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Frequency-Selective and Broadband Measurements of Radio Frequency Electromagnetic Field Levels in the University Campus

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ABSTRACT: Characterization of radio frequency electromagnetic field exposure levels is considered crucial for green and sustainable wireless-empowered campuses. To investigate the university campus electromagnetic characteristics, we conducted concurrent environment-oriented and human-centric measurement campaigns with broadband and frequency selective methodologies, respectively. The broadband results are derived after processing samples of 6-minute averages of measured electric and magnetic field values, taken at various university indoor and outdoor spots using broadband survey meter. Comparative analysis of broadband measurements shows that campus outdoor electric field levels in the sub 3 GHz band average around 1.67 V/m are at least twice higher than the ones recorded in indoor environments such as dormitories, labs, and classrooms. Students' exposure pattern in the 88 MHz–6 GHz range is derived after post-processing of more than 340 thousand electric field samples which were taken every 5 seconds at various campus environments using narrowband frequency selective measurement equipment. The comparison of cumulative distribution functions per wireless technology and environment shows that Wi-Fi is the main contributor to students' personal exposure levels in indoor environments and exceeds the 2G–5G mobile communication emitted electric fields in campus outdoor environments. The presented results can be used for exposure-aware heterogeneous network planning and optimization in university campuses or comparable environments.

1. INTRODUCTION

Digital and green transformation is supported by the rapid development and adoption of ubiquitous smart wireless communication technologies that are embedded in everyday environments and activities, especially embraced by younger generations. Wireless technologies operate in the radio frequency (RF) spectrum and emit electromagnetic fields (EMFs); therefore, the assessment of human exposure to RF-EMF is considered a pertinent research issue and is increasingly being considered as one of the main trade-off factors in multi-parametric network planning and optimization [1, 2], contributing towards safe communication eco-systems and environments.

The research on identifying RF-EMF exposure-sensitive areas is directed toward high-density population microenvironments with multiple and diverse emitting sources, such as schools, hospitals, and shopping malls. The results of potential worst-case scenario of personal exposure to RF-EMF for specific wireless-enabled workplaces and environments are presented in [3] whereas results of indoor and outdoor measurements and RF-EMF personal exposure for pre-university education institutions environments are presented in [4–6].

University campuses are often multi-frequency areas with high density of users and diverse communication technologies, that are inhabited and frequented by age groups that are considered both sensitive to RF-EMF and heavy users of technology. However, to our knowledge, published research data that addresses the EMF exposure levels in different microenvironments within the campus such as dormitories (indoor and outdoor), labs and classrooms, campus restaurants/cafeterias, are very limited, and there are even fewer works that address RF-EMF exposure for students living in university campuses.

Results portraying mean RF-EMF exposure of the adult population and the results from frequency selective assessment of personal exposure to wireless communication electric fields in various environments such as public transportation, office, coffee shops, outdoor, and home environments, are presented in [7]. Therein, authors have identified mobile communications and wireless local networks (WLANs) as the main contributors to EMF levels. However, this study does not address RF-EMF personal exposure levels inside university campuses. Different studies have analyzed personal RF-EMF exposure in different everyday microenvironments, as well as measurement instrumentation specifics and limits, but they did not address methodology for deriving RF-EMF exposure levels of student population [8–13].

Comparison of personal exposure to RF-EMF only from Wi-Fi signals in an indoor faculty environment over three years has been recently published [14]. Results of pilot measurements, broadband or frequency selective, targeting university campuses, or targeting areas located near RF emitting infrastructure (mostly assessment of BTS exposure levels) that includes very few samples in university campuses, are presented in [15–20].

Unlike these works, we use both broadband and frequency-selective approaches to measure and analyze the exposure pat-

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terns inside a university campus, a micro-environment that has been, to our knowledge, scarcely investigated until now. In addition, we use our data to compare and contrast between the two widely used measurement approaches.

To summarize, the objective of our research is twofold: i) to portray RF-EMF personal exposure patterns for the student population within the campus, and ii) to concurrently record broadband electric field (E-field) and magnetic field (H-field) levels in campus environments and derive the EMF characteristics of university campuses. To achieve the first objective, we have conducted an intensive measurement campaign with Personal Exposure Meters (PEMs) in campus environments and captured $\sim$ 350000 samples of E-field in the 14 predefined bands in the frequency range 80 MHz–6 GHz. To achieve the second objective, we simultaneously conducted a broadband measurement campaign in the same measurement environments using an RF survey meter. The broadband measurements consisting of 480 samples are used to derive the mean values of EMF and the cumulative distribution function (CDF) curves. Therefore, our measurement campaign was simultaneously environment-oriented (broadband measurement in campus spots) and human-centric (assessment of students' exposure to RF-EMF).

In addition, the obtained results were used for a comparative analysis of RF-EMF measurement methodologies and instruments.

The results of this study can be used to support a broader comparative analysis of RF EMF exposure characteristics between different environments, including university campuses, kindergartens, schools, and EMF-vulnerable microenvironments like hospitals.

2. MATERIALS AND METHODS

2.1. Measurement Environments and Data Collection

The measurements were conducted inside the campus of the University of Prishtina, which is a large comprehensive university, with more than 30,000 students, 14 faculties spread across several campus buildings. Before drafting the measurement protocol, we interviewed students to identify university environments where they spend most of the time per day. As a result of these interviews, we focused our measurement campaign on university dormitories — indoors and outdoors areas; labs, classrooms, and study facilities of the Faculty of Electrical and Computer Engineering. We selected this faculty due to the higher presence of high-tech equipment and RF sources. One of the measurement locations was the university cafeteria ("mensa") where students spend at least an hour per day for food and beverage. We also included cafeterias near the university campus. Measurement environments include indoor and outdoor, Line of Sight (LOS) and Non-Line of Sight (NLOS) spots, and multi-source RF-EMF environments, while EMF samples were recorded at different times of day, weekends and working days. Some of the measurement locations are depicted in Fig. 1.

Data collection took place during a four-month period in 2023. Since the aim was to capture the RF-EMF characteristics of the student population (18–25 years) and university campuses, in real-life scenarios, participants were instructed to behave normally in terms of usage of technology and lifestyle. For each measured value, the records include: the date, time, location, and brief description of the surroundings of the measurement spot such as the near presence of a base transceiver station (BTS) or broadcast transmission towers and the number of active technology users at the time of measurements.

Using broadband measurement methodology with particular measurement probes we captured E-field and H-field samples at different spots on the university campus. Using frequency selective personal exposure instrumentation, we captured 90,720 E-field samples in campus outdoor spots, 161,280 E-field samples inside dormitories (mostly inside dormitory rooms), and 90,272 E-field samples inside faculty building facilities, such as labs, classrooms, and faculty halls. The higher number of samples collected in indoor environments is intentional since, due to our knowledge, there is very limited research data published regarding personal RF-EMF exposure inside student dormitories.

2.2. Measurement Setup and Equipment

To identify the frequency range of EMF emitting sources present in the university campus, spectrum analyzer NARDA SRM 3006 was used to scan the frequency range up to 6 GHz. For most of the spots, notable signal activity was detected in the frequency range 100 kHz–3 GHz, except for the occasional presence of Wi-Fi signal at 5 GHz in indoor environments. Currently, all broadcast and mobile communication providers operate in the sub-3 GHz range with the exception of recently launched 5G mobile testing services which operate also in 3400 MHz band.

The measurement campaign was conducted spatially and temporally, in parallel, with broadband and frequency-selective narrowband equipment, in the far-field exposure conditions for all technologies and experimental scenarios.

For broadband measurement, the samples were captured with a radiation meter NARDA EMR-300. For measuring the E-field (V/m), the E-field probe that measures in the frequency range 100 kHz–3 GHz was used. To capture H-field samples, we used another probe, which measures the level of H-field (A/m) in the frequency range 27 MHz–1 GHz. All broadband results were time-averaged for 6 minutes [21], while instrumentation during measurements was kept 1.5 m above ground level. All recorded values are within measurement instrumentation detection limits.

To capture students' exposure to RF-EMF, the Satimo EME-SPY 140 PEMs are used. This instrument measures E-field levels, with three axial probes, in 14 predefined frequency bands, in the range of 88 MHz–6 GHz and is capable of differentiating between uplink and downlink signal levels.

Its upper detection limit is 6 V/m while its lower detection limit differs from band to band, ranging from 0.005 V/m to 0.02 V/m.

The measurement of personal exposure to RF-EMF, taken every 5 s, was used to produce the results of total exposure and

FIGURE 1. Measurement locations.

results of student's exposure to the frequency bands depicted in Table 1.

2.3. Measurement Data Processing

The recorded broadband values for E-field and H-field samples were transferred to a personal computer (PC) for data analysis. A MATLAB script was developed to derive the exposure CDF curves per campus environment and to enable the RF-EMF comparative analysis.

All of the measured samples underwent a strict inspection procedure to exclude bias or corrupted samples. Before results post-processing, the samples were technically checked in terms of their values, matching with possible emission sources in specific environments, or whether they are an outcome of possible measurement instrumentation technical errors. Measurements samples were also investigated whether they have been recorded according to the measurement protocol.

The EME SPY recorded values were also transferred to a PC. EME SPY-supported software (EME SPY Analysis) and in-house MATLAB script was used for data processing. One of the known limitations of PEMs is that in all measurement campaigns, a fraction of recorded samples is below the equipment detection threshold. The equipment is hardwired to automatically set all samples below the detection threshold at the lower detection limit. While different statistical methods can be used to estimate the mean electric field values after obtaining measurement results, in this study during post-processing of these samples we applied the widely used half-limit method, to produce reliable cumulative and mean E-field results. When more than 90% of measured samples for a particular technology and environment were below detected limits, the technology was

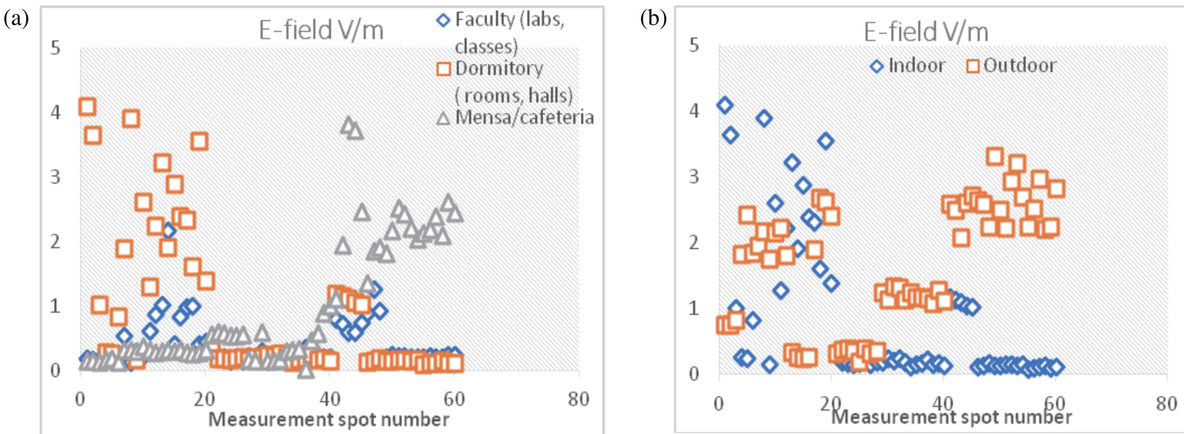

FIGURE 2. (a) Broadband E-field levels (V/m) for various campus indoor environments and (b) Comparative analysis of E-field levels (V/m) for dormitory indoor and outdoor environments.

TABLE 1. Frequency bands measured by EME spy.

FM	88–108 MHz
TV3	174–223 MHz
TETRA	380–390 MHz
TV4&5	470–830 MHz
GSM + UMTS 900 (Uplink)	880-915 MHz
GSM + UMTS 900 (Downlink)	925–960 MHz
GSM 1800 (Uplink)	1710–1785 MHz
GSM 1800 (Downlink)	1805–1880 MHz
DECT	1880–1900 MHz
UMTS 2100 (Uplink)	1920–1980 MHz
UMTS 2100 (Downlink)	2110–2170 MHz
Wi-Fi 2G	2400–2500 MHz
WiMAX	3400-3800 MHz
Wi-Fi 5G	5150–5850 MHz

excluded from further analysis. That resulted in the case with some technologies such as DECT, some TV broadcast transmission bands, and mobile communications in the 2100 MHz range. WiMAX does not operate in the region under the study; however, the frequency band will be used in the future by recently launched 5G mobile testing network.

3. RESULTS

After post-processing, the sample values were used to derive mean and distribution-type results to compare and contrast between E-field and H-field levels detected in different microenvironments and emitted from different wireless technologies. We first present the results from the broadband measurement campaign in Subsection 3.1, while in Subsection 3.2 we present the results from the EMF personal exposure measurement campaign.

3.1. Results from Broadband Measurements on the University Campus

The results of E-field broadband measurements recorded in the different university campus environments are presented in Fig. 2.

The highest measured value of E-field (6-minutes average) is 4.1 V/m, was recorded in dormitory room, in a scenario with presence of mobile phones and laptop generating traffic. The mean values of E-field for various indoor university environments are: mensa/cafeteria 0.97 V/m, dormitory 0.88 V/m, and faculty premises 0.41 V/m.

The mean value of E-field level in outdoor dormitories is 1.67 V/m. All outdoor measurements were taken at a distance of at least 100 m from the nearest identifiable BTS. Results show that outdoor E-field exposure levels in university campus are twice as high as recorded levels for indoor university dormitories and four times as high as those recorded inside faculty premises. E-field values (6-minute averages) were captured in small indoor environments (dormitory rooms and campus cafe-

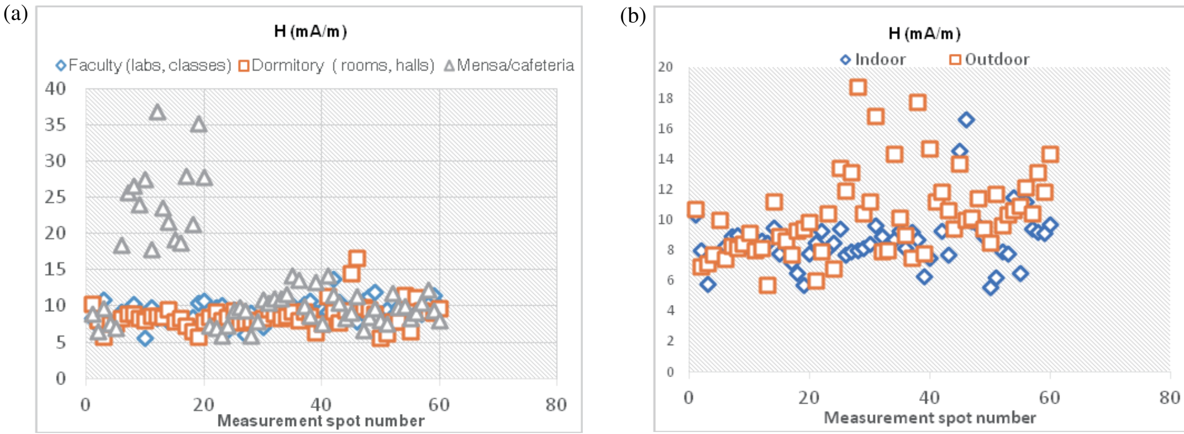

FIGURE 3. (a) H-field levels (mA/m) for various university campus indoor environments; (b) comparative analysis of H-field levels (mA/m) for university dormitories indoor and outdoor environments.

terias) with a moderate to high number of students generating data traffic from smart devices.

As a conclusion, while in indoor environments students may experience high E-field levels for a burst period of time, depending also on the usage patterns of various technologies, and on average the exposure is higher in outdoor areas. The presented results are in good agreement with those given in study [19]. In the mentioned study, the measurements are conducted with NARDA SRM 3006, post-processed with advanced algorithms and indicate that maximum EMF value in campus was 4.314 V/m, the standard deviation 1.157 V/m while the average EMF level is presented as 1.024 V/m.

It should be noted that broadband measurements exclude Wi-Fi at 5 GHz that could increase indoor E-field levels due to equipment limitations.

Outdoor measurements exclude some 5G mobile signals, since EMR 300 measurement instrumentation measures only up to 3 GHz. The results of H-field broadband measurements taken at respective environments are shown in Fig. 3.

For far-field RF-EMF exposure level, the magnitude ratio of the electric and magnetic fields is equal to intrinsic impedance of free space (377 Ohms). Since in our measurement campaign we used particular probes sensitive in different frequency ranges, we present the results of both E-field and H-field characteristics for university campus. H-field samples were not taken at precisely the same locations as E-field samples, but within the same environment. As noted from Fig. 3(a), most H-field samples in indoor campus environments are in the range 8–13 (mA/m).

The mean H-field values for indoor environments, ranked from the highest to the lowest are: inside the cafeteria 13.32 (mA/m), faculty premises 9.25 (mA/m), and dormitory 8.66 (mA/m). The mean value of H-field in outdoor university campus is 10.25 (mA/m). To summarize, we may conclude that average H-field value for 100 kHz–1 GHz in all university environments can be taken as 10 (mA/m).

The statistical analysis of broadband E and H-field values for different indoor and outdoor university campus environments is presented in Fig. 4.

As presented in the figure above, 70% of E-field broadband measurements in dormitory indoor environments are less than 1 V/m, while 70% of outdoor captured dormitory values are less than 2.4 V/m. 70% of broadband E-field levels recorded in cafeteria are below 2 V/m.

80% of H-field levels in university dormitory indoor environments are less than 8 (mA/m) while 80% of university outdoor environments H-field measured levels are less than 12 (mA/m).

3.2. Results from Student's RF-EMF Personal Exposure in University Environments

To study students' RF-EMF personal exposure, we measured E-field levels emitted by technologies operating at 88 MHz–6 GHz in indoor campus environments (faculty premises and dormitories) and outdoor campus environments (mostly dormitory yards). The cafeteria was excluded from results due to previous published data for this environment [7].

Students' exposure to RF-EMF in indoor campus environments is shown in Fig. 5, while a comparative analysis of students' personal exposure in outdoor and indoor campus environments is shown in Fig. 6.

From both figures, we can see that the dominating technologies in all campus environments are WLANs (5 GHz and 2.4 GHz) and mobile communications (2-4G). The presented data include comparative characteristics of downlink vs. uplink E-fields for 2G-4G, operating in 900 MHz and 1800 MHz frequency range in the area under the study.

In Fig. 5(a) we can see that the highest E-field values in indoor faculty environments are due to Wi-Fi-emitted signals, both from access points and user devices. The upper detection limit of PEMs is 6 V/m, a value that was exceeded in some measurement scenarios. Regarding mobile communication technologies inside faculty premises, the highest values are recorded for downlink and uplink 2G-4G operating at 1800 MHz band, and no notable presence of 5G signal was detected. This could be because 5G is still in a pilot phase and might have no coverage indoors. As can be seen from Fig. 5(b)

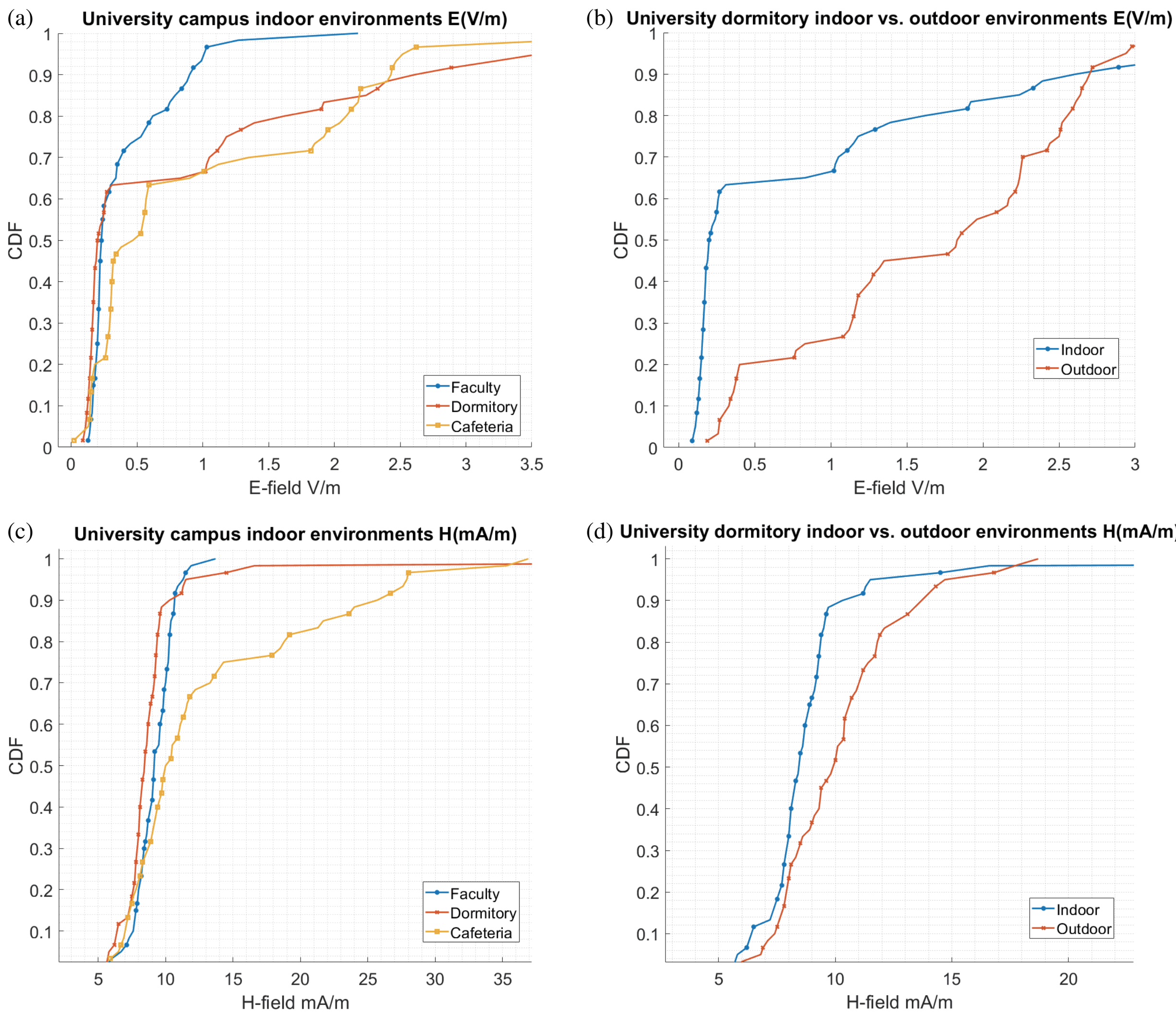

FIGURE 4. Comparative analysis of E-field CDFs for (a) Indoor university environments; (b) Indoor vs. outdoor for university dormitory part of campus (student housing center); and Comparative analysis of H-field CDFs for (c) Indoor university environments and (d) Indoor vs. outdoor for university dormitory part of campus (student housing center).

inside dormitories, the E-fields emitted by Wi-Fi and mobile communication are comparable, with 90% of emitted E-field samples for each technology being less than 1 V/m.

From Fig. 6(a) we can see that in outdoor campus environments, the main contributors to the total RF-EMF exposure are Wi-Fi 2 GHz and 5 GHz emitted signals. In terms of mobile communication technologies, the dominating technologies are those operating in 1800 MHz (3G-4G), both in the uplink and downlink directions which generate higher levels of E-field than other technologies.

We can see from this figure that 50% of measured E-field samples for Wi-Fi 2 GHz in outdoor university environments are higher than 1.1 V/m, while 25% of measured Wi-Fi 5 GHz E-field values are higher than 1 V/m. The comparative analysis of our presented Wi-Fi results for different university environments with focused study on Wi-Fi in university campus over three years [14], and concludes that both study results are in the same range.

As can be seen in Fig. 6(b) from students' total personal exposure to RF-EMF in various university environments, the CDF curves show that 90% of values in dormitory outdoor areas are less than 1.8 V/m, which is consistent with the mean value obtained from broadband measurements. Very few samples inside faculty premises exceed the detection threshold of 6 V/m, which resulted in an underestimation of the total exposure in Fig. 6(b) ($< 0.1\%$ of samples).

In an indoor environment, 50% of samples captured are less than 0.5 V/m, which again is consistent with results that we obtained with broadband measurement, while 90% of samples dormitory indoor are less than 2 V/m. Higher indoor values than broadband measurements can be attributed to the fact that PEMs have a measurement frequency range up to 6 GHz that includes Wi-Fi 5 GHz, compared to the 3 GHz upper limit of the NARDA EMR. However, 80% of indoor dormitory samples are less than 0.9 V/m, which agrees with broadband presented mean values.

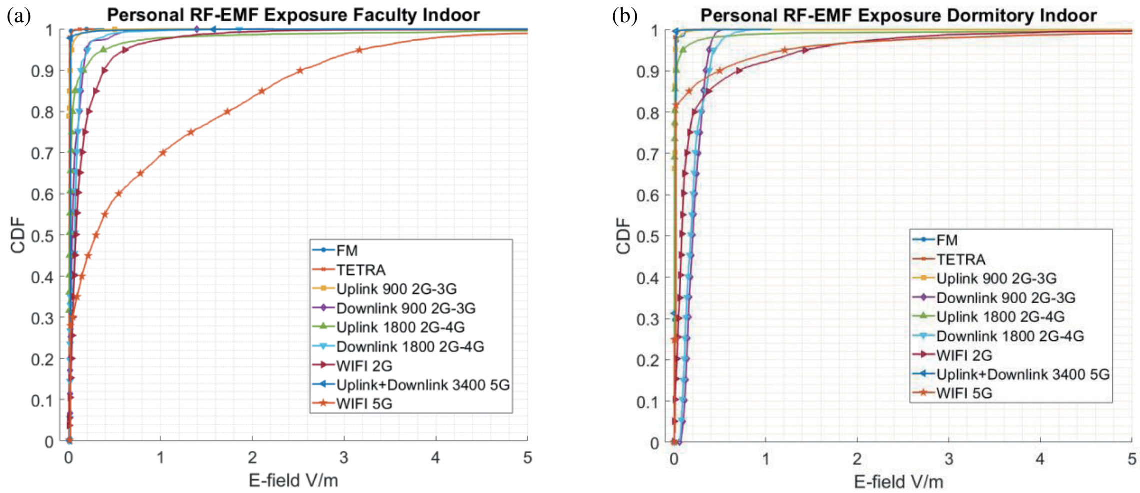

FIGURE 5. CDF of E-field levels for (a) faculty indoor premises and (b) dormitory indoor premises (mostly dormitory rooms).

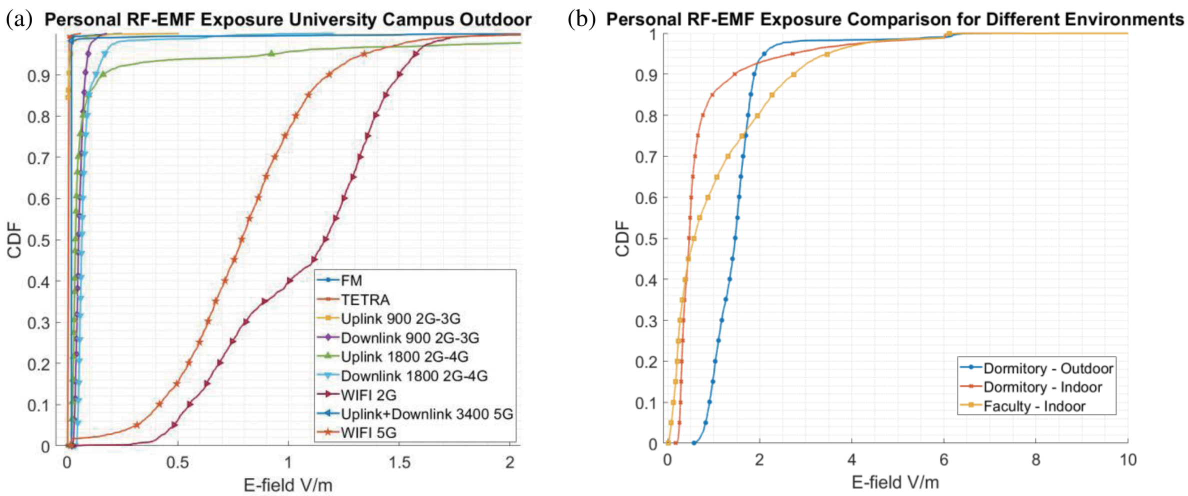

FIGURE 6. (a) CDF of outdoor university campus students' exposure to RF-EMF while part. (b) CDF of students' total exposure to RF-EMF in various environments.

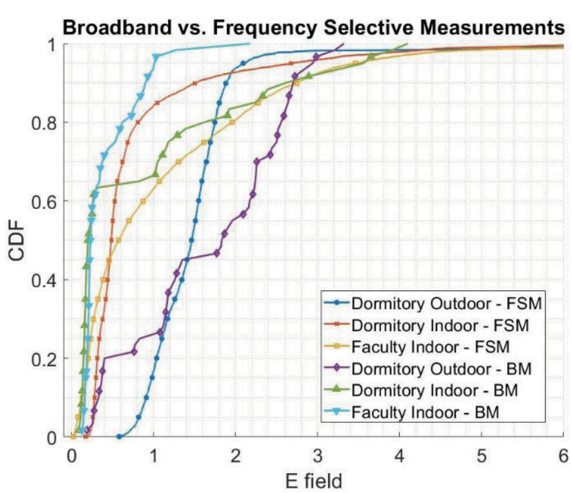

FIGURE 7. Comparative analysis of E-field levels in various university environments.

The comparative analysis of broadband measurement (BM) and frequency selective measurement (FSM) E-field CDFs for various university indoor and outdoor environments is presented in Fig. 7.

As seen from the figure, there is an acceptable agreement between broadband and frequency selective measurement data for most environments. The noted differences for certain percentage of indoor recorded samples are mostly because broadband measurements present sub-3 GHz E-field levels and do not include Wi-Fi 5G. The measurement results reported in [16] show that E-field levels at an outdoor university campus area were typically 2 to 2.5 V/m and for dormitories 1.7 to 2 V/m. This is consistent with our results, which indicate that in indoor university environments, 70% of measured E-field levels are less than 1.4 V/m, while 70% of outdoor captured E-field levels are less than 2.2 V/m, even though different research methodologies were applied.

All measured RF-EMF values presented in this paper, broadband and frequency selective, in indoor and outdoor environments, in scenarios under the study, are well below the exposure levels stipulated by International Commission on Non-Ionizing Radiation Protection [22].

A recently published paper [23] with objective to investigate RF-EMF exposure in areas of sensitive land use such as: schools, universities, and hospitals, before complete rollout of 5G technology, presents broadband E-field levels ranging from 0.28 V/m to 1.87 V/m for outdoor environments. The results presented in this paper are in the same range of RF-EMF exposure considering the comparable situation regarding 5G rollout. Another technique and solution on the reduction of RF-EMF exposure levels to mobile users which gives promising results on the matter is through the design and implementation of multi-stopband frequency selective surface (FSS), as presented in [24, 25].

4. CONCLUSIONS

Exposure levels in indoor and outdoor university environments, and students' exposure patterns, presented in this paper are a result of a measurement campaign conducted with both broadband and narrowband frequency selective measurement instrumentation. Since both methodologies have their advantages and disadvantages in terms of captured frequency range, upper and lower detection limits, result post-processing, and technical limitations, in order to derive reliable outputs and measurement data to compare, we used both.

The average E-field values in various indoor university environments were: 0.97 V/m in cafeterias, 0.88 V/m in dormitories, and 0.41 V/m inside faculty buildings. The highest broadband measured value at 4.1 V/m was captured inside a dormitory room; however since it was captured with a sub-3 GHz broadband equipment, we cannot identify the source. With PEMs, some temporal E-field values emitted by Wi-Fi 2 GHz and Wi-Fi 5 GHz in university indoor environments exceeded 6 V/m, which is the upper detection limit of the PEM equipment. 90% of samples captured using the broadband measurement equipment which calculates 6-minute averages of the E-field levels, in dormitory indoor and outdoor environments were lower than 2.7 V/m.

The difference between H-field averaged values in university campus indoor and outdoor environments is not high; therefore, it can be concluded that in most campus environments, the H-field exposure levels in the frequency range 100 kHz–1 GHz can be taken as 10 mA/m.

The assessment of students' exposure to RF-EMF in various university campus environments reveals that even in dormitory outdoors one of the main contributors to E-field level is WLAN networks. 90% of personal exposure E-field measurement samples in outdoor dormitories were lower than 1.5 V/m for Wi-Fi 2 GHz, lower than 1.2 V/m for Wi-Fi 5 GHz, lower than 0.2 V/m for all mobile technologies respectively in the uplink and downlink frequencies. For most exposure scenarios, there is a good agreement between results obtained through the two methodologies used in this work: broadband and frequency-selective measurement.

The measured RF-EMF exposure in all environments and scenarios under the study were below maximum permissible exposure limits set by International Commission on Non-Ionizing Radiation Protection (ICNIRP) for both occupational and general public exposure.

The 5G mobile communication services which were launched only recently and are still in testing phase appear very little in these measurements, most likely due to limited coverage, and therefore it is not ranked among the main polluting technologies on campus. However, as the technology is rolled out, we consider that it will be necessary to perform a repeat measurement campaign to capture the full effect of 5G technology.

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