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Assessment of the electromagnetic field exposure due to wireless communication technologies in two university campuses of medellin, Colombia

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ABSTRACT

Exposure to radiofrequency electromagnetic fields (RF-EMFs) is considered an area of significant importance in the medical and scientific community. However, the availability of exposure data for indoor and outdoor locations in universities is limited and currently inconsiderate in Latin America. The aim of this work was to evaluate the electric field levels due to mobile telecommunication technologies and Wi-Fi to which students and faculty staff from two campuses of a higher education institution are exposed. Using a portable spectrum analyzer, we carried out 516 short-term measurements in the 800–3000 MHz frequency range at both indoor and outdoor locations. These locations were chosen to cover all areas of the assessed buildings. The electric field differences between floors and buildings are discussed. Finally, we compared the electric field levels with exposure limits. The highest electric field level measured was 13.97 V/m at the 850 MHz band. However, the average electric field values were below 2 V/m. The greatest contribution to the total electric field was due to sources using the 850 MHz and 1900 MHz bands (98%), while the contribution of the Wi-Fi network was low (1.0%). The results show that all the electric field levels measured were lower than the ICNIRP reference levels for radio-frequency exposure.

1. Introduction

In recent decades, there has been concern about the operation of radiofrequency (RF) electromagnetic field sources, particularly in sensitive areas [1]. Recently, there has been an increase in the demand for wireless communications and the installation of an ever-growing number of RF sources. As a result, there is a determined interest in evaluating the possible health risks related to RF sources, particularly in environments such as hospitals, schools, or facilities where sensitive population groups are present [2–6]. Most of the studies conducted on RF-EMF are included in systematic reviews [7–10].

Although there are no scientific studies that allow to establish with total certainty if electromagnetic fields (EMFs) have adverse effects on human health, there are international recommendations on exposure limits for people to these fields [11]. Limit values are determined based on distinguishable short-term effects, such as induced currents, increased temperature, and biological effects whose nature is known [12]. The recommended limits for EMF exposure in many countries, as with Colombia, are adopted from those

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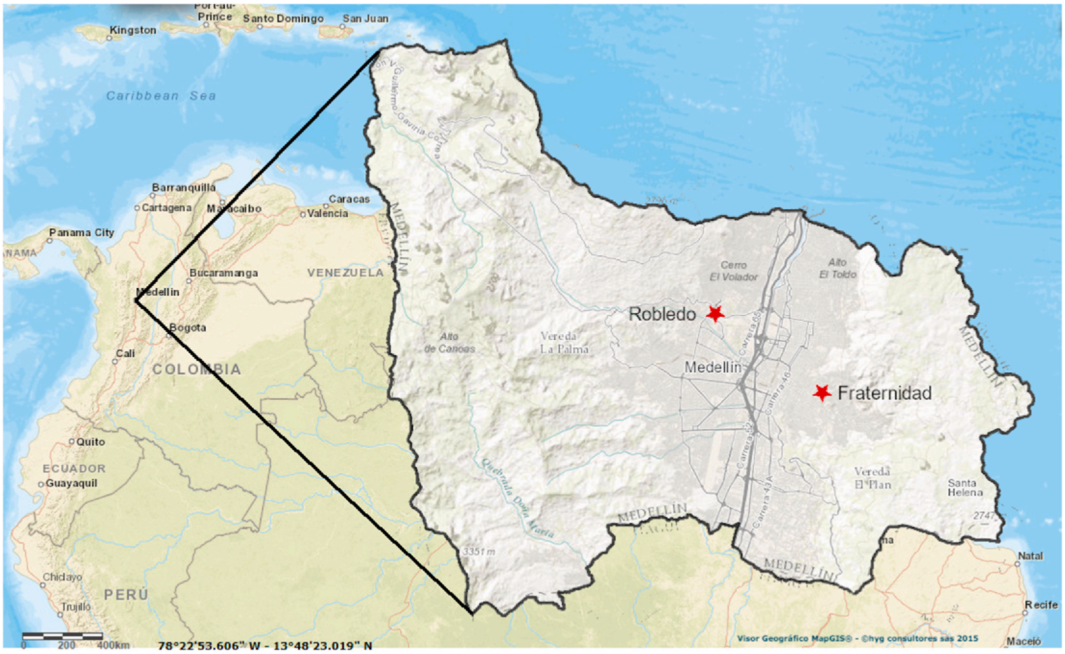

Fig. 1. Location of Robledo and Fraternidad campuses in the city of Medellin, Colombia.

established by International Commission on Non-Ionizing Radiation Protection (ICNIRP) [13]. Compliance with exposure limits helps to control risks while continuing the debate over whether exposure for long periods, at levels below exposure limits, can cause adverse health effects.

Therefore, measurements are required to evaluate the EMF in a repeatable and well-established way by international organizations. Although many EMF measurements have been made at different frequencies and in different environments to assess compliance with exposure guidelines, there are few studies done within universities. For high frequency, some studies report measurements within higher education institutions, not due to a specific investigation into this environment, but within the framework of a measurement campaign in multiple places.

Islam et al. used a portable TS-EMF system from R&S within a university campus in Malaysia to find that the EMF emitted by the Global System for Mobile Communication GSM 900 and GSM 1800 systems was 34% lower than the recommended values [14]. They also noted that the EMF transmitted by Wireless Local Area Network (WLAN) devices in the 2.4 GHz band was approximately 62% of the limit defined by the ICNIRP. They concluded that it is advisable to inspect the EMF produced by other sources before determining if a campus is safe for its population. Considering the increasing concern of the general public about the contribution of different sources of EMF around Najah University in Malaysia, Mousa studied several sources of EMF and found that the primary sources were the GSM and (Frequency Modulation) FM base stations in the frequency range from 0 to 3 GHz [15]. When comparing the values against the norm, the author found that no value exceeded the limits established by the ICNIRP.

Sorgucu and Develi measured the EMF levels of base stations at 80 different points at Erciyes University (ERU), Turkey [16]. They observed that no area in the ERU exceeded national and international limits. Another study evaluated the electromagnetic environment on the Recep Tayyip Erdoğan (RTE) university campus in Turkey in the frequency range from 400 MHz to 6 GHz using a Narda SRM 3006 spectrum analyzer. It was found that all electromagnetic field measurements were below the limits established by ICNIRP [17].

Gil and Fernandez-Garcia studied the level of exposure to time-varying electric fields up to 18 GHz in the main building of the Escuela Superior de Ingeniería Industrial, Aeroespacial y Audiovisual de Terrassa (ESEIAAT) at the Universitat Politecnica de Catalunya (Barcelona, Spain) [18]. They concluded that the level of electromagnetic pollution was low regarding the reference levels for exposure according to ICNIRP. The maximum averaged electric field detected level did not exceed one-tenth of the limit for general public exposure. Celik et al. measured electric field values between 27 MHz–3 GHz frequency band (GSM, Universal Mobile Telecommunications System - UMTS, Wi-Fi, TV, and Radio frequencies) on the Uludag University Görükle Campus (Bursa, Turkey) [19]. The measurement results were evaluated within the defined limits by the national (Information and Communication Technologies Authority-BTK) and international (ICNIRP) standards.

However, the above studies were mainly dedicated to identifying specific EMF sources or making measurements at a few points on campus. In recent years, some studies have been carried out on electromagnetic field exposure within universities. Boz and Denli measured the electromagnetic field intensities at 900 and 1800 MHz in 29 spots at Istanbul Technical University, Turkey [20]. Keskinkilinc et al. performed instant measurements of the electric field in the frequency range of 100 kHz to 8 GHz on all floors of the central campus of İnönü University (Malatya, Turkey) [21]. Zhao et al. measured and analyzed the electromagnetic environment

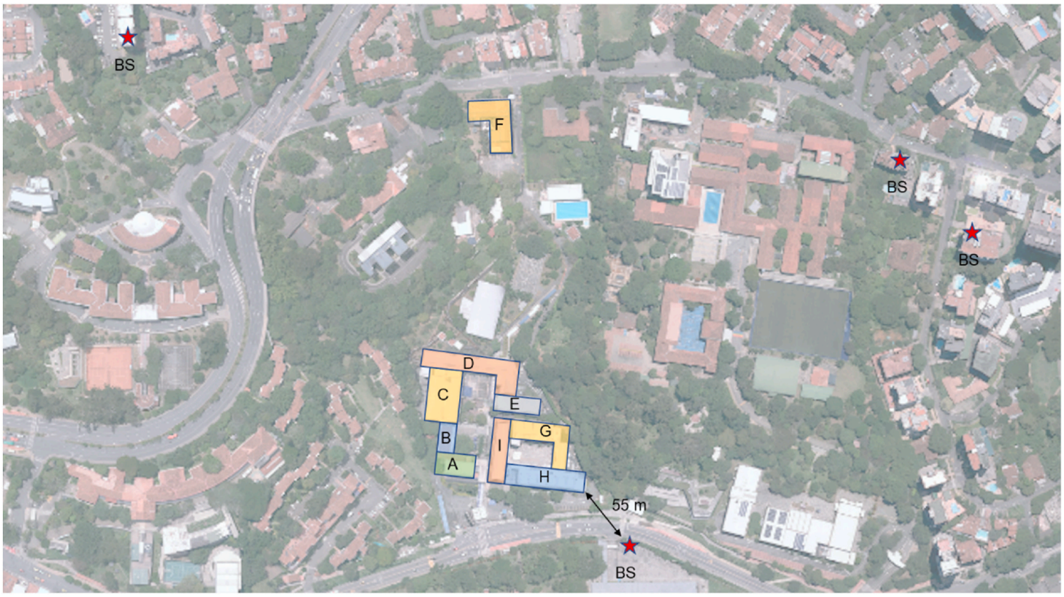

Fig. 2. Location of the Robledo campus buildings and nearby base stations.

characteristics (100 kHz–9.25 GHz) on the Wangjiang campus of Sichuan University in China [22]. Keshmiri et al. assessed compliance with international guidelines of EMF levels at 900 MHz and 2.4 GHz measured at Ferdowsi University of Mashhad (Iran) [23]. Kljajic and Djuric compared the results of two EMF monitoring campaigns (100 kHz–6 GHz) over the University of Novi Sad (Serbia) [24]. Ramirez-Vazquez et al. measured the exposure to RF electromagnetic fields due to Wi-Fi (2400–2500 MHz and 5150–5850 MHz) at the German Jordanian University [25]. Karpat and Bakcan measured electric field values in the frequency range of 27 MHz to 3 GHz on the central campus of the Bursa Uludag University (Turkey) [26]. Ramirez-Vazquez et al. measured the personal exposure levels to RF-EMF from Wi-Fi 2.4 GHz and 5.85 GHz bands at the Faculty of Computer Science Engineering at the University of Castilla-La Mancha (Albacete, Spain) [27].

As can be seen, most of the studies on exposure to RF-EMF within universities have been developed in European or Asian countries. Some studies have been conducted in Latin American countries measuring RF electromagnetic fields [28–30]. However, no studies have been carried out within universities. To the best of our knowledge, this is the first study carried out in Latin America, particularly in Colombia. In this study, we present the results of stationary short-term band-selective measurements in the frequency range from 800 MHz to 3 GHz conducted on two campuses of a higher education institution in Medellin, Colombia. Electric field levels due to mobile telecommunication technologies and Wi-Fi were registered in 516 locations in 10 buildings and analyzed in four bands: 850 MHz, 1900 MHz, 2400 MHz, and 2600 MHz. The results were evaluated and compared with the exposure reference levels established by ICNIRP.

2. Materials and methods

We evaluated the electric field levels to which students and faculty staff are exposed at two campuses of the Instituto Tecnologico Metropolitano (ITM) in the Colombian city of Medellin. The results were compared to the limit values established by the ICNIRP to determine whether these levels pose any risk to students or faculty staff. The ITM is the second largest higher education institution in Medellin, Colombia, with about 25000 students and academic staff. The institution has six campuses throughout the city (Robledo, Fraternidad, La Floresta, Prado, Castilla, and El Poblado). However, we carried out the measurements at the two main campuses: Robledo and Fraternidad. Fig. 1 shows the location of these two campuses in the city of Medellin, Colombia.

The Robledo campus is located in the northwestern part of Medellin. It is the campus where administrative activities are concentrated. The Robledo campus has nine buildings (Buildings A to I) and occupies an area of 42632 m^2. The buildings are distributed as follows: Buildings A and B to administrative offices; C and D to classrooms; E to faculty and welfare offices; F to the library; G and H to classrooms and laboratories; I to the auditorium and faculty offices. The number of floors in each building varies from 3 to 5. Due to the possibility of access, measurements were made in six of the nine buildings (C to H). Fig. 2 shows the location of the Robledo campus buildings and nearby base stations (red stars).

The Fraternidad campus is in the eastern part of Medellin and occupies an area of 73344 m^2. The primary facility comprises four interconnected buildings (K, L, M, and N). This facility has five floors and two basements (in Building M). Buildings K and M house laboratories and classrooms, while Buildings L and N house classrooms, faculty offices, and administrative offices. Measurements were made in the four buildings of the primary facility. Fig. 3 shows the location of the Fraternidad campus buildings and a nearby base station (red star).

Fig. 3. Location of the Fraternidad campus buildings and nearby base station.

Table 1
Number of measurement locations per floor and building.

Robledo campus							
Building	Floor						Total
	B	1st	2nd	3rd	4th	5th	
C	–	–	10	11	11	11	43
D	–	–	16	17	17	17	67
E	–	–	11	11	–	–	22
F	–	–	8	9	8	4	29
G	–	9	11	11	11	–	42
H	–	9	9	10	10	–	38
Total	–	18	65	69	57	32	**241**
Fraternidad campus							
K	–	10	7	7	7	11	42
L	–	27	12	8	12	8	67
M	17	23	16	13	1	–	70
N	–	23	26	24	11	12	96
Total	17	83	61	52	31	31	**275**

B = Basement.

Stationary short-term band-selective measurements were performed using the R&S FSH8 handheld broadband field meter [31] connected to the R&S TSEMF-B1 electric field probe by RF 2.0 m long cable [32]. The FSH8 is suitable for time averaging and establishing the maximum level during the monitored period. The TSEMF-B1 is an isotropic probe with a wide frequency range of 30 MHz to 3 GHz, isotropy $\leq \pm 2.1$ dB, measurement uncertainty $\leq \pm 3.3$ dB, and measurement range of 1 mV/m to 450 V/m. This isotropic probe detects fields independent of direction and polarization due to three orthogonally arranged antenna elements that are electronically switched. The probe was supported on a nonmetallic tripod. The TSEMF-B1 covers most of the frequencies of almost all known sources of the high-frequency electric field. However, we only analyzed the frequency range from 800 MHz to 3 GHz. This frequency range was divided into four bands for analysis: 850 MHz, 1900 MHz, 2400 MHz, and 2600 MHz.

Measurements were made at different locations on each floor to provide results that describe the electric field characteristics of each building and campus. These locations were chosen to evaluate all indoor (classrooms, laboratories, offices, etc.) and outdoor (corridors, rooftops, courtyards, etc.) spaces. The number of measurement locations per floor and building is shown in Table 1. Measurements were made at 516 locations. All electric field measurements were performed at 1.5 m above floor level. Measurements were performed in the daytime (8:00 a.m. to 4:00 p.m.) on weekdays. During measurements in indoor spaces, we placed the probe on a tripod in the center of the space. In outdoor spaces, measurements were made at least 1 m away from building structures.

The measurements were recorded in Average mode for 6 min in the 800 MHz to 3 GHz frequency range. The E_{avg} value was registered according to Eq. (1).

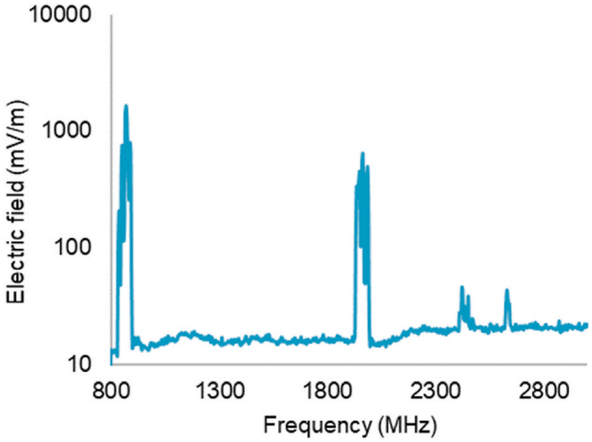

Fig. 4. Example of band-selective measurement.

$$E_{avg}=\frac{1}{N}\sum_{i=1}^{N}E_T \tag{1}$$

where E_T is the root mean square (RMS) electric field value for the ith time, and the interval between two measured values was 500 ms. The probe measures the electric field in three directions (x, y, and z), and the meter calculates the total electric field E_T using Eq. (2).

$$E_T=\sqrt{|E_x|^2+|E_y|^2+|E_z|^2} \tag{2}$$

where E_T is the total electric field and E_x, E_y, and E_z are the electric fields measured in the directions x, y, and z, respectively. For each measurement location and frequency band analyzed, the maximum electric field value were compared with the exposure reference levels recommended by ICNIRP, as in Eq. (3) [11].

$$P_{ICNIRP}\ [\%]=\frac{E_T}{RL_{ICNIRP}}\times 100 \tag{3}$$

where P_{ICNIRP} is the percentage of the electric field value relative to the ICNIRP reference level RL_{ICNIRP}, and E_T is the electric field measured. The reference levels vary in frequency [11]. Related to electric field (V/m), the general public reference level for local exposure and averaged over 6 min in the frequency range 400–2000 MHz is $4.72f_M^{0.43}$ (f_M is the frequency in MHz). The power density general public reference level for frequencies greater than 2000 MHz is 40 W/m^2. Any P_{ICNIRP} value below 100% means that the ICNIRP recommendation is met. Finally, we calculated the contribution of each mobile communication service (band) analyzed in this study to the total electric field measured in each building using Eq. (4).

$$P_{Band}\ [\%]=\frac{{E_{Band,i}}^2}{{E_{Band,T}}^2}\times 100 \tag{4}$$

where P_{Band} is the percentage of the electric field level for *ith* band ($E_{Band,\ i}$) relative to the total electric field measured $E_{Band,\ T}$. The total electric field in each band was calculated as in Eq. (5), where j is the total number of bands analyzed (four).

$$E_{Band,T}\ [V/m]=\sqrt{\sum_{i=1}^{j}{E_{Band,i}}^2} \tag{5}$$

The statistical data analysis was carried out using the meter software R&S®FSH8 View version V2.71 from Rohde & Schwarz and Statgraphics Centurion XVI software (Statgraphics Technologies, Inc., The Plains, Virginia, USA). The analysis was made with the electric field intensity values expressed in V/m. Cumulative Distribution Function (CDF) plots and box plots were used to present the results. The CDF plots show the proportion of data less than or equal to an electric field value. CDF plots are useful for comparing the distribution of different sets of data. In addition, boxplots show the distribution of electric field values: including the minimum value (excluding outliers), first (lower) quartile, median, third (upper) quartile, and maximum value (excluding outliers). The minimum detectable field strength of the R&S TSEMF-B1 electric field probe is approximately 0.001 V/m, and the nondetect data percentage ranged was below 1% in the four bands analyzed. Therefore, the nondetect data was neglected to provide a more realistic physical situation of the exposure values [33].

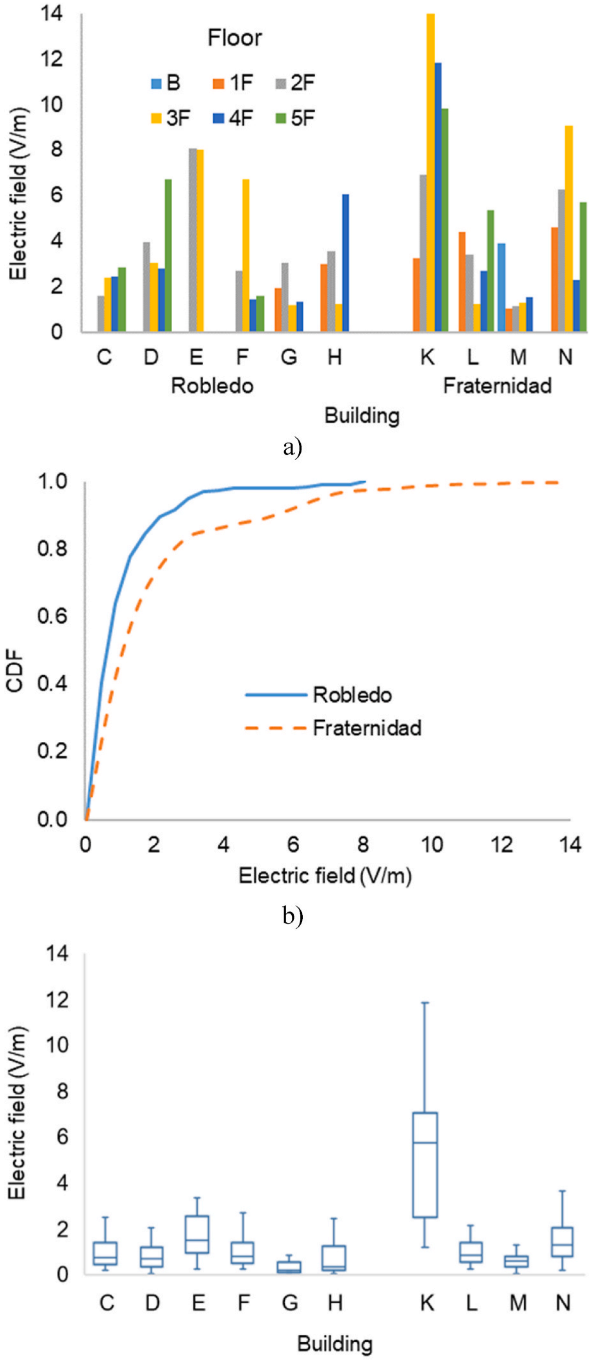

Fig. 5. Electric field measured for the 850 MHz band, a) highest values per building and floor, b) CDF plot for all measurements per campus, and c) boxplot per building and for all measurement points.

3. Results

This section presents the analysis of the electric field measured for each band on both campuses. Based on the results and depending on the services evaluated, the electric field differences between floors and buildings are discussed. Finally, we compare the electric field levels with the exposure limits. The results show that the levels of the electric field on campuses vary considerably by location. There are many reasons for electric field levels to change: the distance from telecommunication systems (e.g., base stations, Wi-Fi

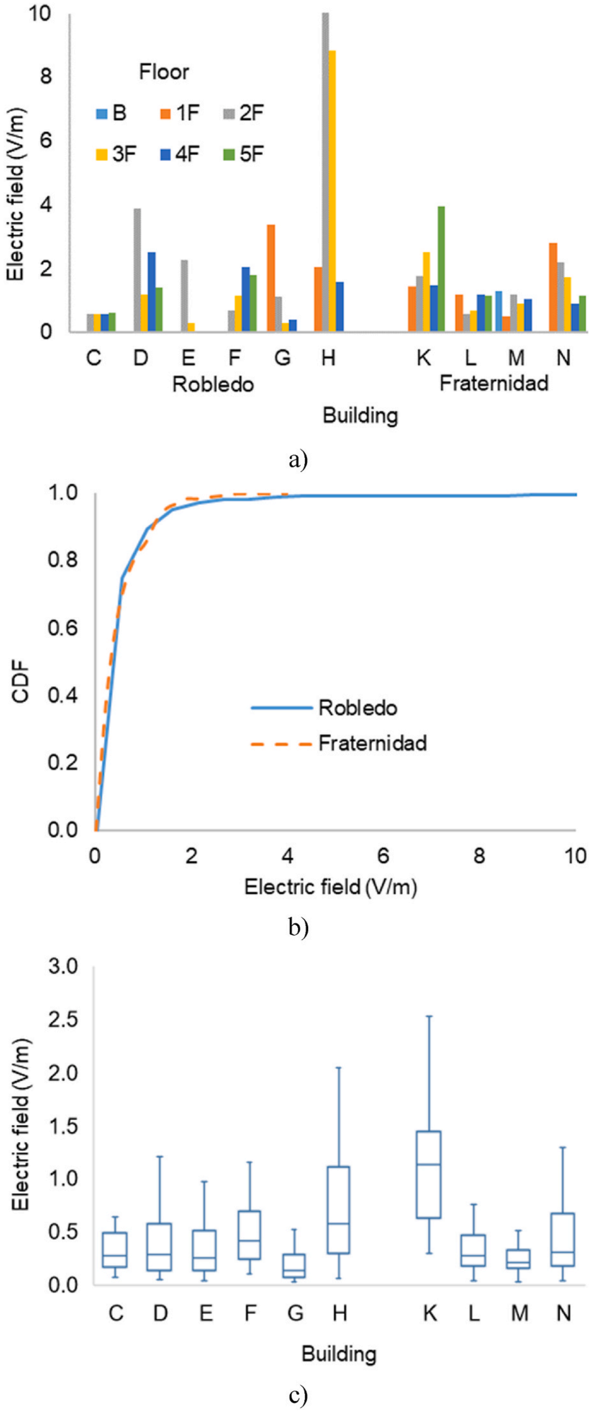

Fig. 6. Electric field measured for the 1900 MHz band, a) highest values per building and floor, b) CDF plot for all measurements per campus, and c) boxplot per building and for all measurement points.

access points), the geographical location in which the base stations are placed, the range of users, and construction features. Fig. 4 shows an example of spectrum measurement from 800 MHz to 3 GHz. The peaks in Fig. 4 represent the electric field values measured in the four frequency ranges analyzed.

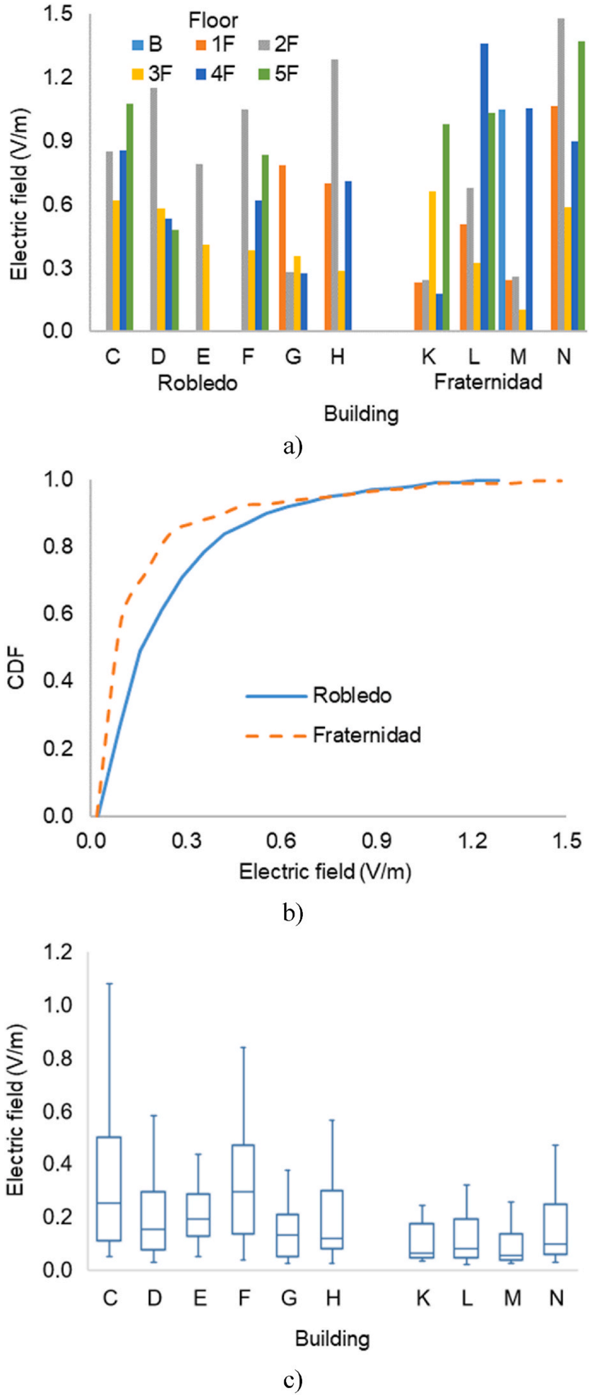

Fig. 7. Electric field measured for the 2400 MHz band, a) highest values per building and floor, b) CDF plot for all measurements per campus, and c) boxplot per building and for all measurement points.

3.1. 850 MHz band

The 850 MHz band is used in most South American countries. This band 850 uses the 824–849 MHz frequency range to send information from the mobile to the base station (uplink) and the 869–894 MHz frequency range for the other direction (downlink). Fig. 5a) shows the electric field levels measured on all buildings and floors for the 850 MHz band. The highest electric field levels occurred on the Fraternidad campus because of the nearby base station (Fig. 3). Precisely, these levels were found on the highest floors (13.97 V/m, 11.82 V/m, and 9.82 V/m on floors 3, 4, and 5, respectively) of the building closest to the base station (K). Building K is

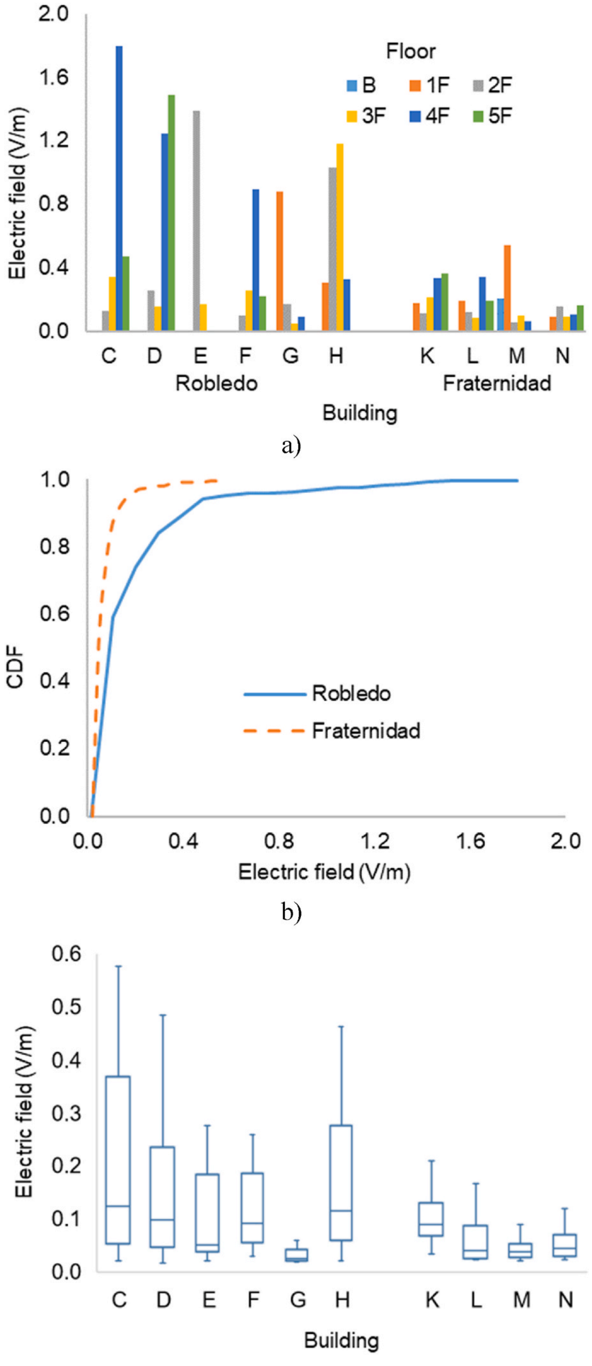

Fig. 8. Electric field measured for the 2600 MHz band, a) highest values per building and floor, b) cumulative distribution function for all measurements per campus, and c) boxplot per building and for all measurement points.

less than 100 m from the base station. In addition, due to the slope of the terrain, floor 3 is at the same height as the antennas. The highest levels of electric field were found close to the windows on these floors. On the other hand, the lowest electric field measured (1.05 V/m) was in building M, the building farthest from the base station. The average of all measurements on the Fraternidad campus (1.89 V/m) was approximately 93.0% higher than the average measured on the Robledo campus (0.98 V/m).

The cumulative distribution function (CDF) values of the electric field for the 850 MHz band are given in Fig. 5b). On the Fraternidad campus, 90% of the electric field levels were less than 5.37 V/m. Meanwhile, on the Robledo campus, only 10% of the measurement data was more than 2.40 V/m. Boxplot, per building, for the electric field level for the 850 MHz band is depicted in

Table 2
Analysis of the electric field measurements [in V/m].

Band	Min	P5	P25	Median	Avg.	P75	P95	Max	Std. Dev.
	Robledo campus								
850 MHz	0.05	0.08	0.27	0.55	0.98	1.21	3.02	8.07	1.20
1900 MHz	0.03	0.06	0.14	0.28	0.54	0.57	1.80	10.09	0.98
2400 MHz	0.02	0.04	0.08	0.16	0.25	0.31	0.79	1.28	0.23
2600 MHz	0.02	0.02	0.04	0.08	0.18	0.21	0.58	1.80	0.26
	Fraternidad campus								
850 MHz	0.04	0.22	0.58	1.02	1.89	2.14	6.94	13.97	2.22
1900 MHz	0.02	0.07	0.18	0.31	0.51	0.67	1.48	3.98	0.52
2400 MHz	0.02	0.03	0.05	0.08	0.17	0.19	0.77	1.48	0.24
2600 MHz	0.02	0.02	0.03	0.05	0.07	0.08	0.17	0.54	0.06

Fig. 5c). As seen from the figure, the highest average electric field level in the measurements was 5.37 V/m in building K. In the other buildings, the average electric field did not exceed 2.10 V/m.

3.1.1. 1900 MHz band

The 1900 MHz band is also used in most South American countries. This band uses the 1850–1910 MHz frequency range for uplink and the 1930–1990 MHz frequency range for downlink. Fig. 6a) shows the electric field levels measured on all buildings and floors for the 1900 MHz band. The highest electric field levels occurred on the Robledo campus because of the nearby base station (Fig. 2). These levels were found on the second (10.09 V/m) and third floor (8.85 V/m) of the building H, the building located less than 60 m from the base station. The highest electric field levels were found in the corridors of these floors. However, the average of all measurements on the Robledo campus (0.54 V/m) was only 5.9% higher than the average measured on the Fraternidad campus (0.51 V/m).

Fig. 6b) presents the cumulative distribution function (CDF) values for the electric field in the 1900 MHz band. The distribution is similar for the two campuses. On the Fraternidad and Robledo campuses, 90% of the electric field levels were less than 1.21 V/m and 1.14 V/m, respectively. Boxplot, per building, for the electric field level for the 1900 MHz band is depicted in Fig. 6c). As seen from the figure, the highest average electric field levels in the measurements were 1.16 V/m and 1.15 V/m in building K and H, respectively. The average electric field did not exceed 0.55 V/m in the other buildings.

3.1.2. 2400 MHz band

Data communication systems operating in the 2400 MHz band (2400–2483 MHz) provide flexibility and accessibility for wireless networks. WLANs are communication systems for transmitting and receiving data. One of the best-known WLAN technologies is Wi-Fi. Approximately 100 Wi-Fi access points operate inside the buildings of the two campuses. Fig. 7a) shows the electric field levels measured on each building and floor for the 2400 MHz band. The highest electric field levels were found on the second (1.48 V/m) and the fifth (1.37 V/m) floors of building N because of Wi-Fi access points along the corridors. The lowest electric field measured (0.11 V/m) was on the third floor of building M. The average of all measurements on the Robledo campus (0.25 V/m) was about 47.1% higher than the average measured on the Fraternidad campus (0.17 V/m).

The cumulative distribution function (CDF) values of the electric field for the 2400 MHz band are given in Fig. 7b). On the Robledo campus, 90% of the electric field levels were less than 0.57 V/m, while on the Fraternidad campus, only 10% of the measurement data was greater than 0.43 V/m. Boxplot, per building, for the electric field level for the 2400 MHz band is depicted in Fig. 7c). As seen from the figure, the highest average electric field levels in the measurements were 0.35 V/m and 0.33 V/m in buildings F and C, respectively. On the Fraternidad campus, the average electric field did not exceed 0.21 V/m.

3.1.3. 2600 MHz band

This service uses the 2500–2570 MHz frequency range for uplink and the 2620–2690 MHz frequency range for downlink. Fig. 8a) shows the electric field levels measured on all buildings and floors for the 2600 MHz band. The highest electric field levels occurred on the Robledo campus. These levels were found on the fourth (1.80 V/m) and fifth floor (1.49 V/m) of buildings C and D, respectively. The lowest electric field measured (0.05 V/m) was on the third floor of building G. The average of all measurements on the Robledo campus (0.18 V/m) was about 157% higher than the average measured on the Fraternidad campus (0.07 V/m).

The cumulative distribution function (CDF) values of the electric field for the 2600 MHz band are presented in Fig. 8b). On the Fraternidad and Robledo campuses, 90% of the electric field levels were less than 0.12 V/m and 0.42 V/m, respectively. Boxplot, per building, for the electric field level for the 2600 MHz band is depicted in Fig. 8c). As seen from the figure, the highest average electric field level was 0.23 V/m in building C on the Robledo campus. In all the buildings on the Fraternidad campus, the average electric field did not exceed 0.11 V/m.

4. Discussion

We found high electric field levels near base stations. The highest level was found in the 850 MHz band (13.97 V/m at 871.6 MHz) and was measured inside a classroom on the third floor of building K on the Fraternidad campus. The third floor is at the same level that base station antennas placed less than 100 m from that building. High levels were also found in rooms next to the one described above

Table 3
Results of some studies that involved measuring the electric field on university campuses.

Ref.	Location	Country	Type of measurements	Frequency range	Highest value (V/m)	ICNIRP compliance
Djuric et al. [36]	University of Novi Sad	Serbia	Stationary long-term broadband	100 kHz - 6 GHz	2.83	Yes
Boz and Denli [20]	Istanbul Technical University	Turkey	Stationary short-term band-selective	900 MHz 1800 MHz	2.72 (900 MHz) 5.50 (1800 MHz)	Yes
Keskinkilinc et al. [21]	İnönü Üniversitesi	Turkey	Stationary short-term broadband	100 kHz - 8 GHz.	2.73	Yes
Zhao et al. [22]	Wangjiang Campus, Sichuan University	China	Stationary and mobile long-term broadband	100 kHz - 9.25 GHz	3.64	Yes
Ramirez-Vazquez et al. [25]	German Jordanian University	Jordan	Stationary and mobile short-term band-selective	2.4–2.5 GHz 5.15–5.85 GHz	0.38[a]	Yes
Kljajic and Djuric [24]	University of Novi Sad	Serbia	Stationary short and long-term broadband	100 kHz - 6 GHz	2.39	Yes
Keshmiri et al. [23]	Ferdowsi University of Mashhad	Iran	Stationary short and long-term broadband	1 MHz–18 GHz	16.0	Yes
Karpat and Bakcan [26]	Bursa Uludag University	Turkey	Stationary short-term broadband	27 MHz - 3 GHz	4.31	Yes
Ramirez-Vazquez et al. [27]	University of Castilla-La Mancha	Spain	Stationary short-term band-selective	2.4 GHz 5.85 GHz	0.187 (2.4 GHz) 0.278 (5.85 GHz)	Yes
Current study	Instituto Tecnológico Metropolitano	Colombia	Stationary short-term band-selective	800 MHz - 3 GHz	13.97 (850 MHz) 10.09 (1900 MHz) 1.48 (2400 MHz) 1.80 (2600 MHz)	Yes

[a] Authors reported power density values that have been converted to electric field values for comparison.

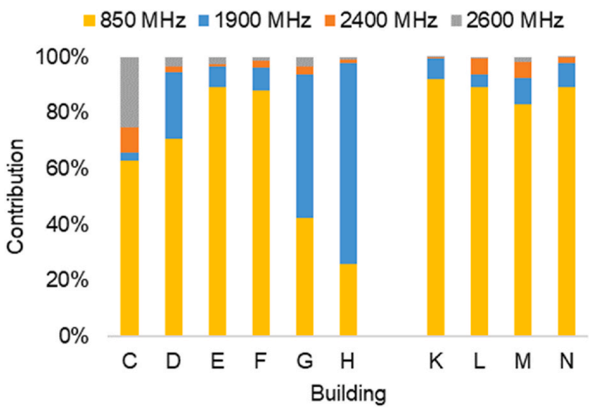

Fig. 9. Contribution of each mobile communication service analyzed in this study to the total electric field measured in each building.

and on the upper floors of the same building. The above shows the influence of the base station near the Fraternidad campus on the electric field levels found. Similar behavior was observed on the Robledo campus, but with a base station transmitting in the 1900 MHz band. The highest electric field was found in this band (10.09 V/m at 1987.6 MHz) and was measured in the corridors of the building located less than 60 m from this base station. However, the median of electric field levels was below 1.02 V/m, and 95% of the electric field levels did not exceed 7 V/m (Table 2).

The highest electric field levels found in the four bands represented 16.11%, 8.16%, 0.0146%, and 0.0215% of the ICNIRP reference levels for 871.6 MHz, 1987.6 MHz, 2400 MHz, and 2600 MHz, respectively, which are low fractions. Therefore, all measured values were below the reference limits established by ICNIRP.

On the other hand, the values presented in Table 2 are consistent with other studies that have established that the electric field due to base stations is predominant in personal exposure, while exposure to Wi-Fi networks is usually low [37,38]. Table 3 presents some aspects and results of the work described here and recent studies. Only a few studies are included in Table 3, as a complete analysis of

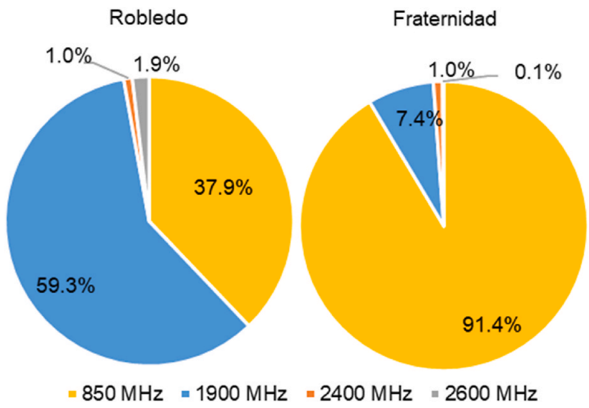

Fig. 10. Contribution of each mobile communication service analyzed in this study to the total electric field measured in each campus.

electric field measurements and exposure is outside the scope of this research. Table 3 shows that the highest electric field values ranged from 0.19 V/m to 16.0 V/m, and were always below the ICNIRP reference limits, regardless of the type of measurement.

Finally, the contribution of each band to the electric field measured for all buildings is presented in Fig. 9. As seen, in all buildings on the Fraternidad campus, the primary contribution was due to one base station using the 850 MHz band (88.3% average). However, on the Robledo campus, the contribution varied depending on the building. In buildings G and H, the largest contribution was due to the base station using the 1900 MHz band (61.5% average). Meanwhile, in the other buildings, it was due to sources using the 850 MHz band (77.7% average). The contribution of base stations (850 MHz, 1900 MHz, and 2600 MHz) was greater than 91% in all buildings (Fig. 10). These results agreed with other studies involving measurements in sensitive environments that concluded mobile communication services contributed most to electric field exposure [34,35].

5. Conclusions

In this study, short-term stationary electric field band-selective measurements were carried out at 516 locations on two campuses of a higher education institution in the city of Medellin, Colombia. We analyzed the primary telecommunications services in the 800 MHz to 3 GHz frequency range. This frequency range was divided into four bands: 850 MHz, 1900 MHz, 2400 MHz, and 2600 MHz. The results indicate that the highest electric field levels were lower than the recommended exposure limits. Therefore, the values comply with Colombian regulations and ICNIRP reference levels for radio-frequency exposure.

The highest electric field levels were 13.97 V/m in the 850 MHz band, 10.09 V/m in the 1900 MHz band, 1.48 V/m in the 2400 MHz band, and 1.80 V/m in the 2600 MHz band. These levels represented 16.11%, 8.16%, 0.0146%, and 0.0215% of the ICNIRP reference levels for 871.6 MHz, 1987.6 MHz, 2400 MHz, and 2600 MHz, respectively. However, most electric field levels (90%) were found to be lower than 6 V/m, while the average values were below 2 V/m.

The highest electric field levels were found in spaces facing the antennas of the mobile phone base station antennas installed on top of the poles. On both campuses, the greatest contribution was due to sources using the 850 MHz and 1900 MHz bands (97.2% in Robledo and 98.8% on Fraternidad). On the other hand, although the entire campus is covered by a Wi-Fi network, we found that the contribution of this service to the total electric field is low (1.0% on both campuses).

Although the electric fields measured are within the reference levels, it is recommended that the electric field levels be measured and checked at regular intervals to evaluate the exposure of students, faculty staff, and administrative staff. The analysis can be extended to include other campuses or higher education institutions in the city, especially those that are close to base stations. Our future work includes measurements in a higher frequency range (30 MHz–3 GHz), outdoor measurements, and long-term measurements. Likewise, we want to repeat the measurements when the 5G network is implemented in Colombia to make a comparative analysis between the two time periods.

Author contribution statement

Fabio L. Suarez: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data.

Sara M. Yepes: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis

tools or data.

Adolfo Escobar: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Data availability statement

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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