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Full Length Article

Methodology for determining the threshold distance for estimating the main EM exposure contribution in WLAN

Marta Fernández *, David Guerra

Communications Engineering Department, University of the Basque Country, 48013 Bilbao, Spain

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ABSTRACT

The location of radiation sources in wireless networks is a key factor to characterize their contribution to electromagnetic exposure levels in order to deploy future networks that account for minimizing electromagnetic field levels. In relation to wireless local area networks, considering that mobile communication devices comply with the SAR (Specific Absorption Rate) limits imposed by the international standardization organizations for preserving human health, the interest is nowadays focused on the signal levels coming from the WiFi access points. This paper presents a methodology to determine the threshold distance at which the field strength levels from the AP are negligible in comparison with the radiation generated by a user equipment. The theoretical concepts, which can be applied to other technologies, were implemented by means of simulations and experimental measurements. For the simulations, actual WiFi antennas were modelled. Experimental measurements completed the results obtained in simulations, resulting in a greater number of real situations. Results showed that the threshold distance depends on the WiFi standard employed by the devices connected to the network.

1. Introduction

The massive growth of mobile internet applications has raised concerns about human exposure due to WiFi signals, present in more and more public and private indoor environments. These signals are defined according to a family of standards that stemmed from the initial IEEE 802.11, published in 1997 [1].

The good knowledge of electromagnetic (EM) field exposure levels, as well as information regarding the contribution of each radiation source to the total exposure, is essential for two main reasons: give response to public concern, and ensure people's protection against these emissions but without reducing the technological benefits because of overly restrictive deployment policies. Thus, exposure to radiofrequency fields is usually assessed in order to compare measured signal levels with exposure limits. These limits are expressed in terms of basic restrictions and reference levels. The reference levels are employed for a practical exposure assessment, and they can be obtained in the far-field region of the radiation sources [2].

In WiFi networks, there are two types of radiation sources: the Access Point (AP) or hotspot and the User Equipment (UE). All over the world, prior to the commercialization phase, any model of these two types of devices has to pass thorough Specific Absorption Rate (SAR) tests that ensure the fulfillment of the basic restrictions in the near-field region [2], which is a regular use case of most WiFi UEs, but not of APs. Precisely, several distances from an AP should be considered for assessing actual WiFi exposure values other than the worst-case ones, and in order to properly assess the cumulative effect of electromagnetic radiation coming from every WiFi hotspot within the area of interest. In addition, UEs may also produce far-field exposure. This would be the case, for example, of a mobile phone placed on a desk at a far-field distance from the user, or of the person sitting next to a person who is using the phone or the laptop. Finally, while a UE device can remain in stand-by mode, thus ceasing its contribution to the EM exposure, the regular operation of an AP requires the generation of radiofrequency emissions, discovery beacons, regardless of whether a UE device is operating or not.

For all the previous reasons, additional field measurements are usually performed in the far-field region of the vicinity of each AP in order to compare measured signal levels with the reference levels [3–7]. In this regard, it was found that the field strength levels from APs are generally higher than those generated by laptops [8] or that the exposure in the 5 GHz WiFi band is nowadays higher than in the 2.4 GHz frequency band [9]. Furthermore, the position and characteristics of the transmitters were found impor-

* Corresponding author.
E-mail address: marta.fernandeza@ehu.eus (M. Fernández).
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Nomenclature

EIRP	Effective Isotropic Radiated Power
G_R	Gain of the receiving antenna
d_{AP}	Distance between the AP and the receiver
d_{UE}	Distance between the UE and the receiver
d_{th}	Threshold distance
L_{FS}	Free space loss
TH	Threshold
P_{R1}	Received power in downlink transmissions
P_{R2}	Received power in uplink transmissions

Abbreviations

AP	Access Point
UE	User Equipment
EM	Electromagnetic
SAR	Specific Absorption Rate
BW	Bandwidth
SWT	Sweep time
RBW	Resolution bandwidth
VBW	Video bandwidth
CIR	Channel impulse response
LoS	Line of Sight

tant factors that affect EM exposure and should be considered at the network planning strategy for minimizing exposure in future networks [10].

Considering that only measurements performed in the far-field region can be compared with the electric field reference levels [2], the distance in the far-field region where the field strength contribution of a UE is significantly higher than the one coming from an AP is defined in this work for WiFi applications in the 5 GHz frequency band. APs located beyond that reference distance will not be a concern in the analysis of human exposure due to WiFi signals within the area of interest, and the fulfillment of exposure limits could be taken for granted as UEs comply with SAR limits at shorter distances.

Furthermore, the methodology employed in this work can be applied to other technologies and networks, such as Internet of Things (IoT) networks in working environments in which an individual can spend several hours in close proximity to some radiation sources and far from many others.

The remainder of the paper is organized as follows. Section 2 describes the theoretical concepts on which this work is based. Using well-known propagation expressions, a system of equations is proposed to obtain the distance at which the signal strength level generated by the AP is much lower than the signal transmitted by a UE. The descriptions of the simulations and measurements carried out in this work are provided in Sections 3 and 4, respectively. Results are presented in Section 5 and the conclusions are summarized in Section 6.

2. Theoretical calculation

In order to calculate the reference or threshold distance, that is, the distance in the far-field region at which the power strength level due to a UE is significantly higher than the power strength generated by an AP, two scenarios have been defined so that each type of source is characterized separately, as shown in Fig. 1(a) and (b).

Let P_{R1} and P_{R2} denote the power values measured by a receiving system when the wireless signal is generated only by the AP and by the UE, respectively, both in the far-field region. As depicted in Fig. 1, these power levels are obtained when the AP and the UE are located at distances of d_{AP} and d_{UE} from the receiving antenna, respectively. The distance d_{UE} does not have to fulfill any condition other than the far-field region condition. In this work it was considered that the UE was placed at 20 cm from the user. This distance allows us to perform measurements in the far-field region and, moreover, it is consistent with the definition of portable devices, since these devices are defined as transmitting devices designed to be used so that the radiating structures of the devices

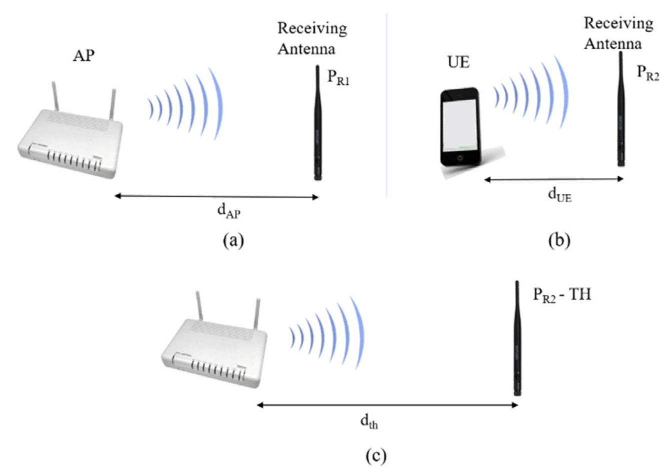

Fig. 1. Scenarios for calculating the threshold distance: (a) AP characterization, (b) UE characterization, (c) estimation of d_{th}.

are at most 20 cm away from the body of the user [11]. Such a maximum d_{UE} will provide a worst case scenario for the analysis of this work, where the AP contribution to EM exposure is maximum with regard to the UE's. It is worth highlighting that EM exposure due to portable devices used in the near-field region must be assessed by means of SAR values obtained by numerical calculations or laboratory tests.

For a specific d_{UE}, it is possible to define the threshold distance d_{th} as the distance at which the power level received from the AP is TH dB lower than the power level generated by the UE (Fig. 1(c)). The calculation of the threshold distance is performed in the far-field region and it is based on the free-space-propagation Friis formula which assumes one Line-of-Sight (LoS) propagation path. This assumption will be discussed in the measurements section of the paper.

Considering that the AP transmits a power level of P(dBm) and that it is characterized by an antenna gain equal to G(dBi) in the LoS direction to the reception antenna, thus being $(P+G)_{AP}$ the EIRP of the AP, we can obtain the following system of equations in logarithmic units:

$$(P+G)_{AP} - L_{FSAP} + G_R = P_{R1} \quad (1)$$

$$(P+G)_{AP} - L_{FSth} + G_R = P_{R2} - TH \quad (2)$$

where G_R(dBi) is the gain of the receiving antenna, and L_{FSAP}(dB) and L_{FSth}(dB) are the free space losses calculated at distances d_{AP}(m) and d_{th}(m) from the AP (see Fig. 1).

$$L_{FSAP} = 20log\left(\frac{4\pi d_{AP}}{\lambda}\right) \quad (3)$$

$$L_{FSth} = 20log\left(\frac{4\pi d_{th}}{\lambda}\right) \quad (4)$$

The threshold distance can be assessed by subtracting Eq. (2) from Eq. (1):

$$d_{th} = d_{AP} \times 10^{\frac{P_{R1} - P_{R2} + TH}{20}} \quad (5)$$

It is worth noting that in this work a threshold level TH = 10 dB was selected for ensuring a one-order-of-magnitude difference of the UE contribution over the AP contribution to the EM exposure. However, a more restrictive threshold level could be selected without any change or additional difficulty of the procedure in order to consider the power of the UE significantly higher than that of the AP.

3. Simulations

The characterization of the radiation sources, i.e. the UE and the AP, was first performed by means of simulations. To this end, the commercial three-dimensional electromagnetic simulation software CST Studio was employed. The AP antenna was designed following the design of [12], since it has the characteristics of a standard AP: the radiation pattern is omnidirectional, the antenna can work simultaneously in the 2.4 and 5 GHz frequency bands and it can be easily fit into the casing of an AP. It consists of a 2.4 GHz monopole and a 5 GHz dipole antenna, made of copper and printed on a 0.8 mm-thick dielectric substrate. The 5 GHz antenna, which is the one of interest in this work, consists of two sub-dipoles printed on both sides of the substrate with a 4 mm ground printed on the top layer. The final design of this antenna is shown in Fig. 2(a), and more details of the 2.4 GHz antenna can be found in [12].

Regarding the UE, a smartphone from the CST Library was selected, which contains the RF systems required for cellular and WiFi applications, as well as standard phone components such as a camera, battery, charging connector or a screen. The electronics of the phone not related to the RF systems are designed as solid metals and it is covered by a plastic housing. The inner side of the smartphone can be seen in Fig. 2(b). It has two PIFA antennas for WiFi applications, which were modified and optimized to work in the WiFi channels of interest (5.49–5.57 GHz), since these were the operating frequencies of the communication link during the experimental measurements (explained in the next section). The dimensions of the PIFA antennas after such optimization are also given in Fig. 2(b). Table 1 shows the gain, the S11 amplitude and the radiation efficiency obtained in simulations for both antennas at 5.51 GHz (in the case of the UE, the antenna was inside the smartphone).

The simulated radiation patterns of the AP and UE antennas can be observed in Fig. 3. In both cases, the radiation patterns are omnidirectional in the horizontal plane and in the case of the AP, the radiation pattern is similar to the typical pattern of a vertical half-wave dipole antenna. The radiation pattern of the UE is influenced by the other components of the phone around it.

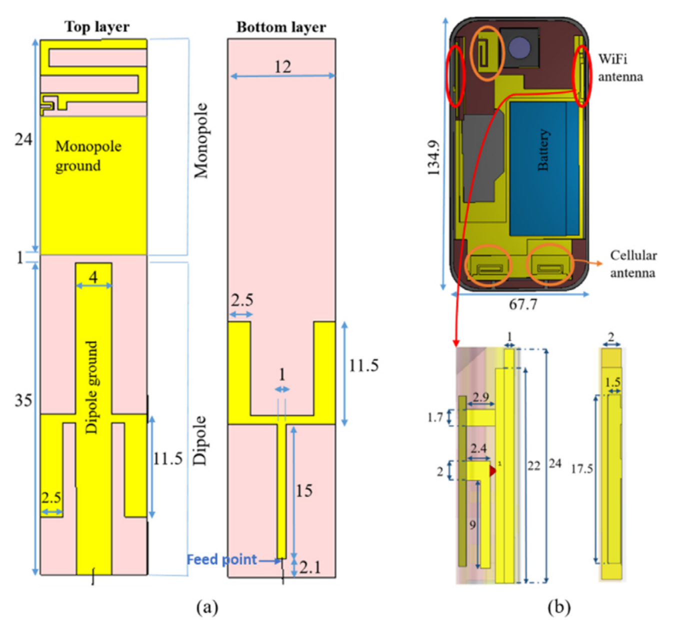

Fig. 2. Antennas designs (dimensions in mm): (a) Top and bottom views of the AP antenna, (b) smartphone and side (left) and top (right) views of the PIFA antenna.

4. Experimental measurements

4.1. Measurement set-up

Experimental measurements were performed to obtain the power strength levels generated by APs and UEs in a laboratory of the University of the Basque Country (Spain), where a Cisco Aironet 1702I-E-K9 access point provides access to the Eduroam WiFi network deployed in the premises of the Faculty [13]. This AP works under the standards 802.11a/g/n/ac and provides a maximum transmitted power of 22 dBm in the 5 GHz WiFi band. The horizontally omnidirectional AP antenna has a gain equal to 4 dBi. During the measurements, this AP was working at frequencies between 5.49 and 5.57 GHz, which correspond to a channel bandwidth (BW) of 80 MHz.

The receiving system was composed of a spectrum analyzer Anritsu MS2690A and an omnidirectional antenna with 3-dBi gain (model VERT2450 from Ettus Research) appropriate for frequencies between 4.9 and 5.9 GHz. The configuration of the analyzer is shown in Table 2, and it is based on [14]. It is widely known that, when measuring WiFi signals, the configuration of the measurement equipment can have significant influence on the results due to the nature of WiFi signals, which are transmitted in the form of pulses of short duration [15]. However, as the experimental tests of this work were made when generating high data traffic, the influence of the measurement equipment was reduced, as demonstrated in [16]. Finally, a laptop running automation software was employed for the collection and convenient storage of the measured data.

Five different smartphones were used as UEs. The main characteristics of the smartphones considered in this study are summarized in Table 3. As shown, all the UEs were using the 802.11ac standard during the measurements and occupying the 80 MHz of the channel, except the UE 1 that was employing the 802.11n standard and therefore using a BW of 40 MHz. The maximum EIRP levels specified in the smartphone guides for the frequency band 5470–5725 MHz are also given in the table.

Table 1
Parameters of the designed antennas at 5.51 GHz.

Antenna	Gain	S11 amplitude	Rad. efficiency
AP	1.66 dBi	−23.12 dB	82%
UE	5.65 dBi	−21.19 dB	96%

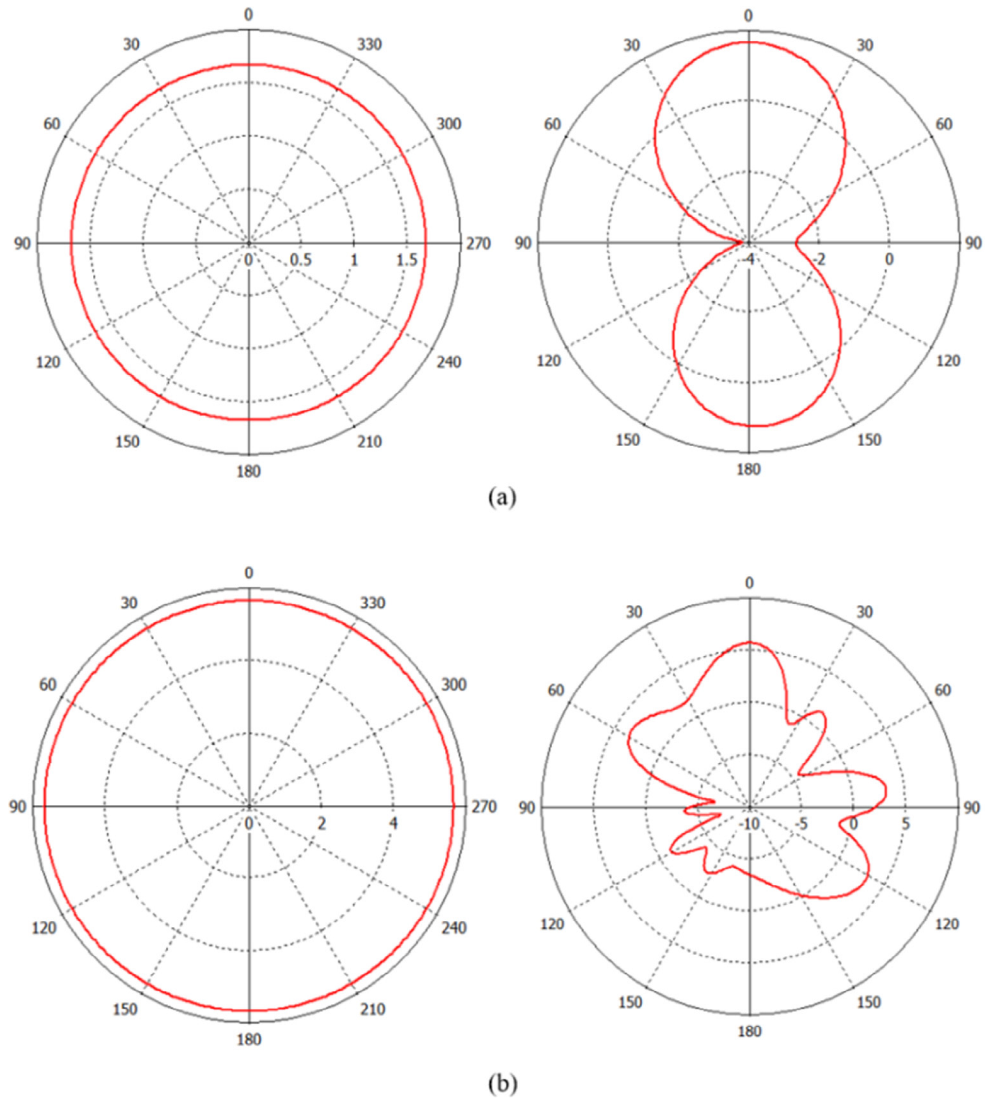

Fig. 3. Simulated radiation patterns in both horizontal (left) and vertical (right) planes (a) for the AP, and (b) for the UE.

Table 2
Configuration of the spectrum analyzer.

Parameter	Value
Centre Frequency	5530 MHz
Span	80 MHz
Detector	RMS
Sweep time (SWT)	5 ms
Resolution bandwidth (RBW)	1 MHz
Video bandwidth (VBW)	3 MHz
Trace Mode	Clear/Write

Table 3
Characteristics of the smartphones in the frequency band of interest.

Smartphone	Standard (5 GHz)	Max EIRP (dBm)	Occupied BW (MHz)
UE 1	802.11a/n	20	40
UE 2	802.11a/n/ac	23	80
UE 3	802.11a/n/ac	24	80
UE 4	802.11a/n/ac	30	80
UE 5	802.11a/n/ac	30 [a]	80

[a] The specific power limit was not found, but in the user manual it is specified that the maximum power is less than the highest limit value specified in the related Harmonized Standard, which is 30 dBm for the corresponding frequency band [17].

4.2. Access point characterization

In this scenario, the signal levels coming exclusively from the AP were measured. First al all, the free space propagation condition of the WiFi signals was verified by calculating the channel impulse response (CIR) of the propagation path. To this end, a network analyzer, a Keysight ENA E5071C, was employed along with two antennas: the same antenna used for reception in the tests and a monopole antenna with roughly the same directivity characteristics of the AP antenna. This analyzer was calibrated with the two connection cables in the interval between 5570 and 5650 MHz, as this was a non-occupied 80-MHz channel adjacent to the one under test. In order to exactly replicate the propagation path under analysis, the monopole antenna was located in lieu of the hotspot while the reception antenna was left on the holder of the measurement scenario. Values of the S21 parameter were measured for obtaining the CIR graph following the procedure described in [18]. This graph verified the free space propagation condition, since the signal level corresponding to the LoS path was 18 dB higher than the one corresponding to next significant delayed path.

Once the free space propagation condition was verified, the receiver antenna was placed at different distances from the AP between 2 and 3 m (in order to get several values of P_{R1} and d_{AP}), while the UE was at least 10 m away from the receiver. This way, according to ancillary measurements, the field strength coming from the UE was at least 25 dB lower than the one of the hotspot. Both contributions occupied the same RF channel, so they were distinguished by changing from downloading to uploading traffic. In order to get the highest power level received from the AP, a large file was downloaded from a local server. Measurement duration was equal to 3 min (shorter than file download) and at least 3 measurements per position were performed in order to ensure repeatability of the results.

4.3. User equipment characterization

To measure the WiFi signals that were coming from the UE in this scenario, the receiving antenna was placed at a distance of 20 cm from it, in order to ensure far-field region conditions ($3\lambda < 17$ cm) [19]. On the other hand, the AP was located at least 10 m far away from the reception antenna, so that the field strength level coming from the UE was 25 dB higher than the one received from the hotspot, according to the results of ancillary measurements. The reception antenna was fixed to a piece of foam attached to the table with adhesive tape, as can be observed in Fig. 4. The UE was fixed on a tripod and, before collecting data, it was placed in an orientation that ensured the highest field strength level at the receiving antenna. In this case, uplink traffic was generated by the UE, uploading a large file to a local server. Measurement duration was also equal to 3 min to ensure data traffic during the whole measurement, and at least 2 measurements per UE were performed in order to get several values of P_{R2} for the calculations.

4.4. Assessment of the influence of nearby APs in the 5 GHz frequency band

As explained in subsection 4.1, the measurements were taken inside a laboratory of the University of the Basque Country, which has one AP installed inside. However, within the University, several APs were working in the vicinity. These APs can work at different channels corresponding to frequencies ranging from 5.17 GHz to 5.71 GHz, and can automatically adjust the channel according to the signals detected in the surroundings, in order to select an unused channel. Particularly, measurements were performed on the 4th floor of the University and there were 11 APs working on this floor. Experimental measurements were performed in the whole 5 GHz frequency band to analyze the effect of other APs on the calculated threshold distance.

A extract of the floor plan of the measurement environment is presented in Fig. 5, where the closest AP corresponds to the transmitter of the laboratory in which the experiments were performed (i.e. the same AP as the one detailed in subsection 4.1). As shown, there is another access point (i.e. AP 2), which was one of the closest APs from the AP of interest. In this case, the signal power levels were recorded at different distances between the red point in Fig. 5 and the AP of the laboratory (Closest AP). This red point was situated at 6.5 m from the AP of the laboratory. As shown, as the receiver was moved away from the AP of interest, it was placed closer to AP 2. As can be observed, each access point was located in a different laboratory of the University, separated by a concrete wall. The results presented in this work will analyze the contribution of these different APs to the total power levels generated in the 5 GHz frequency band.

4.5. Assessment of the influence of multipath effects

The theoretical calculation of Section 2 was based on free space propagation conditions. Nevertheless, even under LoS conditions, sometimes multipath effects can be significant. When multipath propagation exists, the power level received from non-LoS paths is usually lower than the level received in free space propagation due to the attenuation suffered by the signals when they collide with walls or other objects. However, sometimes the total energy received at a point is higher than the energy of the LoS component due to the addition of multipath components. This last case is of interest in this work since if the power level received from the AP increases, the calculated threshold distance would also increase.

In order to evaluate the effect of multipath components on the calculated threshold distance, a model proposed by the IEEE task

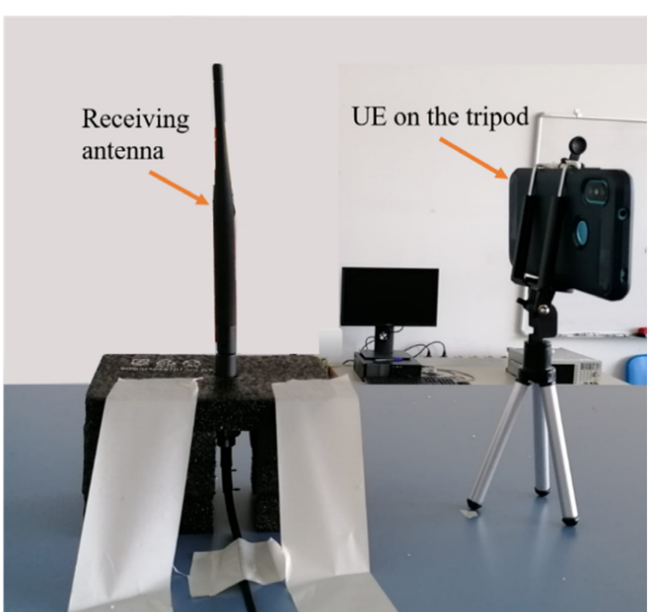

Fig. 4. Measurement scenario for characterizing the WiFi signals transmitted by an UE.

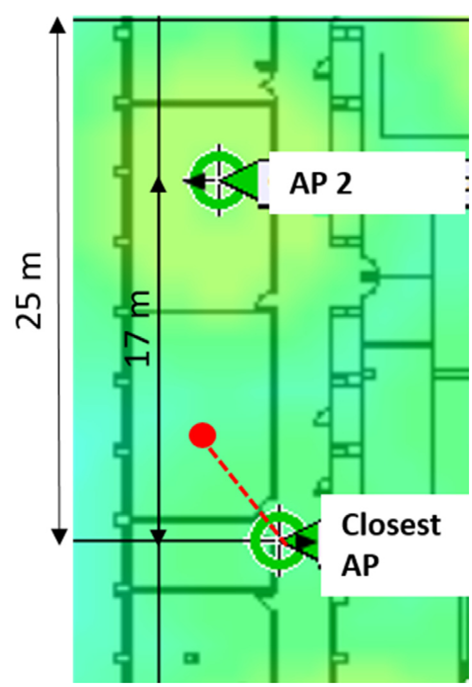

Fig. 5. Floor plan of the measurement environment.

group on 802.11n channel models was employed [20]. In particular, the Model B from [20] was used since it represents a typical channel for large open space and office environments. Table 4 provides the values for the tap delays and corresponding power levels of one cluster. These taps were employed to calculate the total power level received when also multipath components are present, considering that the LoS component, the first one, is the signal received under free space conditions.

5. Results and discussion

5.1. Simulations

It is worth highlighting that although Table 3 reports the maximum EIRP levels that the employed UEs can transmit, the UE usually transmits lower power levels. In this regard, the list presented in [21] shows, among others, the results of transmit power capabilities by many devices when using WiFi at 5 GHz. The maximum transmitted power by the smartphones of that study took values between 14 and 30 dBm. Furthermore, as WiFi signals are transmitted in the form of pulses, the mean power level transmitted for a specific period of time will be significantly lower even in high traffic conditions [16]. For this reason, simulations were performed for UE transmitted power levels ranging from 10 to 30 dBm, while the AP was transmitting 22 dBm. Fig. 6 shows the threshold distance d_{th} estimated using Eq. (5) from the data obtained in simulations, when the UE was placed at 20 cm from the receiver, this is, in the case in which the UE would be at 20 cm from the user. As shown the highest d_{th} was 1.92 m. Thus, according to the simulations results, being at a distance higher than 1.92 m from the AP would ensure that the signals generated by the AP are negligible compared to the signals transmitted by a UE located at 20 cm or closer to the body.

5.2. Measurements

For calculating the threshold distance, the 90th percentile (P90) of the measured data was employed, since it is considered an appropriate statistic for representing the WiFi exposure variations [14]. Table 5 reports the measured levels at frequencies between 5.49 GHz and 5.57 GHz (i.e. considering only the closest AP), when the AP was generating data at different distances from the receiver, and when the UEs were transmitting WiFi signals at 20 cm from the receiver.

Fig. 7 shows the calculated d_{th} for the different UEs. The black error bars represent the differences in the results due to the different values of P_{R1} and d_{AP} (as expected, in simulations d_{th} took the same value for different d_{AP}). As shown, the highest d_{th} was obtained for UE 1, which makes sense since this UE only employed 40 MHz to transfer data, while the o'ther UEs employed the 80 MHz bandwidth of the WiFi channel, so the signal power level received for these UEs was higher than for the UE 1 (see Table 5). For the other UEs, d_{th} took values from 1.64 to 2.16 m, which means that being at a distance higher than 2.16 m from an AP ensures that the EM radiation coming from the AP is negligible in comparison to the radiation from these UEs (using 802.11ac standard) placed at 20 cm or closer to the user. Regarding emissions from APs, two main parameters must be considered, namely, transmitted power and distance. Hence, for a specific data traffic and a specific AP with a specific transmitted power, it was found that the distance between the AP and the measuring point was the only parameter that influenced the results under free space propagation conditions (see section 5.4 for multipath channel effects). However, if data traffic is lower than the one considered in this study (in which the highest traffic was considered for AP and UEs), measured emissions would be reduced for the same distance. An example of exposure levels generated by an AP for different traffic conditions can be observed in [16].

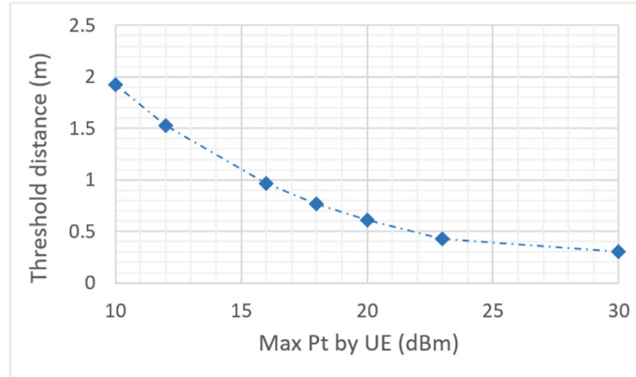

Fig. 6. Threshold distances obtained in simulations for different maximum transmitted power levels by the UE (when d_UE = 20 cm).

Table 5
Measured power levels when generating traffic from the AP or from the UEs.

Parameter	P90 (dBm)
P_{R1} (d_{AP} = 2.2 m)	−46.10
P_{R1} (d_{AP} = 2.9 m)	−49.04
P_{R2} UE 1	−43.21
P_{R2} UE 2	−34.09
P_{R2} UE 3	−35.95
P_{R2} UE 4	−34.48
P_{R2} UE 5	−34.29

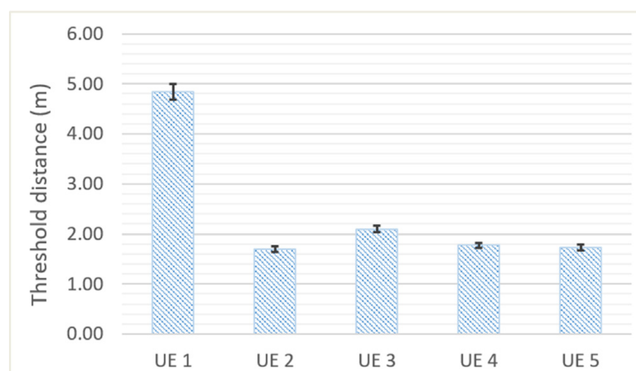

Fig. 7. Threshold distances obtained from the experimental measurements.

Table 4
Values of the tap delays and power levels of the selected model [20].

Tap index	1	2	3	4	5
Delay (ns)	0	10	20	30	40
Power (dB)	0	−5.4	−10.8	−16.2	−21.7

Comparing the results obtained by means of simulations and measurements, there are several reasons for obtaining shorter distances when using simulated data than when employing measured data. First of all, simulations were carried out for a continuous signal. However, WiFi signals are transmitted in the form of bursts. As measurements can account for those periods of time in which the signal is not being transmitted, measured power levels are lower. Moreover, although the maximum transmitted power levels specified in the smartphone guides were used for simulations, it is probable that the UE employs lower power levels in a real situation. Finally, an example of a UE antenna was selected for running the simulations, which resulted in an antenna gain equal to 5.65 dBi. But the employed UE can use a different type of antenna with different antenna gain.

In view of these results, one crucial consideration must be made. Although it may seem that higher power UEs allow lower threshold distances to APs, it must be clearly stated that this allowance refers to and only to assessment purposes. From the safety point of view, the situations with lower threshold distances are to be avoided by all means.

5.3. Influence of nearby APs in the 5 GHz frequency band

Fig. 8 shows the received signal trace after 6 min of a max-hold measurement in the 5 GHz WiFi band, when placing the receiver at 3 m from the closest AP (see Fig. 8(a)) and when the receiver was at 5 m from that AP (see Fig. 8(b)). These measurements were taken in normal working conditions. Thus, there were different UE connected to the different APs of the university, including the closest AP. Moreover, for taking these measurements, LoS conditions between the closest AP and the receiver were ensured, but in this case the free space propagation condition was not checked in order to consider the whole multipath working environment.

Although in the 2.4 GHz frequency band signals transmitted by other APs were noticeable in the measurements when the receiving antenna was placed at 3 m from the AP of interest, at 5 GHz, as shown in the figure, signals coming from other APs could not be distinguished from that position. This difference can be explained because of the shorter wavelength and higher attenuation at higher frequencies. However, at 5 m from the AP of interest, some power level transmitted by other AP can be observed in the lower channels of the 5 GHz WiFi band. To account for the contribution of this second AP, additional measurements with a duration equal to 6 min were performed at a distance of 5 m:

- First set: 3 measurements were performed in the frequency range of the closest AP (between 5.49 and 5.57 GHz).
- Second set: One measurement of the receiver noise level was taken in the 5 GHz WiFi band, except in the frequency range from 5.49 to 5.57 GHz.
- Third set: 3 measurements were carried out considering the whole 5 GHz WiFi band.

Received power levels from the first and second sets were added and this resulted in power levels similar to those recorded in the third set, being the signals coming from the other AP therefore negligible. Table 6 provides the 50th and 90th percentiles of the results obtained in these sets of measurements.

Regardless of the effect of signals coming from other APs at 5 m from the AP of interest, this distance is higher than the calculated threshold distances, so in any case, additional measurements should be performed at such distances from the AP if information about radiation sources is required.

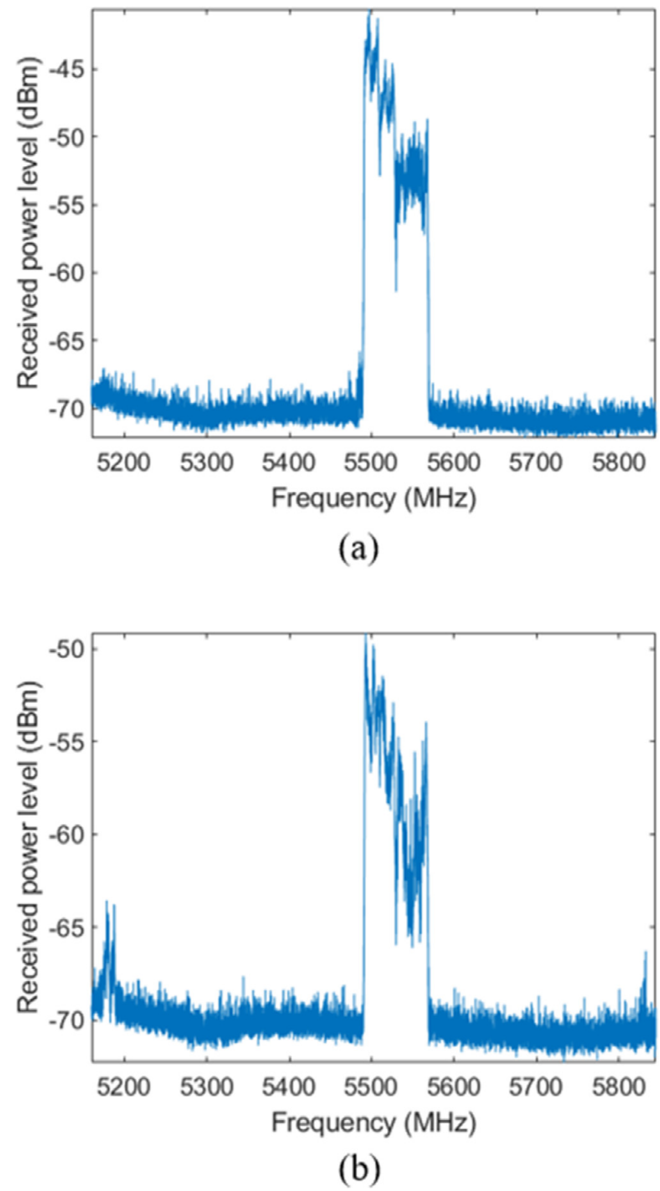

Fig. 8. Power levels received at different distances from the closest AP: (a) at 3 m, and (b) at 5 m.

Table 6
Measured power levels at 5 m from the closest AP.

Percentile	Channel measurements + band noise (dBm)	WiFi band measurements (dBm)
P50	−51.82	−51.69
P90	−51.14	−51.55

5.4. Influence of multipath effects

Received signal power levels were calculated considering the multipath channel model for the signals generated by the AP when the receiver was placed between 2.2 and 2.9 m from it. From these values, the threshold distances were calculated following the same procedure as the one applied in subsection 5.2. For the UEs, the received power levels of Table 5 were employed.

Fig. 9 shows the results of the new threshold distances obtained for multipath channels (red columns). For comparison purposes, the values of these threshold distances are given together with

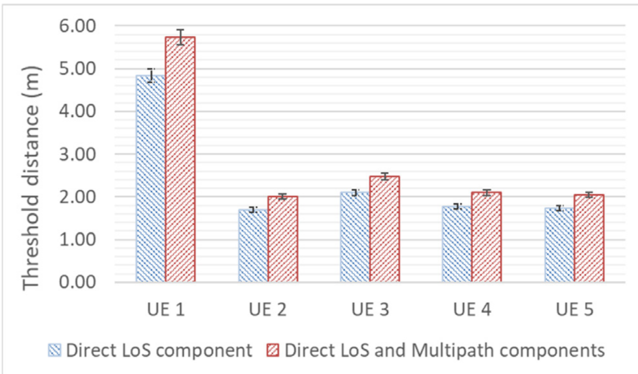

Fig. 9. Threshold distances obtained in free space propagation conditions and in multipath channel models.

the previously calculated threshold distances under free space conditions (blue columns). The black error bars represent the differences in the results due to the different values of power levels measured at different distances from the AP. As can be observed, calculated threshold distances in multipath environments took values between 5.55 m and 5.92 m for UE 1 and between 1.94 m and 2.57 m for the rest of the UEs. Again, the differences in the obtained results between UE 1 and the other UEs is due to the WiFi standard employed by the UEs. During these measurements, the UE 1 was employing the 802.11n standard and therefore using a BW of 40 MHz, while the other UEs were employing the 802.11ac standard and 80 MHz bandwidth.

Finally, Table 7 shows a comparison of the threshold distances obtained from simulations and experimental measurements taken under free space propagation conditions. The table shows the threshold distances obtained for UE transmitted powers ranging from 10 to 16 dBm in the simulations, which better fit the experimental setup.

6. Conclusions

The contribution each of the EM sources to the total exposure in wireless networks is an essential parameter for characterizing EM exposure and develop network deployments that minimize EM field levels. This manuscript presents a methodology for determining the distance at which the EM field levels transmitted by an AP can be negligible in comparison with those transmitted by a UE in order to simplify the assessment of the total exposure. This can also give information about the positions in which measurements should be taken in future measurement campaigns.

In the proposed methodology, the threshold distances were calculated for a specific distance of the UE. In this work the threshold distance was determined by means of a rigorous methodology assuming the worst case scenario, that is, full activity of the WiFi network, 90th percentiles, and a distance of 20 cm between the UE and the reception point. This distance allows us to perform measurements in the far field region and, it can represent scenarios in which a smartphone is placed on a desk at 20 cm from the user, or scenarios in which the exposure is due to the UE of another person. Moreover, it is consistent with the definition of portable devices, since these devices are defined as transmitting devices designed to be used so that the radiating structures of the devices are within 20 cm of the body of the user [11]. Thus, in the selected conditions the results provide the largest threshold distance when the own user or the person next to him/her is exposed to radiation coming from the UE. However, for people who are at greater distances from the exposure source, the threshold distances would be longer. This way, under free space propagation conditions, threshold distances ranging from 1.64 m and 4.99 m were obtained for the cases of hotspots transmitting 160 mW with bandwidths of 80 MHz and 40 MHz, respectively. This distances can increase in multipath environments as demonstrated in Section 5.4, where a maximum threshold distance of 5.92 m was obtained. In all the cases, if the UE was placed closer to the human body, the threshold distance would be lower. This conclusion may lead to a misconception that needs to be clarified. The results point out that the higher the UE power is, the lower threshold distance to the AP is allowed. However, regarding safety as the main scope of this type of research, such threshold situations characterized by maximum power UEs and minimum distances to APs should be avoided by all means. That is, the higher the threshold distance is, the better the exposure scenario will be.

Experimental results showed that the threshold distance depends on the bandwidth employed by the communication link, which is related to the WiFi standard employed by the AP and UE. Furthermore, measurements in the whole 5 GHz WiFi band were carried out in a university environment and it was proved that WiFi signals coming from further APs have lower influence than at 2.4 GHz due to the higher attenuations suffered at higher frequencies. Finally, the threshold distances were also calculated in multipath environments.

The proposed methodology ensures that WiFi APs will not be a matter of concern if the user is located at larger distances than the threshold distance. On the contrary, measurements of the radiation coming from the hotspot would be needed at shorter distances, in order to check the compliance with the reference levels.

Finally, the duration of signal transmission may be of great interest when assessing EMF exposure, especially in places where people spend many hours such as schools, universities or offices. In this regard, WiFi exposure levels at 2.4 GHz were evaluated by means of 24-hour measurements in a university environment in [14]. As can be observed in Fig. 4 of [14], WiFi signals transmission increased in working days compared to weekends. But even during working hours, WiFi activity and therefore AP and UE transmissions varies from one location to another inside the same building.

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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Table 7
Comparison of threshold distances obtained by means of simulations and experimental measurements under free space propagation conditions.

Simulations	**UE Power (dBm)**	**16**	**12**	**10**		
	Threshold distance (m)	0.96	1.53	1.92		
Measurements	**UE**	**UE 1**	**UE 2**	**UE 3**	**UE 4**	**UE 5**
	Mean threshold distance (m)	1.69	1.73	1.77	2.10	4.84

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