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Proposed theoretical approaches for cellular base station radiation level estimation in urban environments

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Abstract: Increasing demand for cellular communication service forced service providers to improve their quality of service by increasing the number of base stations inside or in the proximity of populated areas. Consequently, the level of electromagnetic pollution is increased resulting in great concern about the probable health risk due to exposure to the base station radiations. To estimate the possible health impact due to population exposure to cellular base station radiations, this paper presents two mathematical approaches suggested to evaluate the base station radiation level in terms of power density induced at the exposed objects. The first approach depends on the superposition theorem that considers radiations from all base stations surrounding the exposed object. The second approach uses a fluid model to study and estimate the power density received by the objects exposed to the cellular base station radiations in urban areas. Once the induced power density in the exposed human body is obtained, it is possible to evaluate the health effects, and the safety exposure limits can be set. The proposed model simulations show that in urban areas for the cell radius of 100 m, the resultant power density at the exposed body is equal to 100 mW/m^2 while it is 101.18 mW/m^2 in areas of path loss exponent of 2.5.

Keywords: Exposure to non-ionizing radiations, free space propagation model, power density, safety distance, mobile communications networks, human exposure

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1. Introduction

The rapid growth in cellular mobile communication service demand during the last years led to an increase in the number of cellular base stations near the residence areas to support a large number of subscribers with an acceptable quality of communication service (Buckus et al., 2017). The base stations existing in densely populated residential areas have raised a lot of concern regarding the safety of the public exposed to cellular base station radiofrequency (RF) radiations and the probable health impact of these radiations (ALRikabi, 2016; Marinescu & Poparlan, 2016).

The large number of mobile base station towers placed in residential areas results in intense electromagnetic pollution due to the presence of transmit antennas of mobile communication networks (Koppel et al., 2019; Ramakrishnan & Athikary, 2023). The base station radiations can penetrate through human body living tissues which behave as lossy dielectric materials at radio frequencies (RF) (Seybold, 2005). The cellular base station radiations are classified to be nonionizing, as the energy absorbed by the human tissues exposed to these radiations is insufficient to break chemical bonds in human living biological tissues. Continuous exposure to base station microwave radiations may be unsafe as it could cause to damage human biological tissues (Sallomi & Hashem, 2018).

To decide the health impact of RF radiation exposure, various research has been carried out on the assessment of health effects due to exposure to cellular mobile base station radiations within many areas around the world. Exposure to RF radiation is higher at locations closer to base station antennas. Therefore, it is necessary to apply many proper safety measurements to protect people from excess RF radiation (Marinescu & Poparlan, 2016; Sallomi & Salim, 2009).

The RF radiation exposure impact has been studied in some institutions in Nigeria (Briggs-Kamara et al., 2018). The study aimed to provide scientific information about the RF exposure level generated due to base stations surrounding these institutions and their effects on the students. The field intensity was measured in various institution locations around chosen cellular stations. The obtained results show that exposure levels emitted by mobile base stations in and around the selected sites were far below the permissible standard recommended by the Federal Communication Commission (FCC). Exposure level due to electromagnetic emissions from eleven mobile base stations erected near schools and residential areas was investigated in Bello et al. (2023). The power absorbed by the human body at various distances close to the selected base station was measured and studied. The study concluded that the absorbed power by the adult human body surface is higher as compared with that of children due to their small body surface area. In all sites, it was found that the RF exposure level was lower than the limits recommended by the International Committee of Non-Ionizing Radiation Protection (ICNIRP) limits. Spot measurements were suggested to evaluate the impact of the mobile network technology due to the exposure of populations living near base stations in France (De Giudici et al., 2021). It was noticed that exposure levels at homes are less compared with outdoor locations, and higher during the day as compared with night. Although the measured exposure levels were lower than the recommended limits, the study did not rule out the probable negative health effects of these low exposures.

The review article presented in Ramakrishnan and Athikary (2023) focused on the impact of fifth-generation (5G) technology on human health, and animals. The impact of electromagnetic radiation from 5G telephone towers on birds was studied. Introducing new guidelines for RF exposure protection was suggested to make 5G technology safety one. The study presented in Samaila et al. (2023) showed that exposure level due to the base transceiver station is not dangerous as people are exposed to it for a short period. The study discovered that residents who lived closest to cellular base stations may have harmful side effects such as headaches and sleep disturbance due to exposure to EM radiation. In order to monitor the electromagnetic radiation levels of the 5G network in China, the study presented in Wei et al. (2024) selects several typical sites to investigate the factors that have significant effects on the power density radiated by the 5G base stations. The results show that the transmission distance, base station density, and user density in 5G base stations of China Telecom have important impacts on ambient power density. The central idea of this study is to develop a simplified model to determine the exposure levels due to electromagnetic energy emitted by typical base stations around urban areas by computing the power density using two approaches. To investigate the potential health effect of cellular base station radiations on people living or working around cellular base stations, this study focused on the development of a simplified mathematical approach that can be implemented to predict the produced induced power density level due to cellular base station antenna emission. Two approaches are suggested, the first one considers the radiation of the base station surrounding the cell at which the exposed object is located, while the second approach applies the fluid model framework to evaluate the exposure levels of radiation on people. We first introduce the typical construction of a cellular network and the power density formula in section 2. Two approaches for power density prediction are suggested and derived in section 3. The suggested approaches are simulated, and the theoretical results are presented and discussed in the fourth section. The paper is concluded in the last section.

2. Exposure to cellular networks EM radiation

In cellular land mobile radio networks, the geographical area required to be served by a cellular communication service is divided into several clusters, and every cluster is sub-divided into adjoining hexagonal cells each of which is provided with one fixed base station (Al-Dujaili et al., 2023; Al-Rubaye et al., 2023; Mousa, 2011) Each cell is allocated a certain number of radio channels through which subscribers can communicate with each other. The area covered by each cell is divided into several sectors. Cell sectors are provided with sectored directional antennas that are mounted on towers or building roofs (Garg, 2007; Rappaport, 2002).

As the number of cell phone users increases, a further number of base stations are required to be placed in urban areas to accommodate the increasing number of subscribers. Base stations transmitting antennas are continuously radiating electromagnetic waves even when no subscriber is using the cell phone (Sallomi & Hashem, 2018). Cellular base station antennas are designed in a way so that cell phones can transmit and receive enough RF signal power for proper communication with minimum interference and call drop probability to achieve the required coverage and signal quality as shown in Figure 1. Human exposure quantified by the power density, can be computed through radio wave propagation simulation in the area of interest.

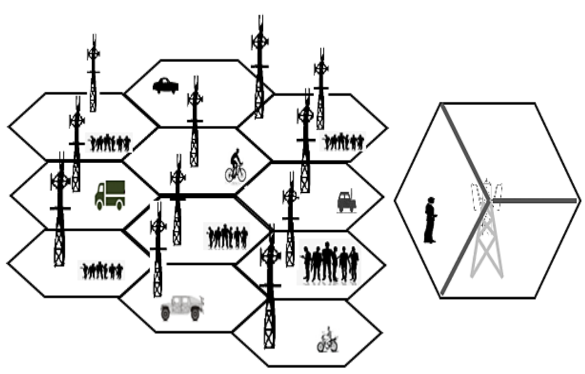

Figure 1. Cellular network.

The power density (P_d) induced during signal propagation in the line of sight (LOS) path is proportional to the output power of the base station transmitting antenna, and inversely proportional to the square of the distance (r) from the base station. It can be expressed by Rappaport (2002).

$$P_d = \frac{P_t\ G_t(\theta,\varphi)}{4\pi r^2} \tag{1}$$

Where P_t is the power transmitted by the base station transmit antenna, and G_t is the transmit antenna gain. Obstacles such as tall buildings and water tanks existing in the signal propagation path may block the LOS path due to the propagation mechanism and cause to reduction in the received signal level. Therefore, the induced power density due to base station radiation will be inversely proportional to (r^{γ}) where γ is the path loss exponent value (Bello et al., 2023).

$$P_d = \frac{P_t\ G_t(\theta,\varphi)}{4\pi r^{\gamma}} \tag{2}$$

3. Theoretical approaches for power density estimation

To assess the effects of cellular network base station radiations, this paper presents two approaches to estimate the exposure levels in terms of the induced power density.

3.1. First approach

In cellular networks of hexagonal cell layout, any cell has six equidistant cells surrounding that cell in the first ring, and twelve equidistant cells at the second ring. Whatever the utilized cluster size, the number of cells surrounding a specific cell at a specific ring is equal to the ring number multiplied by six as shown in Figure 2. Any object within any cell of a cellular system network is usually exposed to the radiation from the nearest base station and the radiation from the other surrounding base stations. Therefore, the body at the reference cell will be additionally exposed to the radiation from the surrounding six cell base stations at the first ring around the centered cell. Furthermore, the body will be exposed to the radiation from twelve cell base stations that are located at the second ring and the radiation generated by the eighteen base stations of the third ring.

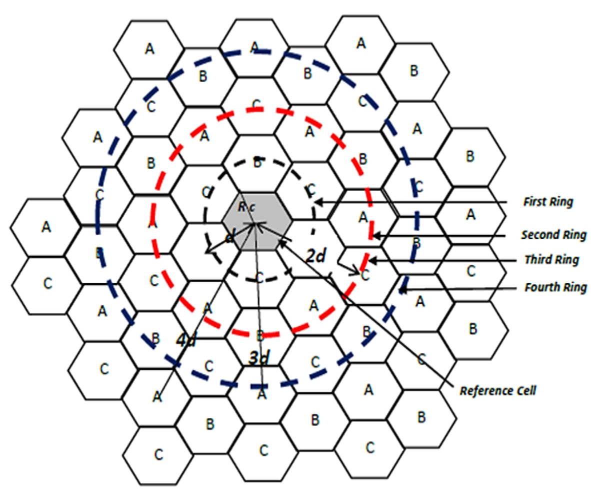

Figure 2. The Reference cell and surrounding cell rings.

As shown in Figure 3, the radius of each cell is R_c. The exposed body at the centered (reference) cell C_o is located at a distance r_o ($r_o \leq\ R_c$) from the base station serving the cell and at an angle ϕ ($0 \leq \varphi \leq\ 2\pi$) with the radiation source (base station antenna). The power density at the exposed object induced due to its serving base station can be given as:

$$P_d = \frac{P_t\ G_t(\theta,\varphi)}{4\pi r_o{}^{\gamma}} \quad (3)$$

Assuming that all base stations transmit the same amount of power, the total resultant power density induced at the exposed body will be the summation of all radiation sources (base stations) surrounding the reference base station, and it can be expressed by superposition theorem as:

$$P_d = \frac{P_t\ G_t(\theta,\varphi)}{4\pi r_o{}^{\gamma}} + 6\times\frac{P_t\ G_t(\theta,\varphi)}{4\pi r_1{}^{\gamma}} + 12\times\frac{P_t\ G_t(\theta,\varphi)}{4\pi r_2{}^{\gamma}} + 18\times\frac{P_t\ G_t(\theta,\varphi)}{4\pi r_3{}^{\gamma}} + 24\times\frac{P_t\ G_t(\theta,\varphi)}{4\pi r_4{}^{\gamma}} + \dots..$$

Where (r_1), (r_2), (r_3), and (r_4) are the distances between the exposed body and the surrounding base stations at the first, second, third, and fourth ring respectively.

$$P_d = \frac{6\ P_t\ G_t(\theta,\varphi)}{4\pi}\left[\frac{1}{6\ r_o{}^{\gamma}} + \frac{1}{r_1{}^{\gamma}} + \frac{2}{r_2{}^{\gamma}} + \frac{3}{r_3{}^{\gamma}} + \frac{4}{r_4{}^{\gamma}} + \dots\dots\right] \quad (4)$$

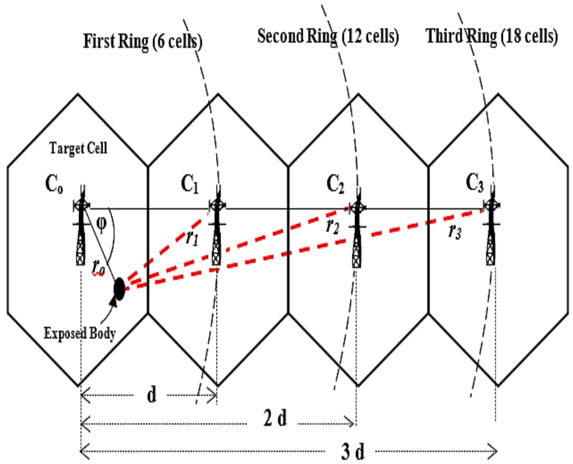

Figure 3. Distances between the exposed body and surrounding cell.

In hexagonal-style cellular networks, the distance between any two adjacent cells from center to center is given in terms of the radius cell (*R_c*) as Rappaport (2002).

$$d = \sqrt{3}\ R_c \quad (5)$$

The distances between the exposed body and base stations located at the first, second, third, and fourth rings denoted *r_1*, *r_2*, *r_3*, and *r_4* can be expressed by cosine law as:

$$\left.\begin{aligned} r_1 &= \sqrt{r_o{}^2 + d^2 - 2r_o d\ \cos\varphi} \\ r_2 &= \sqrt{r_o{}^2 + (2d)^2 - 2r_o(2d)\ \cos\varphi} \\ r_3 &= \sqrt{r_o{}^2 + (3d)^2 - 2r_o(3d)\ \cos\varphi} \\ r_4 &= \sqrt{r_o{}^2 + (4d)^2 - 2r_o(4d)\ \cos\varphi} \end{aligned}\right\} \quad (6)$$

3.2. Second approach

This section aimed to apply the fluid model framework to evaluate the exposure levels of radiation in people living near cellular base stations. The model consists of a cellular network of several base stations that are randomly distributed over the entire coverage area. The downlink (forward transmission) is considered to derive an expression to evaluate the power density induced at the body exposed to all cellular network base stations radiation. The cellular network is assumed to have identical cells that are distributed over a circular coverage area with hexagonal cells each with a radius of R_c. The exposed body is located at a distance of r_o from the serving base station as shown in Figure 4. This body is exposed to all surrounding base stations at different levels of exposure in addition to the power density induced by the serving base station. The area containing the surrounding cells contributing to inducing EM fields at the exposed body is limited over the ring with radius ($\sqrt{3}R_c$ - r_o) and the ring with radius (R - r_o) where R is the radius of the entire coverage area. The first radius represents the distance between the exposed object and any one of the cells at the first ring, and the second radius is the distance between the exposed objects and the farthest ring of the cellular network coverage area. Therefore, the total number of the surrounding base stations whose radiations affect the exposed object can be determined by integrating the elementary surface area (r dr dθ) at a distance r over these two rings. The elementary surface contains (ρ_{BS} *rdrd*θ) some base stations where ρ_{BS} is the base station density.

The total corresponding power density induced at the exposed object will be the summation of the power density from the serving base station and the power density induced by the surrounding base stations which can be obtained by the integration of $\frac{P_t G_t}{4\pi}\rho_{BS}\ r^{-\gamma} r dr d\vartheta$. Therefore, the power density can be given as:

$$P_d = \frac{P_t\ G_t}{4\ \pi\ r_o{}^{\gamma}} + \frac{P_t\ G_t}{4\ \pi}\int_0^{2\pi}\int_{\sqrt{3}\ R_c - r_o}^{R-r_o} \rho_{BS}\ r^{-\gamma} r\, dr\, d\vartheta$$

$$P_d = \frac{P_t\,G_t}{4\,\pi\,r_o^{\,\gamma}} + \frac{P_t\,G_t}{4\,\pi}\,\rho_{BS}\int_0^{2\pi}\int_{\sqrt{3}\,R_c - r_o}^{R-r_o} r^{1-\gamma}\,dr\,d\vartheta$$

$$P_d = \frac{P_t\,G_t}{4\,\pi\,r_o^{\,\gamma}} + \frac{P_t\,G_t}{4\,\pi}\,\rho_{BS}\,2\pi\int_{\sqrt{3}\,R_c - r_o}^{R-r_o} r^{1-\gamma}\,dr\,d\vartheta$$

$$P_d = \frac{P_t\,G_t}{4\,\pi\,r_o^{\,\gamma}} + \frac{P_t\,G_t}{2}\,\rho_{BS}\left[\frac{r^{2-\gamma}}{2-\gamma}\right]_{\sqrt{3}\,R_c - r_o}^{R-r_o}$$

$$P_d = \frac{P_t\,G_t}{4\,\pi\,r_o^{\,\gamma}} + \frac{P_t\,G_t}{2(2-\gamma)}\,\rho_{BS}\left[\,r^{2-\gamma}\,\right]_{\sqrt{3}\,R_c - r_o}^{R-r_o}$$

$$P_d = \frac{P_t\,G_t}{4\,\pi\,r_o^{\,\gamma}} + \frac{P_t\,G_t}{4-2\gamma}\,\rho_{BS}\left[(R-r_o)^{2-\gamma} - (\sqrt{3}\,R_c - r_o)^{2-\gamma}\right]$$

$$P_d = \frac{P_t\,G_t}{4\,\pi\,r_o^{\,\gamma}} + \frac{P_t\,G_t}{4-2\gamma}\,\rho_{BS}\left[\frac{1}{(R-r_o)^{\gamma-2}} - \frac{1}{(\sqrt{3}\,R_c - r_o)^{\gamma-2}}\right]$$

$$P_d = \frac{P_t\,G_t}{4\,\pi\,r_o^{\gamma}} + \frac{P_t\,G_t}{2\gamma-4}\,\rho_{BS}\left[\frac{1}{(\sqrt{3}\,R_c - r_o)^{\gamma-2}} - \frac{1}{(R-r_o)^{\gamma-2}}\right] \qquad (7)$$

When the entire coverage area radius *R* is much larger than r_o , the term $(1/(R-r_o))$ can be neglected as it will be very small especially in in urban environments where the path loss exponent value is equal to four. Therefore, eq. (7) can be simplified into:

$$P_d = \frac{P_t\,G_t}{4\,\pi\,r_o^{\gamma}} + \frac{P_t\,G_t}{2\gamma-4}\,\rho_{BS}\left[\frac{1}{(\sqrt{3}\,R_c - r_o)^{\gamma-2}}\right] \qquad (8)$$

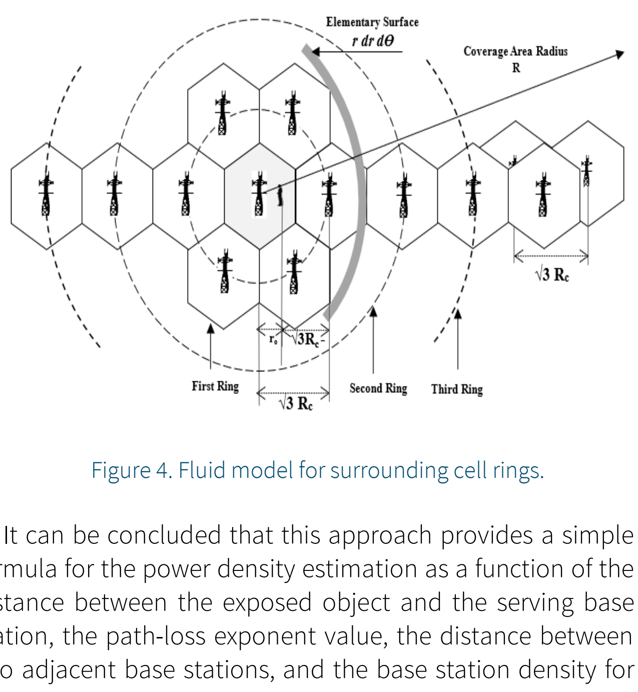

Figure 4. Fluid model for surrounding cell rings.

It can be concluded that this approach provides a simple formula for the power density estimation as a function of the distance between the exposed object and the serving base station, the path-loss exponent value, the distance between two adjacent base stations, and the base station density for the entire network.

4. Models simulation results and discussions

In this section, the models proposed in the previous section will be simulated to investigate the factors that mostly affect the power density induced at the exposed object.

For the first approach simulation, the exposed object is assumed to be at different locations within the reference cell. The distance between the exposed object and the serving base station (r_o) is varied from 0 to R_C, and the exposed object is assumed to be at different direction from the serving base station antenna (ϕ). The power density induced at the exposed object is evaluated considering one ring and many rings of the surrounding cells at different power exponent values. A network of three rings of hexagonal cells around the reference cell is considered.

Figure 4 shows the average power density as a function of the cell radius R_c which is taken to be from 100m to 1.0 km, and path loss exponent between 2.0 and 4. The figure shows that the power density decreases as the cell radius increases for a certain value of path loss exponent. When the path loss exponent is taken to be equal to 2, the power density is equal to 62.3 mW/m^2 where the cell radius is 100 m, while it is decreased to 15 mw/m^2 as the cell radius increases to 1.0 km. Furthermore, it can be noticed that as the path loss exponent is increased, the power density is decreased. For R_c=200 m, the power density is 43.7 mw/m^2 where the path loss exponent is 2, while it decreased to 12.6 mW/m^2 in an urban environment where the path loss exponent is equal to 4.

Figure 5 shows the average power density as a function of the cell radius R_c when the different number of surrounding cell rings is considered. The figure shows that the power density increases in a very small magnitude when more rings are considered. For a cellular network with cells of 100 m radius, the power density is 75.1 mW/m^2 due to the effect of six cells surrounding the centered cell, while it is 75.3 mW/m^2 where 18 surrounding cells are considered. This means that the serving base station closest to the exposed objects is the main contributor in the induced power density. Even in cells of a small radius, the contribution of surrounding cells is very small because the signal transmitted by the base station is attenuated with the square of the distance.

The fluid model is simulated to determine the induced power density at the exposed object considering different path loss exponent values, and a cellular network with a density of ten base stations per square kilometer.

Figure 6 shows the average power density as a function of the cell radius R_c where the coverage area has a radius of $2R_c$ and where the path loss exponent is between 2.5 and 4. From the figure 7, it can be concluded that as the cell radius increases, the power density is decreased. Additionally, when the path loss exponent increases the power density is decreased. For R_c =100 m, the power density is 101.147 mW/m^2

where the path loss exponent is 2.5 while it was 100 mW/m^2 where the path loss exponent is 4.

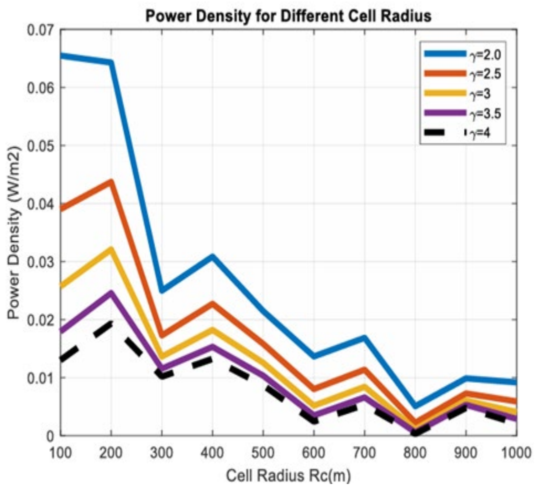

Figure 5. The power density for different path loss exponent values.

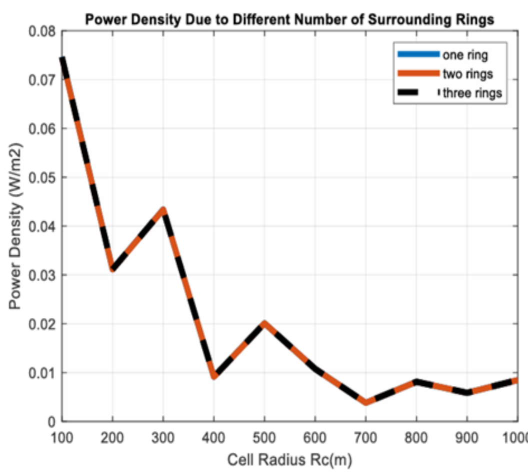

Figure 6. The power density for different surrounding cell rings.

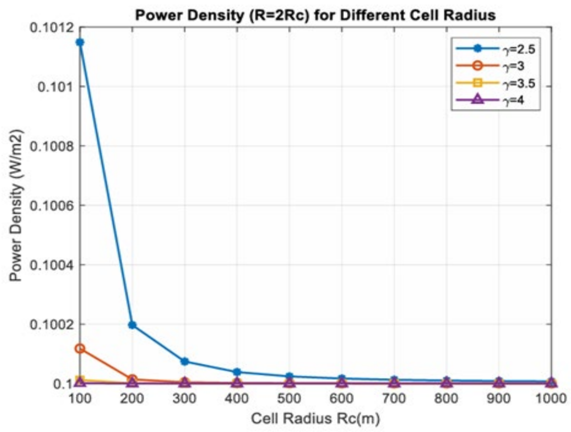

Figure 7. The power density for R=2R$_c$.

Figure 7 shows the average induced power density as a function of the cell radius Rc where the coverage area is assumed to be 4Rc for different path loss exponent values as shown in Figure 8. As illustrated from the figure, when the cell radius is 100 m, the power density is 101.182 mW/m2 where the path loss exponent is 2.5. There is a small difference in power density compared with the case at which R=2Rc due to the larger number of base stations contributing to power density induced at the exposed object.

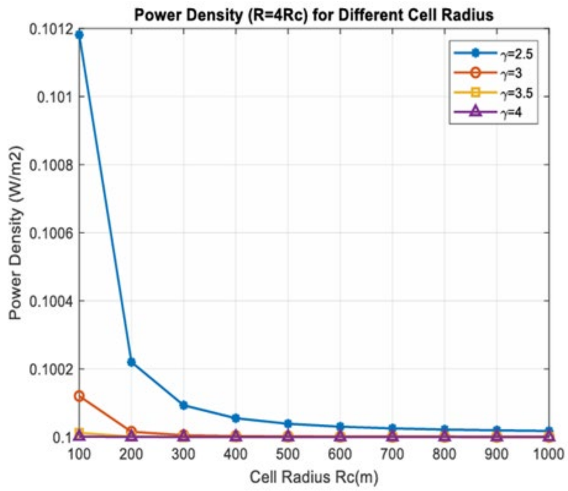

Figure 8. The power density for R=4R$_c$.

It can be concluded that the factors of high impacts on the radiated power density on the exposed body are the transmission distance, the nature of the propagation environment, and the base station density. It can be expected that small radius cells that are required to obtain good coverage in 5G networks can lead to a large number of base stations in populated areas and result in higher exposure to electromagnetic radiation.

5. Conclusions

In this paper, we presented the cellular network model that consists of several rings of surrounding cells for evaluating the power density induced at the object exposed to cellular base station radiations. Then, we derived the expression of induced power density using an analytical model based on the fluid framework. The simulation results obtained by the fluid model are similar to those obtained from the model of several rings. The obtained simulation results indicate that the distance from the radiation source, path loss exponent value, and the base station density may heavily affect the radiation exposure levels. It can be denoted that the fluid model allows us to construct a simplified expression to determine the power density induced at the exposed object considering the radiation of all base stations of the cellular network.

Conflict of interest

The authors have no conflict of interest to declare.

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