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ASSESSING THE COMPLIANCE OF ELECTROMAGNETIC FIELDS RADIATED BY BASE STATIONS AND WIFI ACCESS POINTS WITH INTERNATIONAL GUIDELINES ON UNIVERSITY CAMPUS

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This paper presents a series of electromagnetic field measurements performed on the campus of Ferdowsi University of Mashhad in order to assess the compliance of radiation levels of cellular base stations and WiFi access points with international guidelines. A calibrated, broadband and isotropic probe is used and recommendations of International Telecommunication Union (ITU) are followed up throughout measurements. More than 300 outdoor and indoor locations have been systematically chosen for measurements. The recorded data are post-processed and compared with the guideline of International Commission on Non-Ionizing Radiation Protection (ICNIRP). Measured power densities of WiFi access points are low and do not exceed 1% of the level allowed by ICNIRP. For cellular base stations, measured power density is usually low outdoors, but reaches up to 16% of the allowed radiation level in publicly accessible indoor locations. Comprehensive exposure assessment, as recommended by ITU, has been performed to estimate the maximum possible radiation of one indoor base station. It is concluded that precautionary actions have to be taken by university authorities to limit the presence of students in close proximity to specific indoor antennas. Moreover, comprehensive exposure assessment is more likely necessary for indoor base stations whereas such assessment is not usually required outdoors.

INTRODUCTION

Wireless communication technology has significantly enhanced the quality of life. Despite this fact, authorities have to make sure that the radio frequency signals radiated by wireless devices have no adverse health effects for the general public. One source of concern has been electromagnetic radiation of cell phones and laptops[1–4] as well as cellular Base [Transceiver] Stations (BTS) and WiFi access points[5–9]. To ensure public safety, real-world measurements should be conducted and the results are analyzed by the scientific community.

International Commission on Non-Ionizing Radiation Protection (ICNIRP) is responsible for the scientific assessment of short-term health effects associated with electromagnetic field exposure[10,11]. ICNIRP has determined reference levels for electromagnetic field exposure. Long-term investigation of health effects due to electromagnetic field exposure is the responsibility of International Agency of Research on Cancer (IARC). Several monographs are published by IARC which analyze carcinogenicity of ionising[12] and non-ionising radiation[13,14]. When assessing exposure to electromagnetic fields, short-term health effects are quantitatively investigated by using ICNIRP guideline. Qualitative measures are taken into account to prevent possible adverse health effects in the long-term as noted by IARC.

The general public exposure to electromagnetic fields can be personal and/or environmental. The personal exposure is primary due to cellphones and laptops, whereas environmental exposure is mainly caused by cellular base stations and WiFi access points. Several international studies confirm that the general public underestimates the risk of near-field personal exposure and overestimates the risk of far-field environmental exposure[14–16]. Nevertheless, public concern regarding environmental exposure has to be properly addressed. On-site measurements and analysis need to be performed by academic experts with no conflict of interests. Such measurements provide the raw material for responsible authorities in order to properly communicate the risk of environmental exposure to the general public.

Several published articles have confirmed the compliance of electromagnetic field exposure with reference levels of ICNIRP both for cellular base stations and WiFi access points[17–33]. However, the field level depends on many factors including power and gain of the transmitting antennas, adaptive power control in the transmitter and site-specific nature of the environment[34]. Hence, compliance assessment is crucial and has to be performed regularly for cellular base stations. WiFi access points are usually considered compliant due to low transmitted power. However, it is a point of concern especially for those students whose dorm rooms are equipped with WiFi access points and are constantly and closely exposed to the source of electromagnetic radiation.

The current paper presents the results of measurements performed on the campus of Ferdowsi University of Mashhad. The main goal is to assess the compliance of electromagnetic field levels with ICNIRP guideline. The university has five tower-mounted and one rooftop outdoor base stations as well as two indoor base stations. More than 800 WiFi access points are also installed inside university buildings and dormitories. Measurements and compliance check in >300 locations are performed which include all mentioned scenarios. Measurement results for outdoor base stations and WiFi access points are plentiful in the literature, as referenced above. To the best of authors' knowledge, however, little measurement data are available for compliance assessment of indoor base stations. Indoors, people may unknowingly access locations very close to transmitting antennas and hence be exposed to high levels of electromagnetic radiation. A major contribution of the paper is that comprehensive exposure assessment is found to be necessary for indoor base stations whereas such assessment is usually not required outdoors. Based on this assessment, precautionary actions have been recommended to the university authorities to prevent exposure of students to high levels of electromagnetic radiation.

In the rest of the paper, the second section explains the problem and describes the measurement setup and scenarios. The third section presents the field measurement results and discussion. The comprehensive exposure assessment of indoor base station antennas is explained in the fourth section. Conclusions are given in the fifth section.

FIELD MEASUREMENT

Electromagnetic fields and human safety

The primary short-term effect of exposure to the electromagnetic field is heating caused by the dissipation of electromagnetic energy in the lossy dielectric medium of the body. ICNIRP defines Specific Absorption Rate (SAR) as the amount of power absorbed per unit mass of a body tissue[10]. According to ICNIRP, wireless devices must keep their radiated power as low as possible such that the corresponding SAR does not exceed a certain threshold that is proved to have adverse health effects on the human body. Additional safety margins have also been added to this threshold. The internationally recognised whole-body average SAR is 0.08 W/Kg for the general public in the frequency range 100 KHz–10 GHz[10]. The telecommunication operators as well as WiFi and radio industry designers must control the power of their transmitters in order to meet this restriction.

Measuring the whole-body SAR is not an easy task and requires sophisticated measurement setups. Practically, SAR is only measured in special laboratories due to the cost and portability restrictions. Instead, ICNIRP defines *reference levels* for whole-body exposure to electromagnetic fields. The reference levels are easy to measure with portable devices. Hence, they are more useful in extensive field measurements that are required in environmental exposure assessments. The reference levels are frequency dependent. In terms of power density, the reference level for the general public equals $f_{(\mathrm{MHz})}/200$ in the frequency range $400 < f_{(\mathrm{MHz})} < 2000$, where $f_{(\mathrm{MHz})}$ is the frequency of the electromagnetic wave in megahertz. For higher frequencies, the reference level power density equals 10 W/m^2[10] (Recently, a new version of ICNIRP guideline has just been published[35]. The reference levels are the same as the older version of the guideline in the frequency band of cellular communications and WiFi. Slight differences are observed in other frequencies.). These formulas are derived conservatively from the SAR restrictions and cover the frequency bands of telecom operators (900 MHz-2.6 GHz) as well as WiFi access points (2.4 GHz). If measurements show that reference levels are met, SAR restrictions are also met and the general public are not exposed to any short-term adverse health effects of the electromagnetic fields.

Measurement setup

Measurement setup consists of a measurement probe connected to the SMP (Sistema de Monitorizacion Port´ atil)´ device and mounted on a tripod. The probe and SMP device are made by Wavecontrol, a certified European company and calibrated periodically. The system measures the electric field every second and the recorded data can be downloaded to a personal computer for further post-processing.

The probe model used in measurements is WPF18 with part number 17WP090285 that was calibrated within one year from our on-site measurements. The calibration was performed by LabCal Wavecontrol, and accredited by ENAC as an ILAC MRA certified laboratory for testing and calibrating measurement devices. The probe is broadband and covers a frequency range 1 MHz–18 GHz. The probe is isotropic and receives multipath components from all angles of arrival as desired. The probe is connected to the SMP device which processes the received power and calculates the received electric field. The sensitivity of the SMP device is 0.5 V/m, far below the reference levels designated by ICNIRP.

A tripod is designed and used for mounting the SMP device. Since the measurements should be recorded at various heights, the legs of the tripod should be adjustable. Conventional tripods used in land surveying are usually made of aluminium or steel. Such tripods must not be used in electromagnetic field measurements due to the high reflectivity of metallic structures. In our measurement campaign, a low-reflective dielectric tripod has been designed and used. The legs of the tripod are made of wood and the mounting base is made of plexiglass. At frequencies of interest, the dielectric constant of wood is about 2[37], and the dielectric constant of plexiglass is usually reported at around 2.5–3.5[38]. These values are close to the dielectric constant of air. This ensures that the tripod does not have a practical electromagnetic impact on the measured signal.

In measurements, 6-min temporal averaging is required by ICNIRP guideline (in the recently published version of ICNIRP guideline[35], the temporal averaging is recommended to be performed over a 30-min period. However, the temporal average has been found nearly unchanged when time span extends 2 min[39]. Hence, the validity of measurement results is maintained) and spatial averaging is recommended by International Telecommunication Union (ITU) in order to account for whole-body exposure[36]. The recommended spatial configurations consist of 3-, 6-, 9- and 20-point measurements at a given location. The three-point configuration has been used in the measurement campaign. This configuration measures the field along a vertical line at 1.1, 1.5 and 1.7 m above the ground. Choosing other spatial configurations may slightly enhance the measured field accuracy at the cost of a significant increase in the measurement time. The SMP device records a 6-min interval and calculates the temporal root mean square (rms) of the electric field at a specific height. The tripod is then adjusted to the next height. When the three measurements are accomplished, the spatial rms value is calculated among the three temporal rms values[36]. This final value is the field level that has to be compared with ICNIRP reference level to check the compliance.

Measurement scenarios

A variety of measurement scenarios are present on the campus. These include outdoor base stations mounted on high towers or rooftop, indoor base stations located inside the Engineering Faculty, and WiFi access points inside faculties, official buildings and dormitories. The geometry of these scenarios as well as the rationale behind selecting the locations for measurements are explained in details in the following.

Outdoor Base Stations: Six outdoor base stations are located on the campus. Examples are illustrated in Figure 1a. The right photo in Figure 1a (denoted as BTS 6) corresponds to a rooftop BTS which is located above one of the dormitories. The rest of the base stations, denoted as BTS 1–5, are all located on high towers. The height of antennas is measured by a handheld laser rangefinder and is in the range of 24–30 m above the ground level. BTS 1, 3 and 6 are shared among two telecom operators. This is an important point since each operator serves its own clients and thus radiates independently of the other operator. Hence, radiation exposure effectively increases near the shared sites. For the rooftop BTS 6, exposure assessment is crucial since people may access the roof and be exposed to a close radiation source.

Indoor base stations: Two single-operator indoor base stations, labelled as BTS 7 and BTS 8, are located inside the Engineering Faculty. Indoor base stations provide GSM service in 900 MHz band and are primarily installed to enhance voice coverage in the highly cluttered and heavy-traffic building of Engineering Faculty. Each base station has four antennas and their characteristics are provided in Table I. These antennas are placed at 2.3–3 m above the floor. Bidirectional antennas are used in some sectors in order to cover two long hallways in opposite directions. Sample antennas are shown in Figure 1b. It is evident that people can easily and unknowingly access the vicinity of the indoor antennas. This is a strong motivation for compliance assessment.

WiFi access points: Approximately 800 WiFi access points operate inside faculties, official buildings and dormitories. Since measuring the fields of so many access points would take a long time, only a sample of those access points have been selected for measurement inside 28 buildings all over the university. The buildings have various architectural plans. To systematically select the measurement points, every single access point is first visually observed and photographed. The scenarios encountered include open areas, hallways with various heights and widths, stairs and rooms. Examples are shown in Figure 1c. The photographs of access points are compared in order to derive a variety of scenarios that represent various propagation mechanisms of the electromagnetic waves inside the buildings. When strong electromagnetic reflectors such as metallic lockers are present near an access point, that access point is also selected for measurement. In each scenario, special focus is placed on the ones which radiate closest to the public in everyday life. Almost one out of every four access points have been selected for measurement. Considering every access point for measurement is not even necessary due to the fact that the installed WiFi antennas radiate at 0.5 W power. However, a lot of access points are located inside rooms in dormitories and constantly radiate in close vicinity of students. This causes concern among students and university authorities and justifies the extensive measurements.

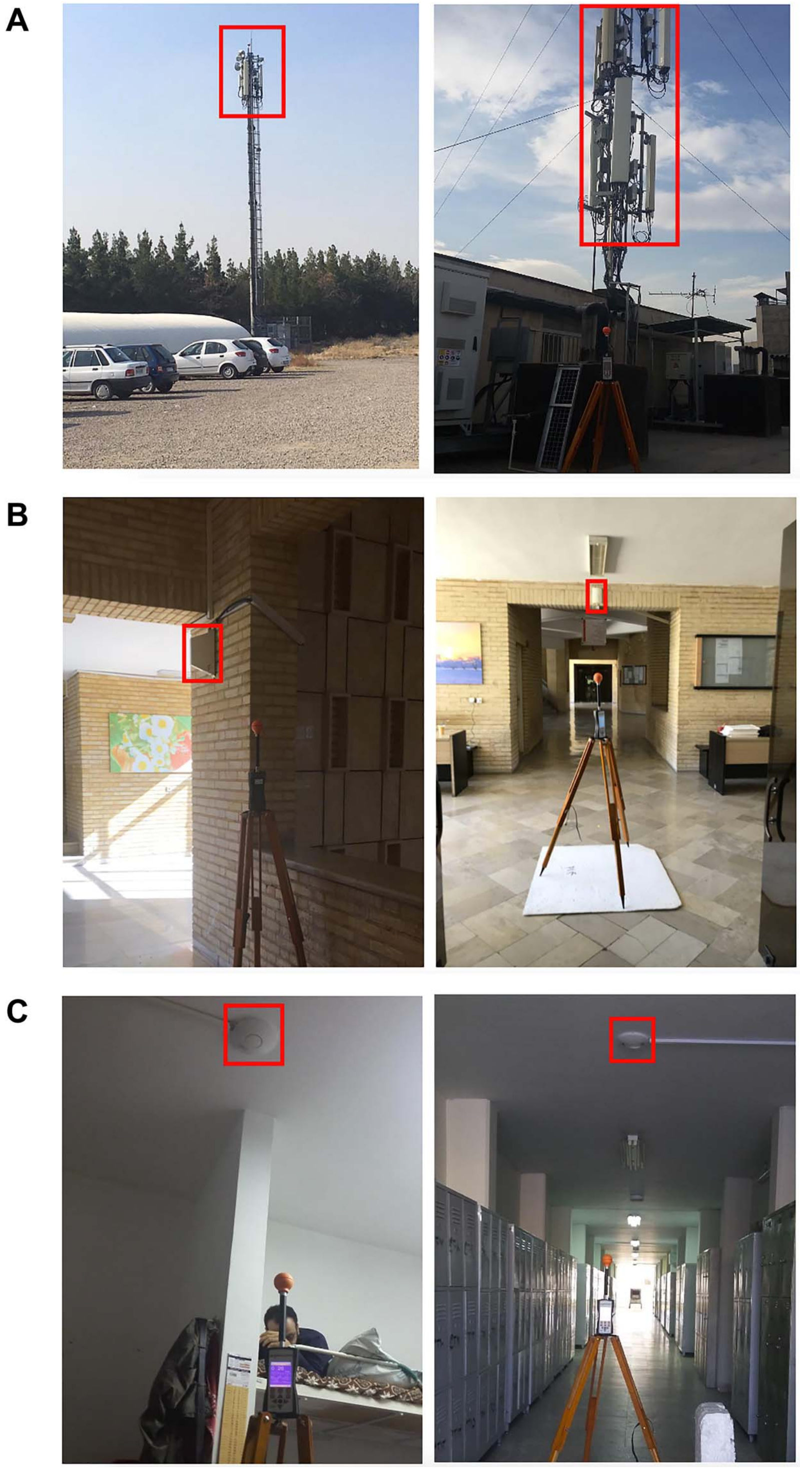

Figure 1: Sample measurement locations: (**a**) outdoor base stations, (**b**) indoor base stations, (**c**) WiFi access points. BTS and WiFi antennas are boxed in red for clarity.

Table I. Antenna characteristics of the two indoor base stations inside engineering faculty.

BTS	Antenna	Pattern	Floor	Colocation
BTS 7	#1	Directional	Ground	Yes
	#2	Bidirectional	Ground	
	#3	Bidirectional	1st	No
	#4	Bidirectional	2nd	No
BTS 8	#1	Directional	Ground	Yes
	#2	Directional	Ground	
	#3	Directional	1st	No
	#4	Directional	2nd	No

RESULTS AND DISCUSSION

Outdoor base stations

The electromagnetic field is measured along various lines moving away from the transmitting antenna. Each RX line is selected along with the maximum azimuth radiation pattern of a sector antenna, i.e. normal to the antenna panel. While moving away from the antenna, field probing is done to find the locations of field local maxima and minima, in order to capture the field variations. The RX lines are located in the far-field of the antenna as recommended by ITU(36). The measurements are all performed at the ground level in areas accessible to the general public. Every RX location has been selected to be at least 1 m away from all surrounding scattering objects(36). During measurements, the person conducting the measurements as well as passerby people stood away from the tripod. All measurements have been conducted from 9 AM to 3 PM that correspond to high-traffic hours.

Field measurements for BTS 1–4 have been performed along one RX line for each BTS. These base stations are mostly located on the boundaries of the campus and one sector per BTS serves the locations inside the campus. All sectors of BTS 5, however, serve the campus and field measurements have been carried out along three lines, each corresponding to one sector. Figure 2a and b shows the measured rms electric field as a function of distance to the transmitter. For compliance assessment of a broadband measurement, stricter reference level has to be considered. Maximum measured field level among measurements of BTS 1–5 (2.8 V/m) is still small compared to ICNIRP reference level at 900 MHz (41 V/m). In terms of power density which is proportional to the square of the electric field level, the measured power density is <1% of the reference power density allowed by ICNIRP guideline.

In the case of BTS 1–5, the reason for compliance of electromagnetic fields with reference level is that BTS antennas are located well above the ground level. The RX locations are far away from the antennas even at the tower base. As we move away from the tower, the separation distance increases but the RX location starts to lie in the main lobe of the elevation pattern of the antenna. Depending on the scattering objects nearby, the field level may either monotonically fall or may reach a maximum and then start to decrease. The general conclusion is that since the antennas are mounted on high towers and the field is measured on the ground level (where public can actually access), the measured field levels for BTS 1–5 are much less than the ICNIRP reference level. No restriction has, therefore, been recommended to the university authorities.

For the rooftop BTS 6, the field levels are higher as depicted in Figure 2c. For this BTS which is a shared site among two operators, on-site field probing is done to find three lines that have the highest field levels. In terms of power density, the observed level is about 4% and 14% of ICNIRP reference level on the roof and the loft, respectively. The reason for higher field levels is the proximity of measurement locations to the BTS antennas of a shared site. Although ICNIRP reference level is not exceeded, it is recommended to limit the unnecessary access of the residents to the roof and especially to the loft.

Indoor base stations

In Indoor scenarios, the field is measured along a line for each BTS antenna. The measurement line is chosen in front of the antenna panel where radiation is maximum. On-site probing is conducted to select sample points corresponding to maxima and minima of field level. This way, the variation of field level is properly captured. The measurements are all conducted from 9 AM to 3 PM. Notable ambient sources are WiFi antennas. However, their radiation power is much less than BTS antennas. Furthermore, the measurement points are away from WiFi antennas. As a result, ambient sources are not practically notable indoors.

Figure 3 shows the measured field levels corresponding to indoor base stations. As observed, the

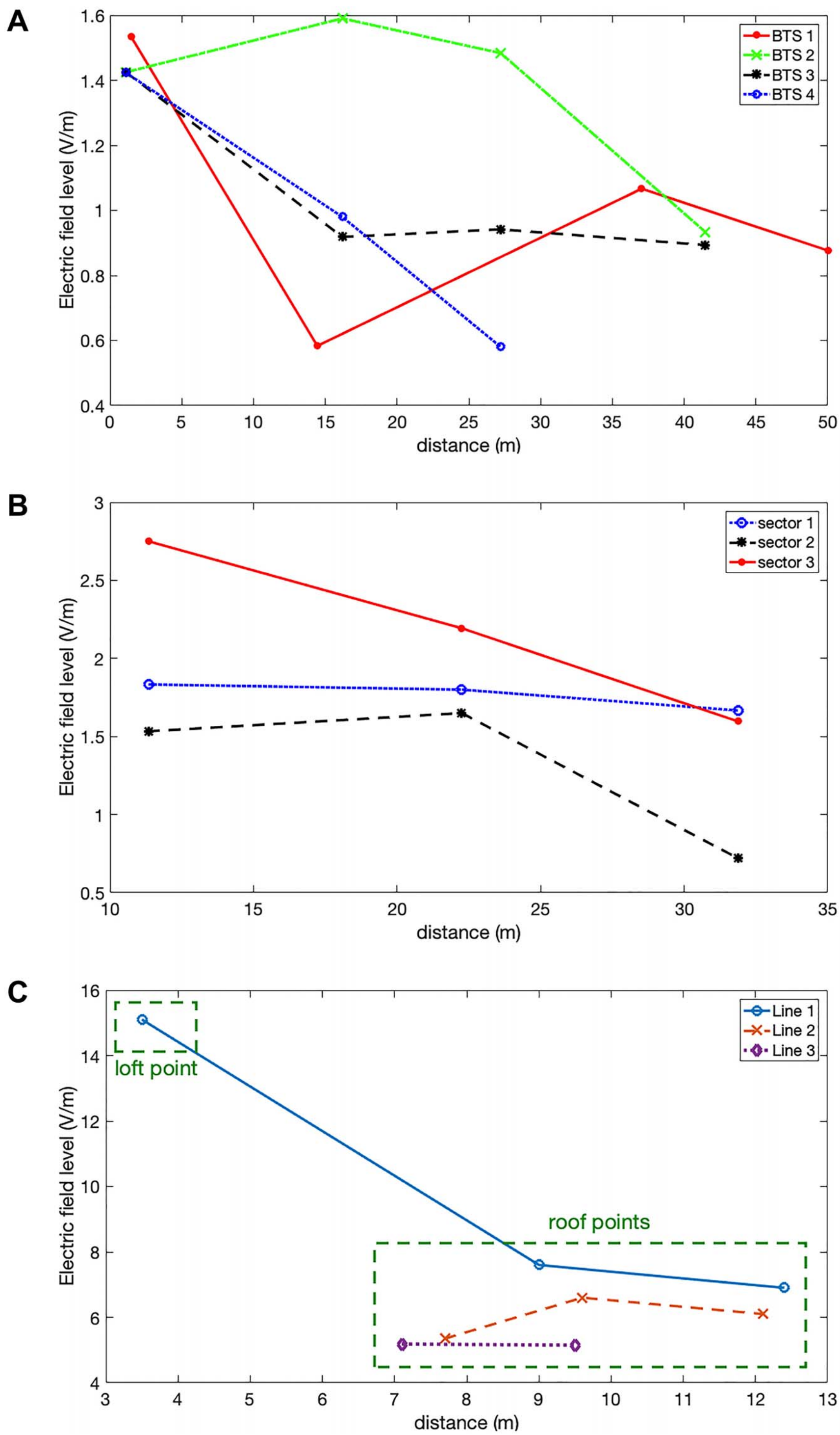

Figure 2: Electric field level as a function of distance from tower base: (**a**) BTS 1–BTS 4, (**b**) three sectors of BTS 5, (**c**) three lines close to rooftop BTS 6.

field levels are generally higher than outdoors but still in compliance with ICNIRP reference levels. The field levels along all RX lines are high in the vicinity of the transmitters but decrease, though not monotonically, as we move away from them. The propagation mechanisms are more diverse, such as strong reflection from the metallic door of the elevator and waveguiding effect of the hallways. The wireless channel is, therefore, richer in terms of multipath components and more fluctuations are observed along the RX lines.

Architectural plan of the building is the main reason for the higher received field level in the indoor locations. The BTS antennas in the Engineering Faculty are only 2.3–3 m above the floor and people can get very close to the transmitters and experience higher levels of exposure than outdoors. The maximum field level observed indoors is 16 V/m which, in terms of power density, corresponds to 16% of the ICNIRP reference level at 900 MHz.

Although compliance is observed, it is recommended by ITU to perform *comprehensive exposure assessment* if measured power density is >5% of the allowed power density at locations accessible to the public. This assessment has been done and the results and recommendations to the university authorities will be presented in the fourth section.

WiFi access points

All 28 buildings of the university have been investigated including faculties, official buildings and dormitories. In faculties and official buildings, most access points are located in hallways and open areas where people usually pass by and are not exposed to constant radiation. In dormitories Fajr 1–5 and Pardis 2, each access point is located inside a room and serves residents of that room as well as several nearby rooms. In other dormitories, access points are located in the hallways. Lots of measurements have been carried out in the dormitories where students are constantly exposed to WiFi radiation.

Access points have been systematically chosen for measurements. The architectural plan of each building has been taken into account as discussed in the third subsection of the second section. Moreover, the traffic data have been provided to the authors by the ITC office of the university. Among similar architectural scenarios, access points with the highest weekly downlink traffic, and therefore maximum radiation, are chosen. For the selected access points, measurements have been carried out during the daily temporal peak hours of downlink traffic.

When conducting measurements, the tripod is usually positioned exactly under the ceiling-mounted WiFi access point. This is because of the downward radiation pattern of WiFi antennas installed on ceilings. In some cases such as cluttered environment or involving metallic furniture, the exact position of peak field level is slightly different which is found by on-site field probing.

Table II shows the maximum value among the rms electric field levels measured for access points in the buildings of the university. The WiFi access points follow IEEE 802.11 g standard and radiate at 2.4 GHz band. Therefore, the field levels have to be <61 V/m according to ICNIRP guideline. Based on the data of Table II, it is observed that radiation of WiFi antennas is in compliance with ICNIRP reference level. The maximum measured field is 4.9 V/m inside the Engineering faculty which, in terms of power density, is <1% of ICNIRP reference level. As a result, field compliance is observed and no restrictions are applicable based on ICNIRP guideline. Note, however, that possible long-term effects of electromagnetic fields are out of scope of ICNIRP and are still under study. As stated by International Agency of Research on Cancer in its monograph on electromagnetic fields[14], ‘it is likely that not all mechanisms of interaction between weak RF fields, with the various signal modulations used in wireless communications, and biological structures have yet been discovered or fully characterized’. In Fajr 1–5 and Pardis 2 dormitories, WiFi access points are located inside rooms and students are exposed to constant radiation. It is therefore recommended, as a precautionary measure, to remove those access points and install them in nearby hallways.

COMPREHENSIVE EXPOSURE ASSESSMENT

The procedure described in the previous sections *may not* accurately reflect the maximum amount of RF radiation that the general public is exposed. The base station antenna does not always transmit at full power. The reason is 2-fold. First, the base station has the capacity to simultaneously serve several users. At the time of field measurement, it is possible that not all traffic channels of the base station are occupied. The second reason is attributed to a mechanism known as adaptive power control. This mechanism provides a trade-off between quality of service, energy-saving and public exposure reduction. When wireless channel between BTS and user is of high quality, BTS radiated power is reduced. For low-quality wireless channel, on the other hand, the BTS power is increased to improve the quality of service. Therefore, the measured field is not the maximum value that could have been had all traffic channels radiated at full power.

ITU recommends a procedure, known as a comprehensive exposure assessment, to find a conservative estimate of the maximum exposure[34]. This procedure is applicable when measured power density at a publicly accessible location exceeds 5% of the lowest power density allowed by ICNIRP in the frequency

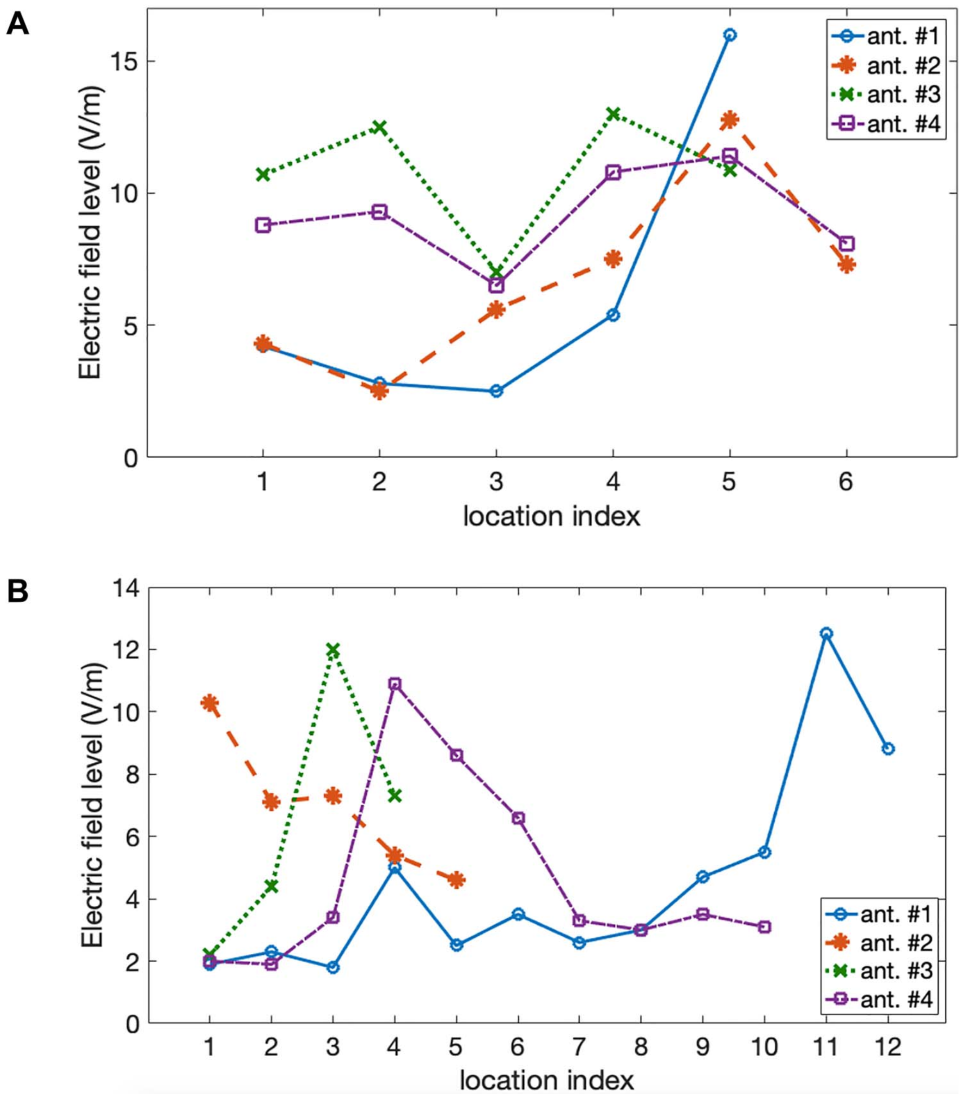

Figure 3: Electric field level along eight lines corresponding to eight indoor BTS antennas: (**a**) BTS 7, (**b**) BTS 8.

band of the base station. With reference to the results of the third section, only indoor base stations (BTS 7 and BTS 8) meet the criteria for comprehensive exposure assessment. Note that the measured power of the rooftop antenna (BTS 6) on the loft exceeds the 5% criterion, but access to the loft is restricted. Hence, BTS 6 is excluded from comprehensive exposure assessment.

Site-specific investigation has been performed to judiciously select the locations for comprehensive exposure assessment. It has been found that only antennas #2, #3 and #4 of BTS 7 need be assessed. A bench-like shelf is located in the vicinity of each of these antennas as depicted in the left photo of Figure 1b for antenna #4. The geometry for the other two antennas is exactly similar. Students frequently sit on or stand in front of the shelf and chat for a while. The mentioned antennas are all bidirectional and their maximum radiation occurs normal to their panel, i.e. towards the direction of such students. Therefore, this location has been selected for a comprehensive exposure assessment.

The mathematical formulas governing comprehensive exposure assessment depend on the service type of the base station. BTS 7 provides GSM service at 900 MHz band. In GSM service, each sector has

Table II. Maximum measured value of electric field (in v/m) for WiFi access points in faculties, official buildings and dormitories.

Faculty/office	$\|E\|$max	Faculty/office	$\|E\|$max
Agriculture	1.8	Psychology	1.8
Architecture	1.2	Science	1.4
Economics	1.4	Sport	1.2
Engineering	4.9	Theology	2.5
Literature	2.7	Headquarter	2.7
Mathematics	2.2	Edu. Office	1.4
Environment	1.0	Museum	1.3
Dormitory	**$\|E\|$max**	**Dormitory**	**$\|E\|$max**
Pardis 1	1.1	Pardis 8	1.2
Pardis 2	1.2	Fajr 1	1.7
Pardis 3	1.5	Fajr 2	1.4
Pardis 4	2.2	Fajr 3	2.3
Pardis 5	2.2	Fajr 4	1.3
Pardis 6	1.5	Fajr 5	2.5
Pardis 7	2.0	Bagha	1.5

several traffic channels that serve the users, and one control channel known as Broadcast Control CHannel, or simply BCCH. The function of BCCH is to transmit the identity of the base station such that users can properly get access to the traffic channels. While traffic channels may sometimes be idle and their transmitting powers are adaptively controlled, BCCH *always* transmits a *constant* power. The power of BCCH is the highest value that can be transmitted by the base station and traffic channels usually transmit at much lower powers. As a result, the maximum transmitted power by the base station can be obtained when traffic channels are all transmitting the same power as BCCH at the same time. If the power density of BCCH, denoted by S_{BCCH}, is measured at a location, the maximum power density $S_{\max}$ at that location can be estimated as[34]

$$S_{\max} = S_{\mathrm{BCCH}} N_{\mathrm{GSM}} \tag{1}$$

where N_{GSM} denotes the total number of channels used by the base station including BCCH. Therefore, it is essential to accurately measure the power density of BCCH at the mentioned locations.

ITU recommends the use of a narrowband or broadband probe to measure BCCH[34]. The narrowband probe is more suitable since it can specifically measure the power of BCCH and omit traffic channels and other ambient sources. The recommendation cautions the use of broadband probe for BCCH power measurement since it also captures traffic channels and hence may overestimate $S_{\max}$. The calibrated probe available to the authors is a broadband one as described in section II.B. However, it is possible to measure BCCH power by a broadband probe as described in the following.

The temporal fluctuations of the measured power density can be incorporated to find BCCH power density. As noted above, the power transmitted by the base station in a traffic channel is usually much less than the power of BCCH. The power density at a location measured by a broadband probe has two components: a constant component which corresponds to BCCH, and a fluctuating component that corresponds to traffic channels. The fluctuations are attributed to the time-varying nature of user calls as well as inherent adaptive power control of traffic channels. As a result, if traffic channels are all off, the measured power density by the broadband probe represents the BCCH power density at the probe location. In the Engineering Faculty, students and staff go home at night. It is therefore expected that traffic channels are off late in the night and in early hours of the morning. Hence, the measured power density at that time can be interpreted as S_{BCCH}.

To find S_{BCCH}, 24-h monitoring of power density has been performed at the designated locations across the three selected antennas. A standard 6-min measurement with 1-s sampling rate has been performed every hour. This way 360 samples of power density are measured every hour at each location. The probe height is fixed at 1.7 m from the floor in order to capture the highest power density[34]. The distance between the probe and the centre of the antenna panel is almost 1 m. Therefore, the probe is in the far-field of the antenna[36]. Figure 4 shows the characteristics of measured power density as a function of time during the 24-h monitoring period. The average power density as well as its standard deviation are depicted as a function of time. At any hour, the average and standard deviation are calculated from the 360 samples of measured power density at that hour. The average power density is expressed in a

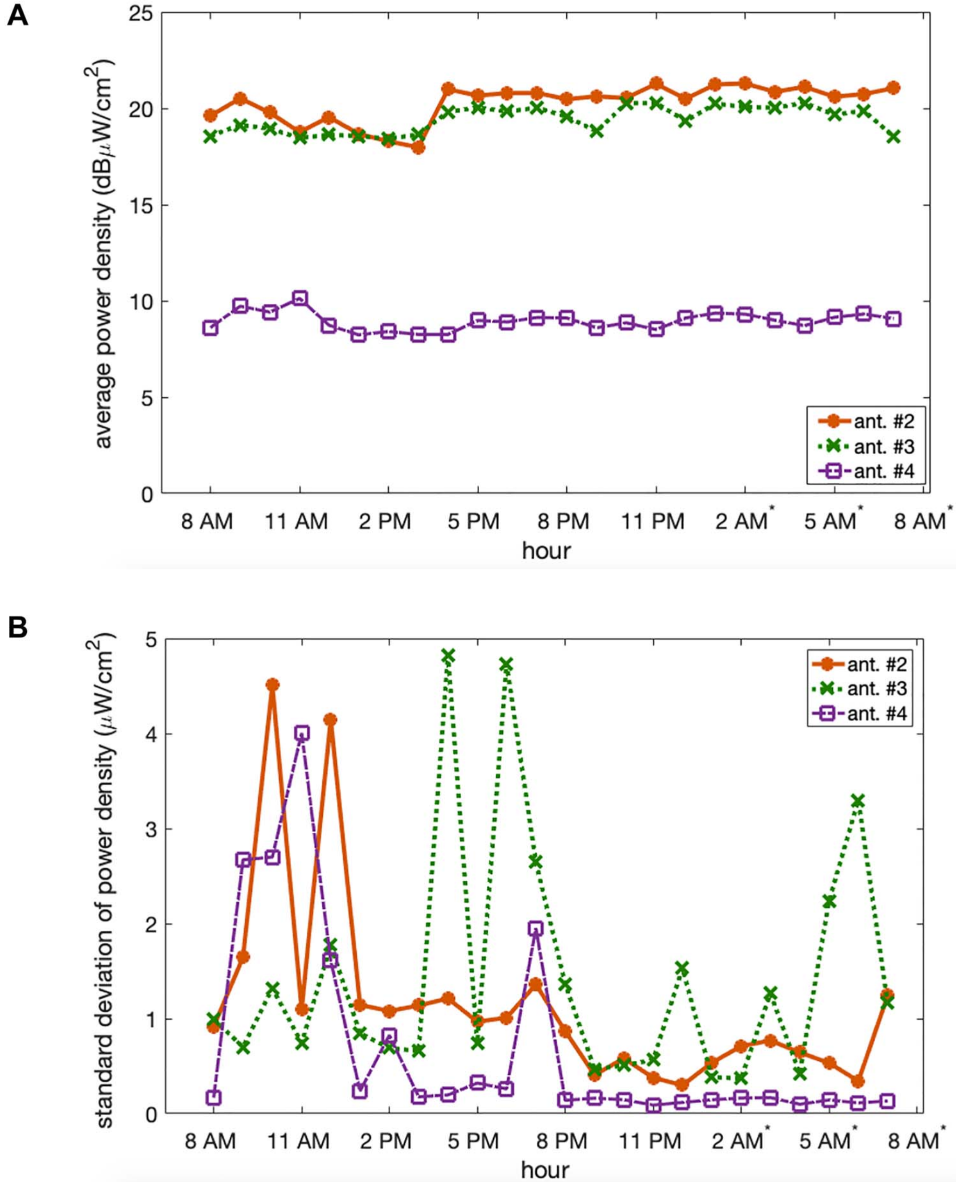

Figure 4: Monitoring power density of BTS 7 in a 24-h period. The power density is measured in the publicly accessible vicinity of bidirectional antennas. (**a**) Average power density, (**b**) standard deviation of power density. Hours of the next day are marked with asterisks.

logarithmic scale in order to include the measured values of the three sectors in the same graph. Analysis of standard deviation of power density (Figure 4b) confirms our expectation that the fluctuations of the received power are minimum late in the night and in the early hours of the morning. Minimum values of standard deviation for antennas #2, #3 and #4, respectively, occur at 12 AM, 2 AM and 11 PM. At these hours, the average measured power density (in Figure 4a) represents S_{BCCH}. Therefore, S_{BCCH} equals 112, 101 and 7 μW/cm^2 at the probe location for antennas #2, #3 and #4, respectively.

The total number of channels for BTS 7 was not readily available to the authors; however, N_{GSM} is reported in the range of 2–8 in the literature[40,41]. Taking $N_{GSM} = 4$ as a typical value, the conservative maximum power density S_{max} is obtained ~448, 404 and 28 μW/cm^2 for the three antennas, respectively. The values of S_{max} for antennas #2 and #3 are close to the 450 μW/cm^2 threshold required by ICNIRP at 900 MHz. It is, therefore, recommended to the university authorities to enforce precautions at the designated locations around antennas #2 and #3 in order to prevent possible exposure of students to high levels of radiation.

The precautions can be either *hard*, i.e. installing a caution sign near the antenna[42], or *soft*, i.e. redecoration of furniture around the antenna. The hard solution may cause panic among students and staff who are already concerned about the possible hazards of RF radiation. The enforcement of soft precaution is recommended such as inserting large flower pots near antennas #2 and #3 on and in front of the bench-like shelf. Those flower pots should prevent students from getting closer than 1–2 m to the antenna. They should not be higher than 1.5 m so that the main beam of the antenna is not blocked. Other decorative options can also be implemented by consulting a professional indoor decorator.

CONCLUSIONS

Compliance assessment of electromagnetic field exposure has been performed in this paper on the campus of Ferdowsi University of Mashhad. A broadband isotropic probe with certified calibration has been used for measurements. Various sources of electromagnetic radiation have been identified and measured at nearby locations accessible to the public. Measurements have been performed by following the recommendations of ITU.

In summary, exposure levels of BTS antennas and WiFi access points all over the campus comply with ICNIRP guideline. More specifically

- Measured power density due to outdoor base stations mounted on towers is <1% of allowed power density. Hence, no action is required.
- Relatively high but compliant field levels have been detected near the rooftop base station. Measured power density is about 4% of the allowed power density on the roof, and up to 14% of the allowed power density on the loft. It is recommended to the university authorities to limit the presence of residents on the roof, and ban their access to the loft.
- Relatively high but compliant field levels have been observed in the vicinity of indoor base stations. Measured power density up to 16% of the allowed power density has been observed in areas accessible to the public. This is mostly attributed to the architectural plan of the Engineering Faculty as well as the high power and directivity of BTS antennas.
- Low field level (<1% of allowed power density) has been measured near WiFi access points.

A comprehensive exposure assessment has been performed to conservatively estimate maximum exposure to indoor base stations. The measurement results show that the maximum power density near specific antennas is expected to be close to the ICNIRP reference level. To limit students' access to those locations, redecoration of furniture around the antennas has been recommended to the university authorities as a precautionary solution. The general conclusion is that comprehensive exposure assessment is likely necessary for indoor base stations whereas such assessment is not usually required outdoors.

Although the measured field levels across the university comply with ICNIRP reference levels, long-term adverse health effects should also be a point of concern when selecting associated strategies. Specifically in the case of WiFi antennas, measurements show good compliance with ICNIRP guideline. However, many residents of dormitories are exposed to access points located inside their rooms. Taking into account the current uncertainties of IARC regarding possible long-term exposure to electromagnetic fields, it is essential that university authorities make every reasonable effort to maintain exposure to radiation as far below the dose limits as practical. This can be achieved primarily by removing WiFi access points that are currently mounted inside the dorm rooms and installing them in nearby hallways. This way, constant exposure of residents are reduced without compromising the network coverage.

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CONFLICT OF INTEREST

The authors declare no conflict of interests.

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