Impact Factor 6.1

Journal of Cyber Security

ISSN:2096-1146

Scopus

DOI

Google Scholar

Spatio-Temporal Profiling and Quantitative Analysis of Indoor and Outdoor RF-EMF Exposure from Cellular Base Stations

Amar Renke
Dept.of Electronics and Telecommunication
Kolhapur Institute of Technology's College of Engineering
Kolhapur

Ramajee Prasad
CTIF Globel Capsule
Denmark

Mahesh Chavan
Dept.of Electronics and Telecommunication
Kolhapur Institute of Technology's College of Engineering
Kolhapur

Abstract— **This research aims to examine outdoor EM field levels, residential indoor exposures, and floor-specific exposures near mobile base stations. The study examines the electrical fields' intensity and strength at various distances and times, specifically during sunny weather, by analyzing data collected from multiple base stations. Individuals' contributions were also calculated. Antenna masts. All EM field measurements were compared against national and international standards, such as those set by the Department of Telecommunications (DoT) and the International Commission on Non-Ionizing Radiation Protection (ICNIRP). Outdoor electromagnetic fields in crowded places measured lower than recommended by ICNIRP standards but higher than those set by Austria. Indoor residential EM areas were evaluated in Kolhapur, a western Maharashtra district, examining potential health risks due to nearby MBS antenna radiation. In the study, efforts were made across multiple areas within the homes, such as the hall, kitchen, bedroom, and roof, to ensure that the power density and strength of the electric field did not exceed the safety standards set by ICNIRP. The results showed that these levels remained well below the permitted limits. The EM field intensity changed depending on where the antenna mast was placed and how many antennas were used. Further, floor-wise EM field exposure was analysed in multi-storey residential buildings. Measurements were taken at various levels, including the ground floor, first floor, second floor, higher floors, and rooftop terraces, using a three-axis EM field meter (Model KM-195). The results revealed that floor exposure levels were also well within standard safety limits. It was found that indoor EM field strength in dwellings depends on the location of the building, the number and height of antennas on nearby MBS, while floor-wise exposure is further influenced by the tilt angle of the antennas.**

Keywords— ***Electromagnetic field exposure, mobile base station, Worldwide Commission for Non-Ionizing Radiation Protection, Department of Telecommunication, floor exposure, European Council***

I. INTRODUCTION

This paper focused on radiation from mobile antenna mast surrounded by citizens in Kolhapur city. Here initially base comm. station sites are selected from urban and rural areas. The criterion for site selection is residents closer to base comm. station. Generally, thickly populated areas are selected for radiation measurement [1],[2]. Measurement of power density and electric field is known as EM field exposure. Purpose of measurement is to create awareness in Indian society regarding EM field exposure from base comm. stations. In developed countries, it is already done, and people are asking about EM radiation levels, expressing worries about adverse health issues of EM radiation [3],[4]. Also, they are aware of standard guidelines and restrictions set by ICNIRP, European Council, WHO, NRPB etc [4],[5]. Therefore, it is necessary to make aware of EM field exposure, its guidelines and unfavorable health issues to Indian society mostly those are living closer to MBS [1],[2].

There are many devices which are transmitting EM field in free space. The different devices which are transmitting this EM field are AM/FM/TV transmitters, Wi-Fi transmitters and most important one is antenna masts which are technically called base stations (MBS)[6]. On each mobile tower there are at least 20 antennas mounted according to survey in Kolhapur city. And each antenna was transmitting power from 2W to 20W. So total radiated power density will be Total *Power density = power transmitted by each antenna x number of antennas on the tower*. Therefore, If the maximum power radiated is 20W by each antenna then total power radiated will be [1],[2] equal to 20w x 20 = 400 watts/m^2.There are different methods to measure the EM field exposure from base comm. stations. These are single spot method, three-point, six point, nine points, 20 point and moving average method as shown in figure 1.1 [1].

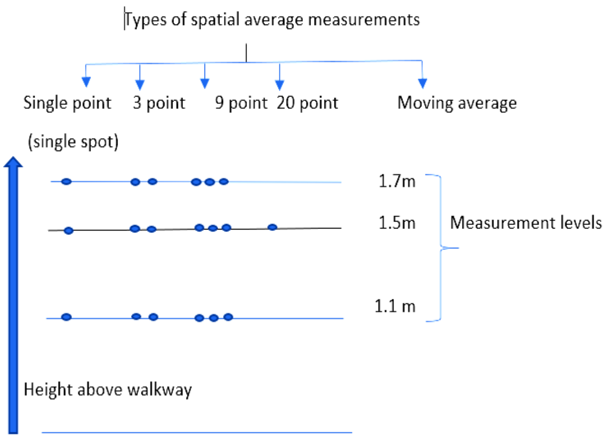

FIGURE 1 MEASUREMENT APPROACHES

Outdoor exposure measures will be performed at three levels 1.1m 1.5m and 1.7m to cover all variety of people around base comm. stations from 10m to 300m distance from base comm. station. Measurement will be performed with help of KM-195 EM field meter [2]. Here height considered is 1.5m which is approximately 5 feet. The reason for 5 feet is that average Indian people height is about 5 feet [2].

Before measurement of EM field exposure from MBS, first base comm. stations from thickly populated urban/rural areas were selected. After selection of base comm. stations measurement of EM field exposure starts. There are two main components of EM field exposure i.e. electric field and power density which is measured by three axis RF field strength meter details of which are as follows [1],[2].

II. Outdoor Electromagnetic Field Exposure

General Field exposure means EM field is measured outdoors. That is on roads, nearby schools, commercial areas, outside the residential areas etc. First such antenna sites were identified and then measured the EM field exposure [1].[2]. Before measuring outdoor field exposure some important information is noted down that is antenna height, number of antennas, types of antennas, whether it is located on ground or building etc.

The general area exposure is noted for 10,20,30,40,50,50,60,70 …… 150 meters in terms of power density and electric field [1]. The meter has three options actual reading, average reading, and maximum average. In most cases, all options are noted down [2]. The measurements were conducted for all selected sites on sunny days. Finally, measurement readings were compared with theoretical readings and with ICNIRP standards [3],[4].

TABLE I. BASE STATIONS

Sr. No.	Mobile Base Station (MBS)	Area where Station is located	Tallness of base station (feet)	Number of antennas
1	CM-BS 1	Kandalgaon	65	17
2	CM-BS 2	R. Nagar	75	20
3	CM-BS 3	More wadi	85	16
4	CM-BS 4	Datt Colony	65	17
5	CM-BS 5	Sanchayani colony	155	16
6	CM-BS 6	Ramanand nagar	125	17
7	CM-BS 7	Postal colony	150	18
8	CM-BS 8	Hockey stadium area	165	16
9	CM-BS 9	Jai Prabha studio	150	16
10	CM-BS 10	Tarabai park area	155	17
11	CM-BS 11	Area near RTO office	165	16
12	CM-BS 12	Area near main post office	200	17
Average Tallness and No. of antennas			125	16

For measurement of electromagnetic (EM) field from cellular mobile base stations (CMBS), sites were chosen primarily from areas with densely populated areas. Kandalgaon, R. Nagar, Dutt Colony, Postal Colony, Jai Prabha Studio, RTO office and main post office, where the population density was relatively high. On these sites, the outdoor EM field exposure was measured at an altitude of 1.5 meters. This height was chosen as it corresponds to the average height of an adult (about 5 feet or 1.5 m) in India. The EM field exposure was determined in terms of electrical density and power of the electric field. The power density was recorded in microwatt per square meter (μW/m c), while the electric field was measured (mV/m) [1]-[3].

III. Indoor Electromagnetic Field Expousure

To estimate the level of risk of the worst condition in residential houses, electromagnetic (EM) field measurements were held in various parts of the houses located near the base communication station towers. The selected towers were ground-mounted, with an average of 16–20 antennas per mast. All investigated houses were near these antenna masts, with 10 meters to 50 meters, and in most cases about 20 meters.

Measures were made in various parts of houses including halls, bedrooms, kitchens, balconies and roofs. Considering the average height of Indian individuals, the EM field exposure was recorded at 1.5 meters using three -axis EM field meters (model KM -195). The process included selecting the first base station antenna mast sites, followed by the electrical density and systematic measurement of the electric field in different parts of the housing [15], [16]. To ensure accuracy, the measurement in each location was repeated several times, and the average was assumed. During the sunny days, the assessment was done during hours of day (8:00 am to 8:00 pm), in which with reading every hour to catch ups and raise in electrical density. For analysis, three representative matters were considered.

Case 1: EM field exposure measured in dwellings located on the ground floor, 20 m away from a cellular mobile tower.

Case 2: EM field exposure measured in nearby dwellings where the mobile tower was installed on the second floor.

Case 3: EM field exposure measured in nearby dwellings where the mobile tower was installed on the seventh floor.

IV. Floor Exposure Assesment

An antenna is a device that works with Electromagnetic fields. It is made to send and receive these fields. It has several important features like directive gain, beam width, radiation pattern, operating frequency, and polarization Antennas are grouped into three main types based on how thy send out signal: directional, sector and omni-directional. The gain of an antenna makes the signal stronger and sends the power in a particular direction. Directional antennas send signals in one specific direction, while omni directional antennas spread the signal evenly in all directions. The amount of gain as antenna has depends on its radiation angles[2].

Sector antennas with a beamwidth of 120° are commonly used in GSM base communication stations. Typically, three such antennas are mounted together to provide 360° coverage of the surrounding area. Sector antennas gain usually ranges between 12 and 18 dBs, with lengths varying from 1.5 to 2.5 meters. On the other hand, omni-directional antennas are generally used in densely populated areas. Since GSM systems employ vertical polarization, all antennas are aligned accordingly.

Down-tilting of antennas is an essential practice for mast installations. In some cases, antennas are mechanically down tilted at an angle (e.g., 90° with respect to the horizontal plane) to ensure that the radiated energy is directed toward the intended coverage area. Sector antennas with horizontal beamwidths of 60°, 90°, 120°, and 180° and vertical beamwidths ranging from 3° to 10° are widely deployed. The

EM field radiated by an antenna mast depends strongly on both mechanical and electrical down-tilt angles, and the actual radiation values should closely match the design specifications of the radiation pattern.

Short-term and long-term EM field sources include smartphones and mobile base stations (MBS), respectively. In recent years, MBS installations have increasingly been placed in densely populated urban areas. Kolhapur, being a rapidly developing city, has seen the construction of numerous tall buildings, apartments, and commercial towers. Quantifying power density and electric field levels in such high-rise structures is essential for determining exposure values of residents on different floors, thereby assessing compliance with standard EM field exposure limits.

On average, residential buildings in Kolhapur have about five floors, though measurements were carried out in 4- to 7-story apartment complexes. In some cases, antenna masts were mounted on the rooftops of these buildings at heights of 5 to 10 meters. Buildings were carefully selected such that an antenna mast was located directly in front of them. EM field measurements were conducted on each floor, both indoors (inside rooms) and outdoors (balconies, terraces), as well as on the rooftops. All measurements were recorded in terms of power density (μW/m²) and electric field strength (V/m).

V. RESULT AND DISCUSSION

Power density measurements were conducted at five different locations in Kolhapur city, India, covering approximately 15 cellular mobile base stations. Table 1 presents the measured values of power density and electric field intensity at the base station sites, where population density was relatively high. The results indicate that power density increased with distance up to 120 m from the base station and then decreased. This base station operated under line-of-sight (LOS) conditions. The maximum average power density and peak power density recorded were 25,550 µW/m² and 40,380 µW/m², respectively. The maximum average electric field intensity observed was 2,857 mV/m.

TABLE II. MEASURED DATA AT BASE STATION CMBS10

Distance (m)	Normal power density μw/ m^2	Normal Electric field mv/m
10	2771	1471.5
20	2906	1246.5
30	2111	1402
40	2486	1186.2
50	1786.9	1168
60	3169	1308.4
70	2306	1227.7
80	2347	1301.5
90	3039	1385.0
100	6027	2195
110	12471	2268
120	10019	2429
130	4176	2466
140	18431	3879
150	20171	3167

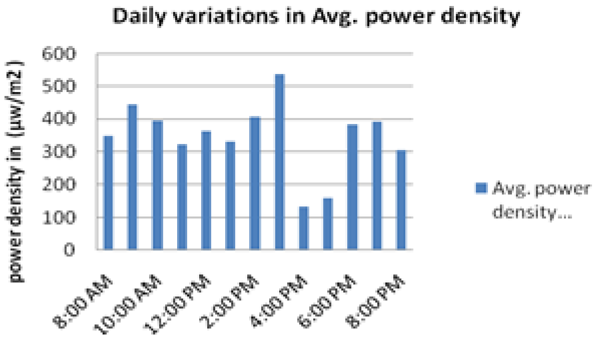

FIGURE II. DAY TO DAY VARIATION IN POWER DENSITY

It was observed that EM field exposure varied with both distance and time. Significant fluctuations in the measured values were recorded at each location. The maximum and minimum exposure levels for each cellular base station (CBS) also showed considerable variation [12], [13].

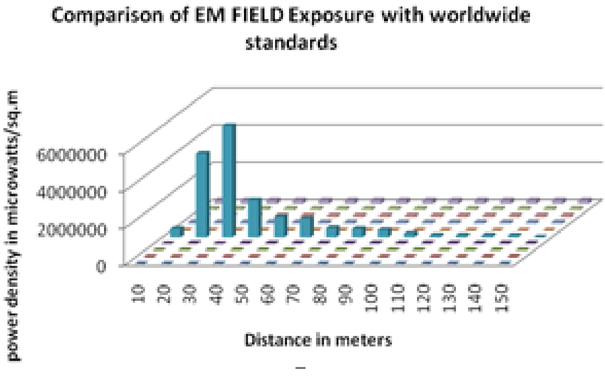

FIGURE III. COMPARISION OF POWER DENSITY VALUES

Figure III illustrates a comparison between the measured EM field exposure levels and the reference limits set by various countries. In most cases, the recorded exposure levels were well below the respective standards. However, in Austria, the measured values exceeded the national reference limit due to its comparatively stricter guidelines. Figure III presents the variation in power density, measured at intervals of 10 meters from 10 m to 150 m. The results indicate fluctuations in power density with distance. Initially, the values were relatively high but gradually decreased as the distance increased. These variations were influenced by line-of-sight (LOS) and non-line-of-sight (NLOS) conditions [14], [15], [27], [28].

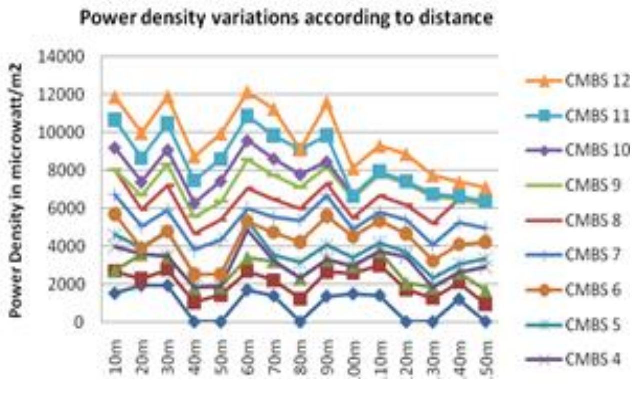

FIGURE IV. POWER DENSITY VARIATIONS ACCORDING TO DISTANCE

Figure IV clearly indicates that power density decreases as the distance from the source increases. A total of twelve sites (CMBS 1 to CMBS 12) were selected for analysis. Among them, CMBS 5, 6, 10, and 11 were in more densely populated areas compared to the others. Notably, CMBS 5, 10, and 11 had the tallest antenna masts, with heights ranging between 200 and 250 feet [16].

TABLE III ELECTRIC FIELD INTENSITY AND POWER DENSITY OF INDIVIDUAL CMBS AND PROPORTION CONTRIBUTION

Base stations	Location	Avg. Pd in microwatt/m2	Avg. Electric Field mv/m	% involvement
CMBS I	Kandalgaon - I	2673.78	1900.44	10
CMBS II	Rajendra Nagar	1366.90	1102.47	5
CMBS III	More wadi	1011.30	781.63	4
CMBS IV	RK Nagar2	3383.98	3271.87	13
CMBS V	Shanta-Durga Colony	1322.16	1811.48	5
CMBS VI	Jarag Nagar	2333.70	1613.37	9
CMBS VII	Postal colony area	1352.92	966.74	5
CMBS VIII	Mahalaxmi Nagar	2548.49	2512.46	10
CMBS IX	Dhairya Prasad hall area	1205.15	742.41	4
CMBS X	Tarabai Park	6271.12	1861.12	24
CMBS XI	Main Post Office area	3013.09	1300.09	11
CMBS XII	Kandalgaon- II	468.872	543.44	3

Above table shows the contribution of general EM field exposure of each cellular base station. The major contibution is from CMBS 10 and lower from CMBS 12.

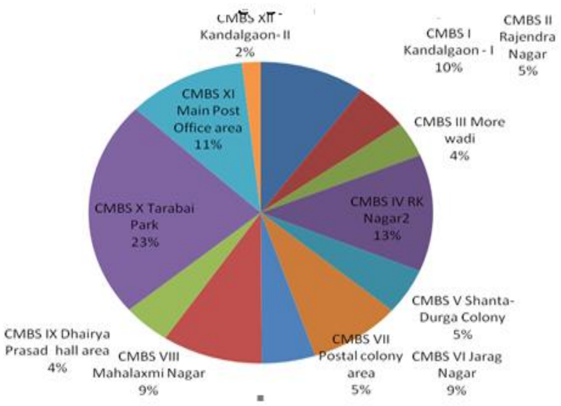

FIGURE V. PROPORTION INVOLEMENT OF POWER DENSITY FROM EACH BASE STATION

The exposure to electromagnetic field from each CMBS has decreased as distance increased. It is observed that the number of antennas on each must varied, with an average of around 20 antennas per mast. Fluctuations were noted in power density and electric field level. In this study, 20 CMBS were analyzed with an average power density of 2416.41 μw/m² and electric field of 1615.21mV/m. CMBS 12 had the lowest power density of 551.54 μw/m². and their interactions affect EM field exposure. CMBS10 Shown the highest power density of 6280.12 μw/m². CMBS 1,4,8 and 10 have contributed most to EM field exposure. All average, maximum values were found to be below the norms established by DoT and ICNIRP [20].

TABLE IV RESULTS ON GENEGAL ELECTROMAGNETIC FILED EXPOSURE

Parameter	Unit
Maximum Power density	6280.12 μw/m^2
Maximum electric field	3282.97 mv/m
Normal power density	2416.41 μw/m^2
Normal electric field	1615.21mv/m

a. Results of Indoor EM Field Exposure

It was found that inside homes, the levels of power density and electric field strength changed depending on where you were. To get better measurements, power density and electric field were checked near the windows inside the homes. Table 5 and Table 6 show the daily changes in power density and electric field at the terrace and bedroom respectively [21].

TABLE V DAY TO DAY DIFFERNCE IN EM FIELD AT (ROOF TOP) TERRACE

Home-based	Place	Roof-top
Time	***Power density µw/ m^2***	***Electric field mv/m***
8 AM	2976	1523.1
9 AM	2866	1483.8
10 AM	2679	1488.6
11 AM	2797	1426.8
12 PM	2742	1449.3
1 PM	2903	1460.2
2 PM	3046	1492.2
3 PM	3201	1471.2
4 PM	2872	1407.8
5 PM	2911	1497.4
6 PM	3748	1408.6
7 PM	2197	1388.8
8 PM	2550	1323.7

The power density and electric filed were more at the roof top and balcony, lower in kitchen, and medium in the hall and bedroom, to ensure accurate results, measurements were repeatedly taken and averaged [22].

TABLE VI DAILY VARIATION IN EM FIELD AT BEDROOM

Time	Power density µw/ m2	Electric field mv/m
8 AM	394.5	544.8
9 AM	523.1	523.4
10 AM	529.8	532.7
11 AM	512.6	515.4
12 PM	407.2	517.7
1 PM	610.3	418.8
2 PM	390.3	502.9
3 PM	569.8	481.3
4 PM	485.8	550.2
5 PM	580.0	530.4
6 PM	479.7	439.2
7 PM	527.8	456.0
8 PM	473.2	545.3

To analyze the measured data and understand the results from the perspective of residential exposure [85], the measured electromagnetic field levels for all cases ranged from 45.92 to 13860 µW/m². The power density was higher near the base stations and decreased as you moved away from the antennas. The power density also changed depending on the direction the base station was facing. In our study, we found that power density was low in the hall and kitchen, moderate in the bedrooms, and high in the balcony and on rooftops [22].

TABLE VII NORMAL POWER DESNSITIES AT VARIOUS RESIDANCIES

Place	Normal power density μw/ m^2		
	Case I	*Case II*	*Case III*
Hall	339.67	4313.59	339.67
Bedroom	374.12	1075.13	259.12
Kitchen	251.35	195.79	46.67
Terrace	2598.65	11492.98	13860.75

The strength of the signal and the electric field can vary based on how many people are making phone calls, how far they are from the cell tower, and the height of the antenna. Table 7 lists the average power levels in different parts of homes. About 70% of the radio frequency fields in the environment are from mobile cell towers. The regulations in India regarding exposure to electromagnetic fields follow the guidelines set by the Department of Telecom [5].

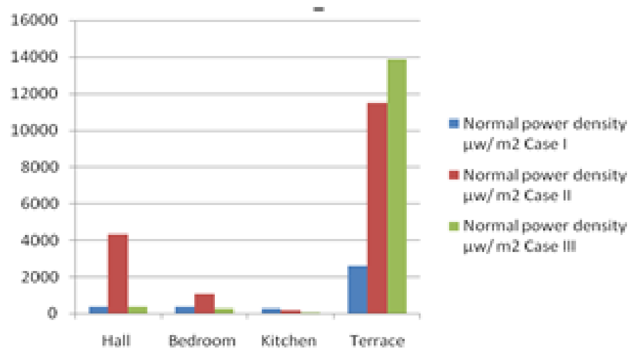

FIGURE 6 POWER DENSITIES AT DIVERSE PLACES

Figure 6 shows the graphical representation of table 8. It shows that EM field exposure is higher at terrace and lower at other places in the dwellings [23].

TABLE VIII ELECTRIC FIELD MEASURED AT HOME

Place	Normal electric field mv/ m		
	Case I	*Case II*	*Case III*
Hall	358.55	1276.13	376.55
Bedroom	376.27	637.43	313.19
Kitchen	308.01	272.14	132.58
Terrace	1267.26	2692.17	9267.25

For the frequency bands 800, 900 1800 and 2100 MHz, the reference levels are 28, 43, 58 and 61 v/m respectively.

Figure 7 shows how much electromagnetic field exposure there is in different areas of a home, such as the hall, bedroom, kitchen, and terrace. The findings show that electromagnetic field exposure is higher in the terrace and on the second floor, but lower on higher floors in buildings [25]. The measured electromagnetic field exposure for each case and location was 890 μw/m², 4268.62 μw/m², and 3625.80 μw/m² for case1, case2, and case3 respectively. These measured power densities are all below the reference limits set by ICNIRP and DoT.

b. Results of Floor EM Field Exposure

The results of the measurements show that the highest power density is found on the floor that is at the same height as the antenna, which means the antenna is in direct line of sight. Also, both power density and electric field strength were higher outside the home than inside.

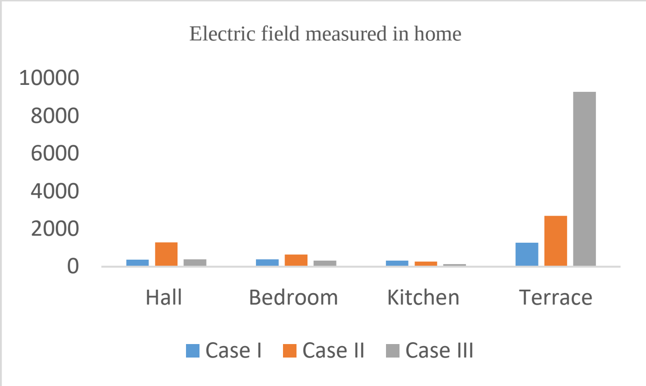

FIGURE 7 ELECTRIC FIELD MEASURED IN HOME

The data also shows that exposure increases as you go up from the ground floor to the level where the floor height matches the antenna height. After that point, exposure starts to decrease as you go higher up the building. The shape of the graph looks like a bell curve. The findings also suggest that the antenna effectively covers heights up to approximately 20 meters, corresponding to about six floors.

Floors above this level receive reduced coverage. In summary, the middle floors of a building experience higher EM exposure than either the lower or upper floors, with exposure levels also influenced by the location and distance of the mobile tower relative to the building [27].

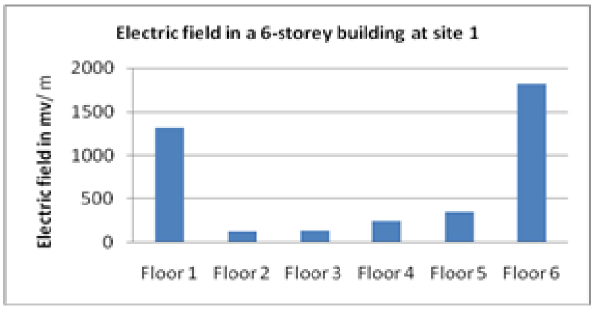

FIGURE 8 ELECTRIC FIELD INSIDE A 6-STOREY BUILDING IN THE MIDDLE OF THE ROOM

From figure 8 it is seen that exposure was more at ground and last floor and goes on increasing from floor 2 to floor 6.

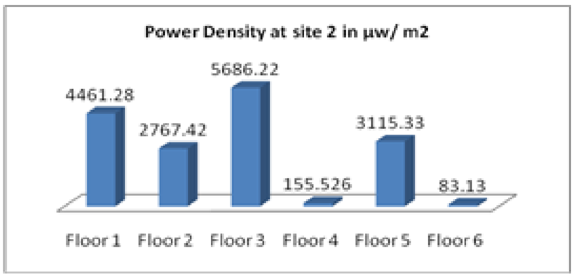

FIGURE 9: POWER DENSITIES INSIDE A 6-STOREY BUILDING IN THE MIDDLE OF THE ROOM.

Figure 9 shows that floors 4 and 6 are having less EM exposure. Medium at floors 1, 2 and 5, highest at floor 3. From figure 3.16 it can be concluded that floor 3 is in line with the transmitting antenna.

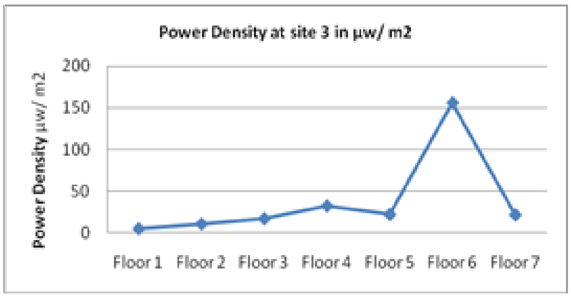

FIGURE 10 POWER DENSITIES INSIDE A 7-STOREY BUILDING IN THE MIDDLE OF THE ROOM.

From figure 10 the power density is high at floor six, so they get more EM field exposure than other floors.

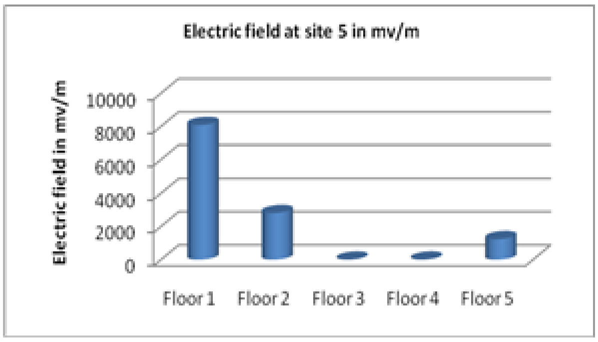

FIGURE 11 POWER DENSITIES INSIDE A 5-STOREY BUILDING IN THE MIDDLE OF THE ROOM.

Figure 11 shows that EM field exposure is high at floors 1 and medium on floors 2 and 5, very low on floors 3 and 4.

VI. CONCLUSION

Outdoor EMF exposure from base stations was assessed by measuring power density and electric field at 1.5 m height, from 10 m to 150 m distance. Radiation patterns were obtained by measurements at 20 m around 0°–360°, and daily variations were recorded from 8 AM to 8 PM. The results, on average per site, were compared with ICNIRP and DoT standards, showing all values well below limits. Graphs of power density/electric field vs. distance revealed higher values near the base station that decreased with distance. Contribution analysis showed Tarabai Park had the highest exposure (24%), while Kasba Bawada, Mahalaxmi Nagar, and R.K. Nagar contributed 11%, 10%, and 13%, respectively. Daily fluctuations were significant. Indoor exposure depended on antenna direction, being higher in bedrooms facing the tower, and in tall buildings, exposure increased when antenna height and tilt aligned with floor level. In conclusion, The study reveals that outdoor EMF exposure from base stations decreases with distance and remains well below ICNIRP and DoT safety limits. Exposure contribution varies across sites, with Tarabai Park showing the highest levels. Daily measurements indicate noticeable fluctuations. Indoor exposure is influenced by the orientation of antennas toward living spaces, while in multi-storey buildings it increases when antenna height and tilt coincide with floor levels. Overall, EMF levels are within permissible limits, though site location and antenna orientation significantly affect exposure.

ACKNOWLEDGMENT

The authors sincerely thank *CTIF Global capsule Denmark* and *Kolhapur Institute of Technology*, *Kolhapur India* for their invaluable support in the form of resources, technical guidance, and research facilities, which greatly contributed to the successful execution of this study. Their encouragement and collaboration are deeply appreciated.

REFERENCES

[1] A. L. Renke and M. S. Chavan, "An estimation of electromagnetic field exposure from cellular mobile base station towers in densely populated residential areas," *Commun. Appl. Electron.*, vol. 4, no. 3, pp. 5–9, Jan. 2016, doi: 10.5120 / cae2016652039. CAE Access

[2] A. L. Renke and M. S. Chavan, "Electromagnetic field exposure on different floors of buildings from mobile base station antennas in Kolhapur city," in *Radio Frequency Electromagnetic Field Exposure Assessment in Urban and Rural Areas*, River Publishers, 2016, pp. 129–146. [Online].

[3] A. B. Renke and M. S. Chavan, "Comparative study of RF electromagnetic field exposure standards," *Int. J. Sci. Res. Eng. Manage.*, vol. 8, no. 2, pp. 1–9, Jun. 2024. [Online]. IJSREM

[4] International Commission on Non-Ionizing Radiation Protection (ICNIRP), "Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz)," *Health Phys.*, vol. 118, no. 5, pp. 483–524, 2020, doi: 10.1097/HP.0000000000001210.

[5] Telecom Engineering Centre (TEC), Department of Telecommunications, Government of India, *White Paper on Human Exposure Requirement for EMF Exposure in view of ICNIRP 2020 Regulation*. New Delhi, India: TEC, 2022. [Online].

[6] Press Information Bureau (PIB), Government of India, "EMF radiation norms and compliance of telecom towers," Aug. 10, 2022. [Online].

[7] International Commission on Non-Ionizing Radiation Protection (ICNIRP), *Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz)*. ICNIRP, 2020. [Online].

[8] World Health Organization (WHO), *Electromagnetic fields (EMF) — background & resources*. WHO. [Online].

[9] International Agency for Research on Cancer (IARC), *Non-ionizing radiation, Part 2: Radiofrequency electromagnetic fields (IARC Monographs Volume 102)*. Lyon, France: IARC, 2013. [Online]. Available: https://publications.iarc.fr

[10] European Commission, SCENIHR, *Potential health effects of exposure to electromagnetic fields (EMF) — Final opinion*. Brussels, Belgium: European Commission, 2015. [Online].

[11] IEC/IEEE, Basic standard for in-situ measurement of electromagnetic field strength related to human exposure in the vicinity of base stations (see also EN 62232 developments). iTeh Standards. [Online].

[12] P. Frei, A. H. Poulsen, C. Johansen, et al., "Comparative international analysis of radiofrequency exposure from mobile base stations: multi-country surveys," *J. Expo. Sci. Environ. Epidemiol.*, 2012. [Online].

[13] W. Joseph, L. Verloock, L. Martens, et al., "Radiofrequency exposure levels from mobile phone base stations: large-scale measurements and trends," *J. Expo. Sci. Environ. Epidemiol.*, 2021. [Online].

[14] J. F. B. Bolte, M. Eeftens, J. F. Brosschot, et al., "Personal RF-EMF exposure measurement studies: protocols and findings," *Environ. Int.*, 2019. [Online].

[15] S. Aerts, W. Joseph, L. Verloock, and L. Martens, "Residential exposure to RF-EMF from mobile phone base stations: measurements vs. model predictions," *Sci. Total Environ.*, 2019. [Online].

[16] A. Bollmann, J. Bolte, W. Joseph, et al., "Public exposure to radiofrequency electromagnetic fields in Europe: systematic review and update," *Environ. Res.*, 2020. [Online].

[17] K. R. Foster and M. H. Repacholi, "Biological effects of RF fields: standards, guidelines and research needs," *Health Phys.*, 2004. [Online].

[18] Public Health Ontario, *Health effects of radiofrequency electromagnetic fields, including 5G — Technical Report*. Toronto, ON: Public Health Ontario, 2022. [Online].

[19] MDPI, "Systematic review of exposure studies to radiofrequency electromagnetic fields: methods and quality assessment," *Appl. Sci.*, 2022. [Online].

[20] Spandidos Publications, "Measurements of RF radiation in apartments near base station rooftops — time-series study," 2018. [Online].

[21] ResearchGate, "Measurement of EMF exposure around small cell and 5G base station sites," 2019–2022. [Online].

[22] W. Huang, Y. Hu, J. Zhu, Z. Cen, and J. Bao, "Measurement and evaluation of the electromagnetic environment from 5G base stations," *Detection*, 2022. [Online].

[23] E. Larchêveque, C. Dale, M. Wong, and J. Wiart, "Analysis of electric-field averaging for in-situ RF exposure assessment: implications for measurement protocols," *Int. J. Comput. Appl. Res.*, 2008. [Online]. ijcaonline.org

[24] ARPANSA (Australian Radiation Protection and Nuclear Safety Agency), *Radiofrequency radiation — public information on measurement & exposure*. ARPANSA. [Online].

[25] Local studies: "Measurements of electromagnetic radiation from mobile phone base stations in Tripoli; Columbia, SC downtown 5G/4G route surveys; Turkey/Cyprus longitudinal base-station exposure studies," *ResearchGate/Spandidos/DergiPark*, 2019–2022. [Online].

[26] ITU/IEC, *Workshop & standards materials on human exposure assessment, EN 50383/EN 50385 and evolution to EN 62232 for base-station assessment*. ITU, 2006–2017. [Online].

[27] International Commission on Non-Ionizing Radiation Protection (ICNIRP), "Statement on research gaps relevant to RF exposure," ICNIRP, 2025. [Online].

[28] "RF-EMF exposure assessment with add-on uplink — comparative international analysis," *Environ. Res.* (Elsevier), 2025. [Online].

[29] "In-situ measurements of radiofrequency electromagnetic fields at active 5G macro base stations," *PMC Open Access*, 2025. [Online].

[30] "Assessing radiofrequency electromagnetic field exposure in multiple scenarios," *Sci. Total Environ.* (Elsevier), 2025. [Online].

[31] WHO-funded review, "Systematic review on RF radiation and cancer in animals," *Environ. Int.*, Apr. 2025. [Online].