a massive MIMO base station operating at 28 GHz in a densely populated urban scenario. Multiuser beamforming technique is employed at the BS to support multiple users with one data stream per user. Each data stream transmission assumes an 8x8 transmit antenna array with both vertical and horizontal polarizations (total 128 antenna elements). Ray tracing is used for determining the channel state information at the transmitter by simulating the interactions between the transmitted signal and the propagation channel. To ensure accuracy and reproducibility of the results, commercial software called Wireless InSite (Remcom, 2016) is utilized. For uplink, a single antenna is assumed for the UEs.

2.2. Ray-Tracing Simulation

3D ray-tracing simulation is performed using a combination of Shooting and Bouncing Rays (SBR) technique (Schuster & Luebbers, 1996a; 1996b) and Geometric Optics (GO) and Uniform Theory of Diffraction (UTD) methods. Ray paths are first launched and traced from the source point. Specularly reflected rays from the building walls and objects are continuously traced up to the maximum number of reflections or when the rays hit the study area boundary. GO, and UTD are then employed to evaluate the complex electric fields and received power associated with each ray path. This ray-tracing approach is used to determine the following parameters:

2.2.1. MIMO Channel Coefficients

The complex-valued channel coefficient between the *n*th antenna element to the *k*th user can be expressed as (Remcom, 2016) (equation 1),

$$h_k[n]=\sqrt{G_k[n]}e^{-j\theta_k[n]} \tag{1}$$

where $G_k[n]$ is the ratio of power received by user *k* and power radiated by element *n* when all other elements are turned off and $\theta_k[n]$ is the phase (in radians) of the voltage across a matched load at user *k* under the same conditions. The gain $G_k[n]$ and phase $\theta_k[n]$ take into consideration the coherent sum of all the propagation paths in a complex urban environment from antenna element *n* to user *k*.

2.2.2. DL Received Power

For DL, the received power can be expressed as (Remcom, 2016) (equation 2),

$$P_{R_k}=\left|h_k^H w_k\right|^2 \tag{2}$$

where $(.)^H$ denotes conjugate transpose, $\mathrm{h_k}=\left[\mathrm{h_k}[1],\ldots,\mathrm{h_k}[\mathrm{N}]\right]^{\mathrm{T}}$ is the complex channel coefficients vector and $\mathrm{w_k}$ is the precoding weights vector for user k. The precoding weights depend on the beamforming technique used.

2.2.3. UL Electric Field Intensity

For UL, the SBR method finds the propagation paths from all the transmitters (or UEs) to the receiver points. Once the propagation paths are determined, the GO and UTD are used to evaluate the electric field for each path. The computation of the electric field depends on whether the path is a direct line-of-sight, reflected, or diffracted path. The details of the calculations are available in (Remcom, 2016). The results are coherently summed up to produce the total electric field intensity at the receiver point.

2.3. Beamforming Technique

The maximum ratio transmission (MRT) technique is considered so that the maximum power can be delivered to the intended user using beamforming for EMF exposure evaluation. To this end, for user *k*, the weights of the antenna elements are set to be proportional to the channel values of the respective elements. In other words, the precoding weights vector for user *k* is given by (equation 3),

$$\mathrm{w_k}=\frac{\mathrm{h_k}}{|\mathrm{h_k}|}\sqrt{\mathrm{p_k}} \tag{3}$$

where $\mathrm{p_k}$ is the power transmitted towards user *k*.

2.4. Downlink and Uplink EMF Computation

The EMF exposure due to downlink transmission is evaluated using total power density. The power received by the receiving antenna can also be written as (Rappaport, 2002) (equation 4),

$$\mathrm{P_R}=\mathrm{P_D}\mathrm{A_e} \tag{4}$$

where $\mathrm{A_e}$ is the effective area or aperture of the receiving antenna and P_D is the power density of the radiation in any particular direction from the antenna. For an isotropic antenna, the effective area is given by (equation 5),

$$\mathrm{A_e}=\frac{\lambda^2}{4\pi} \tag{5}$$

where λ is the wavelength of the signal. In this work, the total received power for the entire study area is first determined using ray tracing simulation. Then the power density is computed by (equation 6),

$$\mathrm{PD}=\frac{\mathrm{P_R}}{\mathrm{A_e}} \tag{6}$$

On the other hand, the EMF exposure due to uplink transmission is evaluated using the specific absorption rate (SAR) and electric field strength (E-field). SAR measures the energy from electromagnetic sources absorbed per unit mass by human tissues. It can be expressed as (Nasim, 2019; Remcom, 2016) (equation 7),

$$\mathrm{SAR}(\rho)=\frac{\sigma|\mathrm{E}(\rho)|^2}{\rho} \tag{7}$$

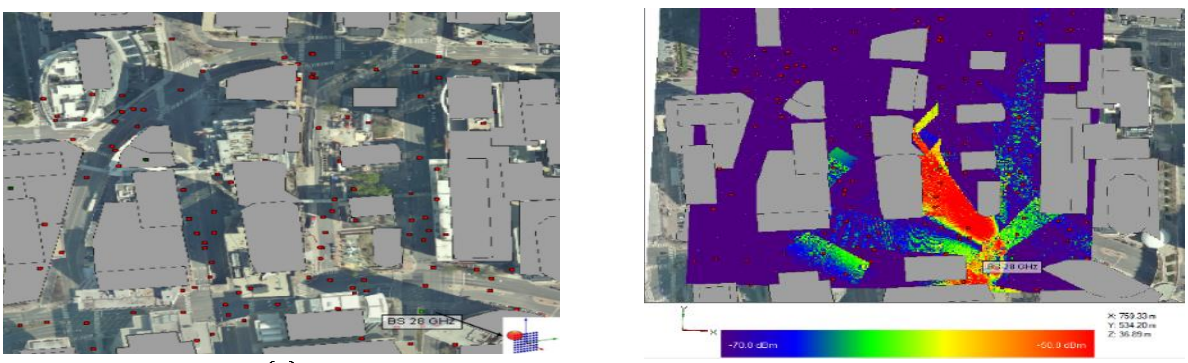
where σ is the conductivity of tissue in S/m, E(ρ) is the electric field intensity in V/m, and ρ is the mass density of tissue in $\mathrm{kg/m^3}$.

3. Results and Discussion

Table 1 shows the simulation parameters considered in this paper for the 5G dense urban network. For the downlink, the complex-valued path gains for each sub-channel between the BS and the users were obtained from a realistic ray tracing simulator (Wireless Insite) to calculate the beamforming (or precoding) weights. These precoding weights are calculated using the MRT beamforming technique to ensure that the users receive the maximum power. Then, the received power for the entire study area is simulated and used to evaluate the EMF exposure level. Figure 2b illustrates the received power heatmap where the beam is directed towards a user near the map's middle. In the simulation, the precoding weights are calculated to direct 93 beams toward the 93 outdoor users. The distance between two adjacent sample points on the map is 1 m. At these sample points, the received power and the electric field strength are simulated to produce the EMF heatmap. The power density is then calculated to evaluate the downlink exposure level.

Table 1 Simulation parameters

Parameter	Description	Remark
5G System & Scenario		
Frequency	28 GHz	-
BS antenna	8x8 array per data stream	Total 93 data streams
BS height	10 m	
BS Tx power	30 dBm per data stream	(Skidmore et al., 2016)
UE Tx power	20 dBm	(Skidmore et al., 2016)
UE antenna	Single halfwave dipole	(Skidmore et al., 2016)
UE height	2 m	
Conductivity of tissue	21.86 (S/m)	(Lak et al, 2021)
Mass density of tissue	1041 (kg/m^3)	(Lak et al, 2021)
Ray-Tracing Parameters		
Number of reflections	6	(Skidmore et al., 2016)
Number of Paths	25	(Skidmore et al., 2016)
Ray Spacing	0.15	(Skidmore et al., 2016)
Ray tracing Technique	SBR	(Skidmore et al., 2016)
Propagation Model	Full 3D (X3D)	(Skidmore et al., 2016)
EM Properties of Materials		
Material	ε_r	σ[S/m]
Buildings (Concrete)	5.31	0.8967
Vegetation-Leaf	26	0.39
Vegetation-Branch	20	0.39



(a) (b)

Figure 2 (a) Location of base-station and random users' locations in a dense urban environment, (b) Received power heatmap for a single beam directed towards a user located near the middle of the map

Figure 3 shows the average and peak values of the total power density versus distance from the BS.

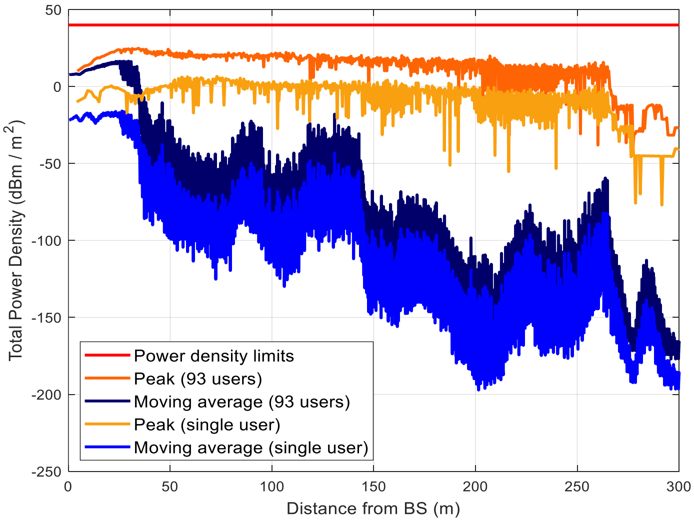
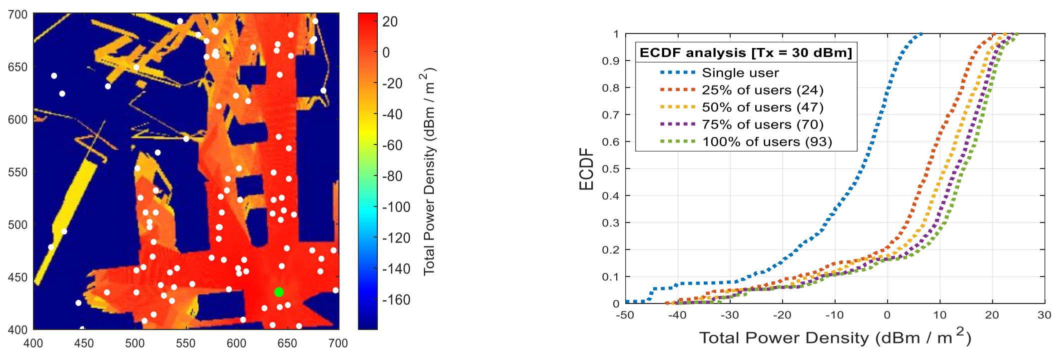


Figure 3 Downlink power density

Figure 3 shows the peak and average PD for the extreme case where all the 93 beams are activated simultaneously. The same figure shows the maximum limit given by ICNIRP and the case where only one beam is directed towards a single user. It is observed that the power density is mainly dependent on two factors: the distance from the base station and the concentration of the users in a specific area. Generally, the power density drops as the distance increases. However, at some locations far away from the base station, the total power densities are higher compared to those of nearer locations. This is due to the higher density of UEs operating near each other in those areas. Many beams are directed toward the same location at the same time, and this causes elevated EMF levels. Based on Figure 3, the peak PD increases from 6.65 to 24.92 dBm/m^2 when the number of active users increases from a single user to 93 users. For the worst-case scenario (i.e., when all the beams are activated simultaneously), the PD exposure reaches 62% of the ICNIRP's limit.

Figure 4a shows the spatial distribution of the total power density in the dense urban environment due to massive MIMO multiuser beamforming when all the beams are activated simultaneously.

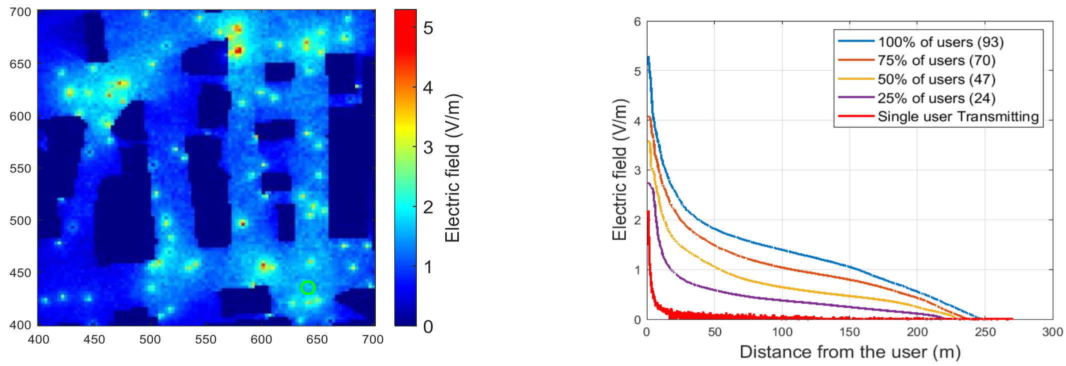


(a) (b)

Figure 4 (a) Spatial distribution of the total downlink power density, (b) ECDF of power density

Compared to Figure 2b, it is obvious that the EMF level in the study area has increased substantially when each user is actively served by one beam from the BS. This worst-case scenario shows that almost all the areas previously with very low EMF exposure (when only one beam is activated) are now experiencing high EMF exposure. In Figure 4b, the empirical cumulative distribution function (ECDF) of total PD is plotted. It can be observed saturation of EMF exposure starts to occur when the number of active users in the area is above 25%.

For UL, the EMF exposure level is evaluated using the electric field strength and the SAR metrics. Figure 5a shows the spatial distribution of the total electric field strength within the densely populated urban environment considered in this study. Figure 5b shows the E-field strength versus distance from the user for different percentages of actively transmitting outdoor users.

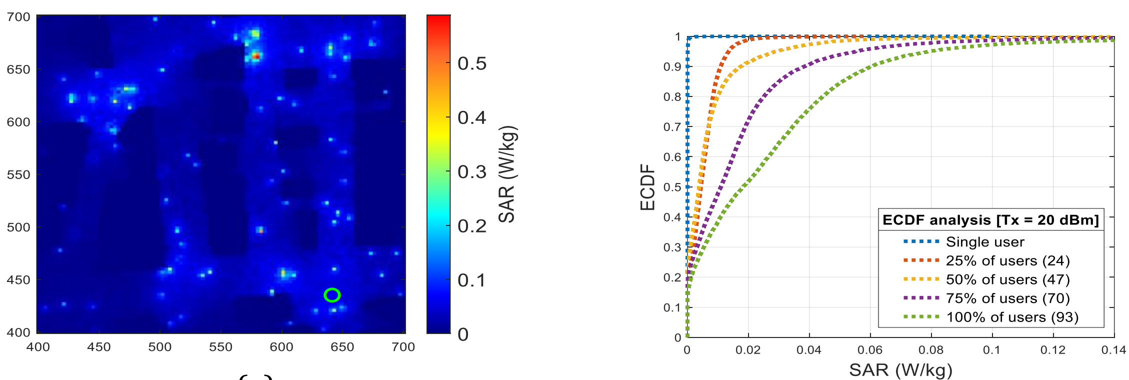


(a) (b)

Figure 5 (a) Spatial distribution of total E-field strength for uplink, (b) Total E-field strength versus distance from the user

It is observed that the electric field strength decreases with the distance from the user's position. However, the exposure level is also dependent on the percentage of active UEs radiating at the same time and the density of users within a certain area. Considering a 5 m radius from a user, the average E-field may increase from 2.40 to 3.98 V/m (or 66%) when the number of active users increases from 25% to 100%. The total uplink E-field did not reach the limit set by ICNIRP (ICNIRP, 2020), which is 36.5 V/m. The exposure level is significantly higher for some places where the users are more concentrated (see Figure 5a). This leads to the observation that UL EMF exposure may increase with the densification of wireless devices operating near each other at the same time.

Since SAR is electric field strength dependent, higher electric field strength results in higher SAR. The spatial distribution of total SAR due to UL is shown in Figure 6a.



(a) (b)

Figure 6 (a) Spatial distribution of total SAR for uplink, (b) ECDF of total SAR

Figure 6b presents the ECDF of SAR levels within the considered study area (with total of 93 active outdoor users). Based on Figure 6b, when all users are actively transmitting, there is a 10% probability that the SAR may exceed 0.06 W/kg, which is equivalent to only

3% of the ICNIRP's limit. The spatial EMF exposure level increases gradually with the increase of the number of active users from 25% to 100%. This is mainly due to the omnidirectional antenna employed by the UEs.

4. Conclusions

This paper investigates the EMF exposure level of a 5G network employing massive MIMO multiuser beamforming in downlink transmission based on the total power density (PD) exposure metric. The EMF exposure due to uplink transmission is also investigated using total electric field strength and specific absorption rate (SAR). A ray-tracing-based EMF evaluation framework is proposed to exploit detailed information of the network scenarios, including 3D building geometry, EM characteristics, multipath propagation, user locations, and beamforming radiation pattern, to effectively evaluate spatial variations of the EMF levels. Following this evaluation procedure, the impact of different user densities and distributions has been evaluated in terms of PD and SAR. Both worst-case and average-case scenarios are analyzed for a dense urban environment using the proposed framework. Based on the results, all the metrics did not exceed the limits set by ICNIRP. However, the exposure level is significantly increased by the densification of the users and the distribution of the radiating user devices. The exposure level may increase further for an environment with denser users. This study contributes to understanding the expected EMF exposure level in the entire densely populated urban area where 5G uplink and downlink transmissions are considered. For future investigation, it is recommended to study the EMF exposure effects of other digital beamforming techniques and the hybrid analog/digital beamforming.

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