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Measurements of Human Exposure to EMF from 4G systems: some experimental issues in urban environments

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Abstract. Assessments of human exposure to EMF in urban environments represent one of the most complex tasks because of the factors causing large temporal variations and spatial non-uniformities of the measurement results among which are increased number of RF sources, numerous reflections, and scattering objects. In this sense, human exposure to 4G systems became a real challenge due to its current wide spreading. Following the guidelines provided by the relevant technical standards in force, this paper describes the experimental results achieved by performing a long-term analysis for several days and weeks on three network operators and three frequency bands adopted in Italy for 4G communications. In particular, the stability of the 4G pilot signal levels, i.e. PBCH, is analyzed. Indeed, such a level is involved in the maximum extrapolation techniques which should always warrant worst-case and time-independent estimations of the maximum E field. The effects of the averaging time on raw data is evaluated for quantifying its effect on the possibility of reducing the variability of human exposure assessment based on the use of the extrapolation techniques. Another important issue that is related to exposure safety requirements is the determination of compliance boundaries from RBS transmitting antennas (when put into service), mainly estimated by measurements and calculations (or simulations) for the areas accessible by the general public. In this regard, here are illustrated examples for measurement and simulation approaches for a roof terrace exposure conditions at two different locations in Austria.

1. Introduction

The continuous spread of 4th generation (4G) cellular networks is in close connection with humans' growing need for using communication devices exploiting the 4G assigned frequencies. From one side, the high variations of 4G data and voice traffic (also due to the multipath propagation [1]) make reliable human exposure forecast very difficult. On the other side, an objective forecast of EMF (Electromagnetic Field) levels is important. To mitigate these issues and to control the impact of EMFs on the population, the standards (international and national ones) that limit the exposure of different RF-EMF (Radiofrequency-Electromagnetic Field) sources (both in the near- and far-field zones) are recently redefined [2-3]. Since most users are primarily exposed to the EMF radiation of their mobile phones (near-field exposure), EMF levels coming from them are of huge interest to the scientific community. In that sense, some factors (not only the SAR parameter) such as the device's instantaneous radiated power, a duty cycle of the signals, or its crest factor (CF) have to be taken into consideration during various operation situations. Some investigations aimed to identify the gaps in the time-amplitude variation of the emitted signals from devices connected to 4G-LTE (Long Term Evolution) and 5G-NR (New Radio) cellular network in very close proximity to the human body are made in the previous two years for completion of new metrics considering external physical quantities, such as Instantaneous Power

Density (IPD) [4-6]. In addition, a comprehensive understanding of the user exposure's dynamics could be achieved by applying the method based on CCDF (Complementary Cumulative Distribution Function) information in conjunction with a signal analyzer and a specific-developed software [7].

Similar to questioning the near-field exposure assessment methods, in more recent literature [8-11], it has been illustrated how factors such as instrument settings and time intervals in which measurements are recorded, can largely affect the measurement results and their repeatability. In some cases, such effects were comparable to or even higher than typical uncertainty components of the measurement chain. Additionally, in [8-11] has been proved how the variability of EMF levels during the day and week, can be considered as either bias and/or measurement uncertainty components, thus making the actual human exposure evaluation unpredictable or unreliable. In particular, starting from the technical standards in force [12-13], an improved measurement and post-processing procedure was proposed, under the assumption that a basic Spectrum Analyzer (SA) is adopted as a measuring instrument. The focus has been devoted to examining the pilot signals' power consistency (i.e., stability analysis of the PBCH, Physical Broadcast Channel) for three operators and three frequency bands.

Another important issue that is related to exposure safety requirements is the determination of compliance boundaries from RBS (Radio Base Station) transmitting antennas (when put into service), mainly estimated by measurements and calculations (or simulations) for the areas accessible by the general public. In principle, determination of the compliance boundaries can be determined by different methods described in [12]. Especially, in cases where measurements involve considerable efforts, usually in terms of time (i.e. long-term field analyses are not possible) different approaches could be taken. This considers the fact that the calculation of the safety distances from RBS antennas could be determined in advance. Such approach also involves the visual inspection of the site by checking whether there is a publicly accessible area within the compliance boundary or not. For this evaluation, a multi-stage procedure can be used, always considering relevant sources, as required by [12]. For example, the corresponding compliance distances are calculated according to the box-shaped compliance boundary as defined in Section 6 of [12]. This procedure has to be done for every new RBS and relevant upgrades. If accessible areas are identified in such cases, either an alternative position for the new RBS is planned, or compliance can be demonstrated using a simulation tool calculating the compliance boundary as an iso-surface considering precise antenna parameters and environmental conditions. However, the limitations of simulation tools primarily lie in the exact replication of the environment as a complete 3D scenario such as buildings, rooftops, trees, etc. Therefore, in individual cases, it is unavoidable to perform measurements. Besides the necessary access to the measurement point, the situation could become even more difficult in case of conducting measurements in private facilities such as houses, flats, private roof terraces, etc. In situations of detailed analysis of compliance it must be ensured by the suitable methods, given in [12], that the reference levels are complied with the safety limits at any time of a day (taking into account the averaging time of the relevant guideline or standard) and in any possible operating state of the RBS.

Since a long-term measurement is hardly possible in these situations, a constant part of the signal is measured (i.e. PBCH if basic SA is used or CRS (Cell Specific Reference Signal) in case of VNA (Vector Network Analyzer)), and the actual or theoretical maximum possible exposure is calculated based on it. In case the pilot signal PBCH is observed (as done in this paper) for EMF exposure assessment purposes, it is of great importance to derive its better stability using different trace processing and averaging techniques which will be described in detail in the following subsections.

2. Materials and Experimental procedure

2.1. Testing scenarios for experimental long term-analysis

For analyzing the RF-EMF emitted by a 4G LTE RBS it is necessary to focus the attention to the LTE downlink (DL) physical signal. This signal adopts an OFDM (Orthogonal Frequency Division Multiplexing) scheme which divides the transmission bandwidth into several subcarriers with equal spacing (15 kHz), and each subcarrier can be modulated with a different modulation scheme [14]. The smallest entity that can be scheduled in the frequency domain is the Resource Block (RB) and it is composed of 12 consecutive subcarriers, with a bandwidth equal to 180 kHz.

As DL transmissions regards, LTE standard defines many physical channels. Among them, the PBCH is considered for RF-EMF intensity evaluation, because the power associated with the PBCH is independent of the channel bandwidth of the LTE signal. This is due to the fact that it occupies a bandwidth of 6 RBs, approximately equal to 1 MHz, and it is at the center frequency of the LTE signal.

As the LTE human exposure evaluation concerns, [12] introduces an extrapolation techniques, for the assessment of the maximum exposure level from an LTE RBS, which makes use of a basic SA equipped with zero–span measurement mode for measuring the PBCH power (P_{pbch}).

The SA settings suggested by [12] for measuring the PBCH power are described below:

- set the center frequency equal to the LTE signal center frequency;
- set the frequency span equal to 0 Hz (zero–span mode);
- set the RBW (Resolution Bandwidth) equal to 1 MHz, for assuring to integrate the entire PBCH;
- set the sweep time equal to 70 µs times the number of trace points for assuring an integration time approximately close to the symbol duration for each trace point;
- set the RMS detector;
- set the max–hold functionality selected with a minimum time equal to 20 s.

Applied the above–mentioned settings, P_{pbch} is equal to the measured peak value of the displayed trace. It is worth noting that the PBCH measurement is closely connected to the maximum field extrapolation analytical formulation, reported in eq. 1.

$$E_{max} = \sqrt{nPBCH}E_{PBCH} \quad (1)$$

where n_{PBCH} is a constant multiplication coefficient taking into account the signal bandwidth and E_{PBCH} is the electric field associated to the acquired PBCH signal power.

The measurement set-up reported in Figure 1 has been adopted to perform the experimental campaign able to gather data coming from three MNOs (Mobile Network Operators, later simply named OP (Operators)), operating in Italy and simultaneously trasmitting from the same RBS. Each of the MNO has three frequency bands where to deliver its signal, 800 MHz (B1), 1800 MHz (B2), and 2600 MHz (B3), except for OP2 in the considered test-site at the second floor of a University building in Cassino (Italy). The set-up includes an active directional antenna, namely the Rohde & Schwarz HE300A log periodic antenna, a basic SA (Rohde & Schwarz FSH8 Handheld SA having a 9 kHz – 8 GHz frequency range, characterized by a measurement uncertainty lower than 1 dB with a 161 dBm sensitivity, and a PC (Personal Computer) running a Matlab™ script to get, process and remotely store (in a Cloud Space) acquired data. The acquisition process is designed to get one full week of data for each OP and each frequency band. The whole measurement campaign lasted 8 weeks. Measurements have been carried out according to the international standards regulating the applicability of ET (Extrapolation Techniques) [12-13].

2.2. Testing scenarios for determination of the compliance boundary

In terms of determination of the compliance boundary, measurement and simulation analyses were carried out at two different locations in Austria. The measurement was conducted at site on a rooftop in the north of Vienna (Figure 2) (observed RBS at the time was also equipped with GSM and UMTS in the 900 MHz and 2100 MHz frequency bands). The attic of the building was reconstructed into apartments and terraces were built. The terrace is located in the immediate vicinity (less than one meter) near one of the two poles used for the antennas. The initial inspection showed very quickly that the terrace was too close to the antennas and a reconstruction of the RBS was initiated. The pole of the antennas near the terrace was removed and the antennas were moved to the second pole, representing more distant antenna support (behind the satellite antenna, an old pole which was dismantled, is still visible in Figure 2). This reconstruction work could be evaluated directly on site, as unhindered access was still possible. This verification measurement took place on 27.09.2013 between 10:30 and 12:30. Due to the undisturbed conditions in the direct vicinity of the antennas and to be able to work in a time- saving manner, the individual measurement runs were reduced, so the 6-min measurements were not necessary. The exact position of the measurement point was determined on one hand based on the positional relationships of the main beam directions and the other hand by a preliminary measurement to find the points of maximum exposure. At two points where the highest exposure was determined, measurements were made on a tripod at three heights (170 cm, 150 cm, and 110 cm) according to [15] (applicable at that time). Considering the measurement setup in this case, a hand-held SA Narda SRM-3006 was used together with a 3D isotropic antennas Narda 3502. This antenna covers a frequency range from 420 MHz to 6 GHz. The expanded measurement uncertainty of the instruments together with the 1.5 m long cable is in range +3.1 to -4.9 dB (confidence interval 95%) for the frequencies between 420 and 6 GHz.

During the measurements, overview measurements in the frequency range from 420 MHz to 6 GHz were performed to identify all the sources that may be present at the measurement site. In Figure 3 the result at a height of 150 cm is presented. Dominant signals were GSM at 900 MHz, GSM 1800 and UMTS at 2100 MHz. As can be seen, there was not traffic present at the time of measurement, so extrapolation to maximum possible values for checking compliance is necessary.

To make this measurement reproducible, the main measurement setting of SRM-3006 were as follows: RBW 500kHz, VBW was switched off, sweep time 1,081 sec for the isotropic measurement (there are three antennas inside the used 3502 antenna from NARDA, whereas the measuring instrument use one antenna after the other, therefore, having the antenna as quasi-isotropic), and measuring time less than one minute to have an overview and to save the time spent on the field. No other relevant source were identified (5% of the limit as defined in [15]) in this frequency range. Green line from Figure 3 represents an Average values averaged over 4 runs, whereas magenta line represents the Standard in force as defined in [16-18]. In parallel, a broadband measurement from 100 kHz to 6 GHz (using Narda NBM-550 Broadband Field Meter with the E-Field-Probe EF 0691) was performed. If these results match as far as possible, it can be assumed that no other relevant sources are overlooked. For an accurate assessment of mobile communications, frequency-selective measurements are carried out with the NARDA SRM-3006 in all downlink ranges of mobile communications that were present atthe measurement site and, at locations where necessary code-selective measurements are also carried out for UMTS, LTE and, more recently, for 5G.

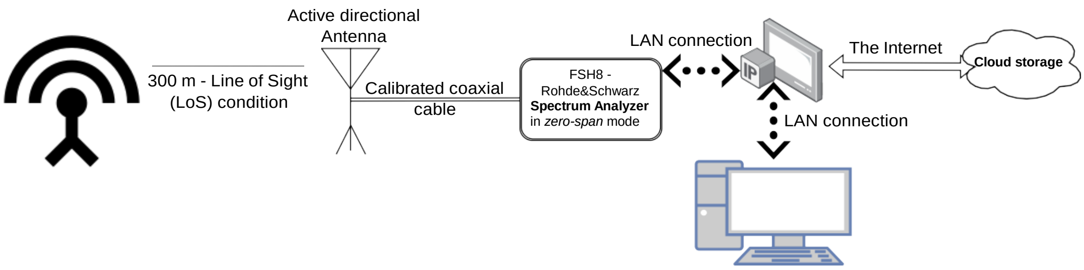

Figure 1. The adopted experimental set-up.

In the second example, a measurement was not possible because the site was in the planning phase. Therefore, the simulation analyses involved mobile communications systems from all three operators in Austria on the tower of a historic castle in the north of Lower Austria. This tower has a viewing platform that was originally closed for public access. However, since this platform is again being used for public access and compliance with the safety distances could thus no longer be guaranteed, the site was reconstructed. This had to be solved in close coordination between the radio-technology requirements and the monument protection authorities. The result, in terms of compliance with the reference levels, was a compromise to place the antennas on the highest possible position on a central mast. One operator left the antennas on the outside of the parapet to the viewing platform and two operators including A1 positioned the antennas on a central mast. To ensure compliance with the reference levels for all the operators in the planning phase, a simulation of the safety distances was carried out in advance, considering all the relevant sources. The software EMF Visual [19] was used for this purpose. It is an EM exposure simulation software that can accurately simulate exposure in both near- and far-fields of the antennas. It can also consider its environment and other sources of EMFs. The computation is based on the ray-tracing techniques. The user can select the mesh size of the computation volume and use a non-uniform grid in order to improve the resolution around the antennas and save computation time. Concerning a simulation, the environment of the antennas must be simulated as accurately as possible. In a first step it is necessary to define the complete 3D scenario. This means that at least the nearest environment surrounding the RBS must be reproduced three-dimensionally. It can be done directly in the software based on existing components provided with the software (buildings, ground profiles, etc.) or by rebuildingit in CAD (Computer-aided Design) software. Furthermore, the antennas of all operators (in this case 3 3 antennas) have to be positioned exactly like in reality. In addition, radio parameters (antenna type, maximum antenna input power per system, frequency range, down tilt) of all operators must be available.

2.3. Pilot signals stability analysis for evaluating the repeatability of the PBCH power measurement

To evaluate pilot signal power constancy, a suitable figure of merit, namely $R_{MAX,min}$, has been defined as in eq. 2.

$$R_{MAX,min} = 10log_{10}(\frac{\max(P_{pbch})}{\min(P_{pbch})}) \quad (2)$$

In eq. 2, P_{pbch} is the power obtained by acquiring the PBCH pilot channel. The meaning of the proposed figure of merit is to quantify the distance (in decibel, dB) between the maximum and minimum values experienced during a day-time acquisition. The lowest $R_{MAX,min}$, the better the signal stability and, consequently, the closer the theoretical hypothesis of PBCH signal constancy. In an ideal case, $R_{MAX,min}$ should be equal to 0 dB.

Figure 2. View of the rooftop terrace in the north of Vienna with RBS and measurement point chosen for compliance boundary assessment.

2.4. Experimental analysis for evaluating compliance boundary assessment

Before RBSs are put into service following the Product standard [20], it is necessary to conduct EMF compliance assessments to make sure that such RF sources satisfy relevant regulatory requirements on EMF exposure. The purpose of these assessments is to determine compliance boundaries always taking into account all relevant sources outside which the RF-EMF exposure is below the applicable exposure limits. The distance at which the exposure level is always below the limit is called the 'compliance distance'. The compliance distance may be based on the evaluation of several parameters such as field strength, power density, or SAR (primary for small cells, portable devices, and tablets). In either case, the compliance distance provides a conservative safety margin. Concerning the field distribution around RBSs, two main approaches, such as measurements and calculations (simulations), can be applied to get an insight into the EMF exposure levels in its immediate vicinity.

As for the measurement approach, EMF exposure can be determined by measuring the actual value of exposure and calculate the maximum possible theoretical or actual maximum exposure as defined in [12], whereas calculating the maximum usually includes post-processing.

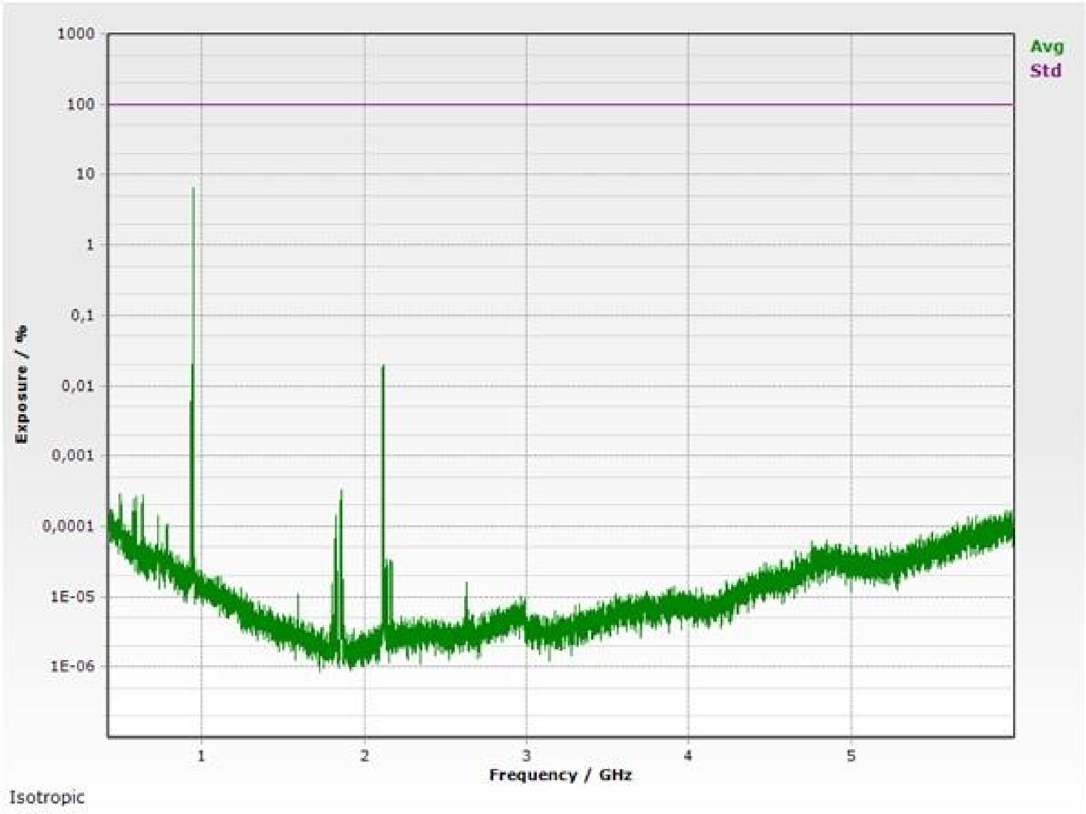

Figure 3. Spectrum overview at the measurement site located on the rooftop terrace in the north of Vienna.

Therefore, it is of great importance to derive better stability of traffic independent pilot signals using different trace processing and averaging techniques which are used in the calculations of compliance boundary exposure as well.

As for the calculation (simulation) approach, a multi-stage procedure is often used. This includes some of the following steps such as (i) Calculation of the safety distance (only as a single distance) with the far-field formula (if no area with public access is near then no further step might be necessary), and (ii) Calculation of the compliance distances according to the box- shaped compliance boundary as defined in Section 6 of [12] (here also applies: if there is no public access within the box-shaped compliance boundary no further step might be necessary). However, if there is public access, then step (iii) Reconstruction and/or simulation of the RBS site is necessary.

In situations of detailed analysis of compliance, it must be ensured that the reference levels are complied with the safety limits at any time of the day (taking into account the averaging time of the relevant guideline or standard) and in any possible operating state of the RBS.

3. Results and Discussion

For the sake of clarity, here are presented and discussed the results of long-term and compliance boundary measurements as well as the results of simulation analysis. In addition, conclusions that follow are based on the behavior observed during the whole measurement period.

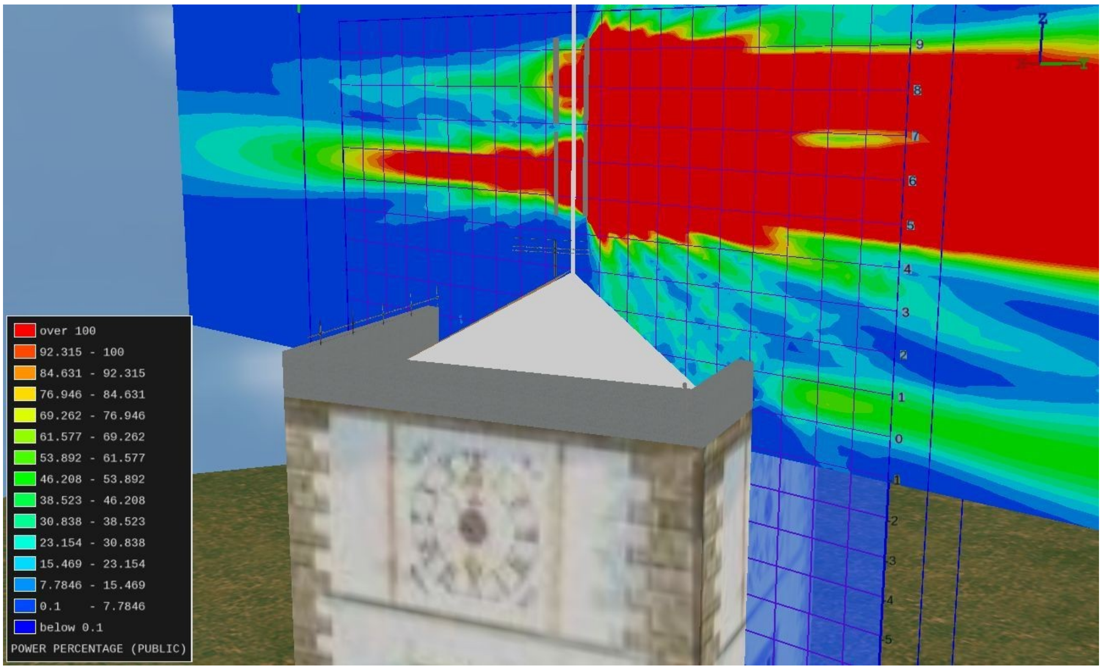

Figure 4. Simulation analysis for two RBSs situated on the central mast of a historical castlein the north of Lower Austria.

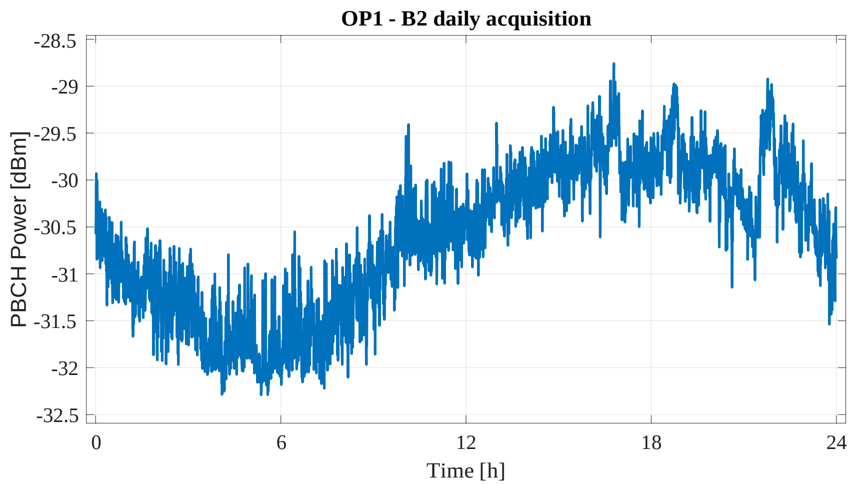

Figure 5. OP1–B2 daily acquisition - PBCH signal power

In particular, as for the experimental tests related to the PBCH signal power measurements, two kinds of analyses will be described: the former shows the behaviour of $R_{MAX,min}$ when applied on row data (collected each 20 s), whereas, the latter shows the effects of different averaging times on such a figure of merit.

Considering the determination of compliance boundary for the measurement site illustrated in (Figure 2), the measurement results were evaluated for maximum possible exposure and the

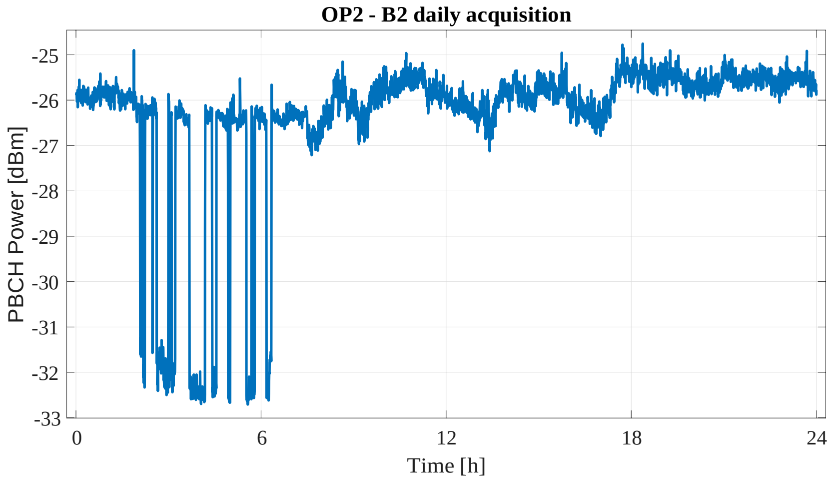

Figure 6. OP2–B2 daily acquisition - PBCH signal power.

measurement uncertainty specified by the manufacturer of the measuring device was added to the measurement results. After that, the average of the three measured values was taken. The results, in this case, were significantly below the reference values with a maximum of 19.38% of the reference level. Since access to the terraces was no longer possible after this detailed evaluation, the extension with LTE was carried out by calculations according to the far-field formula, considering the corresponding angular attenuations of the antenna according to [12]. Since the calculation results were also significantly below the reference values, the extension with LTE (in the 800 MHz frequency range) was carried out in the same way. The results of the simulation from Figure 4 has shown that a reference value exceedance is only given at a height of 3.5 m above the viewing terrace.

3.1. Raw Data Analysis

As previously described, for each combination operator-band, one whole week has been recorded for analyzing the behaviour of the PBCH signal power. As an example, Table I reports $R_{MAX,min}$ as its mean value over the week along with its range of variation. This parameter was calculated according to eq. 2 for every day of the week. The value out of parentheses represents the mean of the daily values for each day (considering 7 values in total), whereas the value in parentheses represents the range (difference in dB) between the highest and the lowest mean values during the week.

As it can be seen, in all cases, the observed values are far from the ideal one (0 dB), which highlights how such signal is not constant during the day and week. In particular, the most significant mean values of $R_{MAX,min}$ have been observed in the case of OP1-B1, OP2-B2, OP3-B2 and OP1-B3.

Furthermore, since the variation ranges are quite small in the most of cases, it also means that the observed values of $R_{MAX,min}$ seems quite systematic.

Since the PBCH signal power is directly linked to the maximum power expected by applying the eq. 1, the achieved results highlight that some problems could arise in the comparison with the emission limits in all cases in which $R_{MAX,min}$ is significantly far from the ideal value (i.e.0 dB).

In addition, the variations in PBCH transmitted power are subject to the operation modes of RBSs and the OPs sometimes adjust them to account for different traffic conditions, area coverage, etc. The variations in the received signal strength also happen due to the variation in PBCH transmitted power as well as to multipath propagation effects such as reflection, scattering, diffraction, especially in dense urban environments.

Table 1. $R_{MAX,min}$ [dB] on raw data: mean value (range value) in a week–time.

OP/B	B1	B2	B3
OP1	5.19 (3.27)	3.25 (1.76)	18.40 (0.49)
OP2	2.44 (1.62)	8.57 (1.91)	/
OP3	2.95 (0.54)	6.00 (0.51)	5.47 (1.92)

3.2. Analysis of the variability reduction due to the averaging process

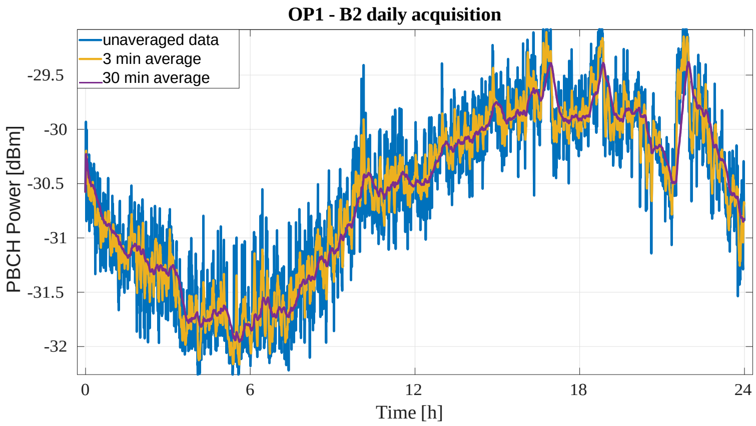

Figure 7. Effect of the averaging time on OP1-B2.

This section analyses the effects of the averaging time on $R_{MAX,min}$. ICNIRP guideline defines the averaging times to account for temporal variations of EMFs in tissues considering the local or whole-body exposure. Averaging effects smooth such variations, whereas higher exposure than the limit is permitted for short-term exposures [21]. Indeed, starting from behaviours like ones observed in Figures 5–6, it is obvious that the averaging could help in smoothing the traces,thus also potentially reducing the variability of resulting values. As an example, Figures 7–8 report such effects for several values of averaging time, in the case of OP1-B2 and OP2-B2. Moreover, Figures 9–11 report the evolution of the mean value (evaluated over the week) of $R_{MAX,min}$ and the related ranges versus the averaging time. As for averaging time values they have been selected on the basis of both practical considerations (about the time required for making a measurement) and also the typical values of time intervals considered in the definition of the ICNIRP emission limits. Looking at Figures 9–11, as expected, the smoothing effect due to the averaging time is evident because an increasing of the averaging time leads to a decreasing of $R_{MAX,min}$ (the traces of the acquisitions are better smoothed, and the results of measurements are more stable having the range values lower). Such trend is kept in all Figures, and such analysis may help in calculating the uncertainty regarding the result obtained

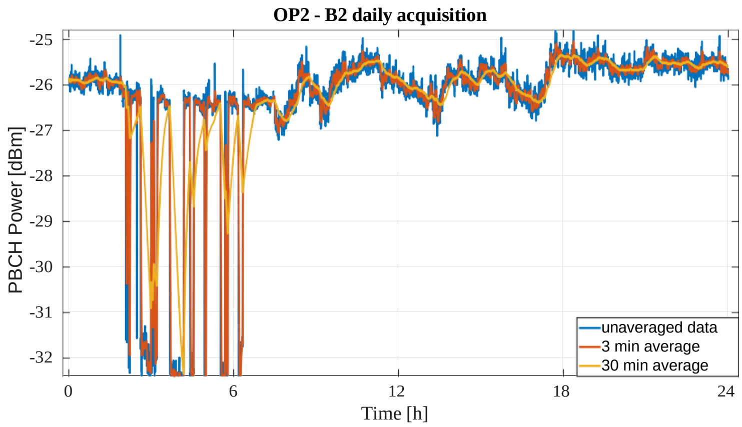

Figure 8. Effect of the averaging time on OP2-B2

in shorter observation time compared to ones at longer times. However, in many combination of Operator-Band, $R_{MAX,min}$ still remain significantly high concerning the expected experimental variability (typically less than 3 dB). This is particularly true for the case of OP1-B1, OP2-B2, OP3-B2, OP1-B3 and OP3-B3. As for the variability ranges of $R_{MAX,min}$ observed in Figures 9–11, they are not affected by the considered averaging time, which means that the variability over different days does not depend on the averaging time.

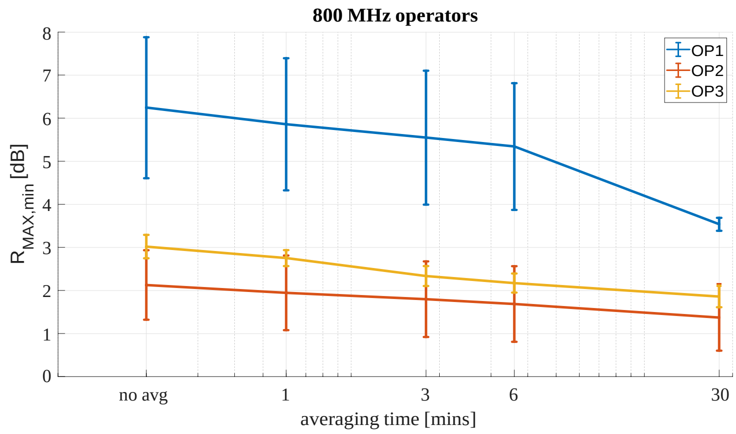

Figure 9. $R_{MAX,min}$ values at 800 MHz band: the averaging effect.

3.3. *Issues related to determination of compliance boundary exposure*

The examples given for the determination of the compliance boundaries show that both on-site measurements and simulations require considerable effort. In addition to the considerable effort required for the evaluation as well, the accessibility of the measurements is also of decisive importance. In recent decades, data traffic in mobile networks has been increased significantly, which is one of the reasons why more and more frequency ranges have been allocated to mobile communications. Nowadays in Italy and Austria, frequencies in the 700 MHz, 800 MHz, 900 MHz, 1500 MHz, 1800 MHz, 2100 MHz, 2600 MHz, and 3400 MHz bands are allocated to mobile communication.

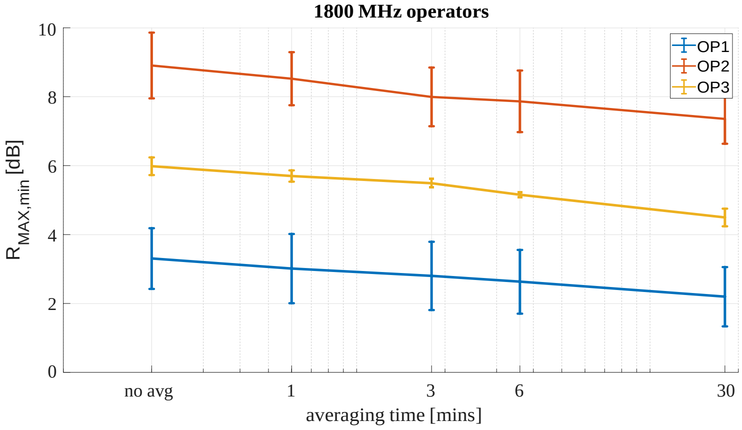

Figure 10. $R_{MAX,min}$ values at 1800 MHz band: the averaging effect

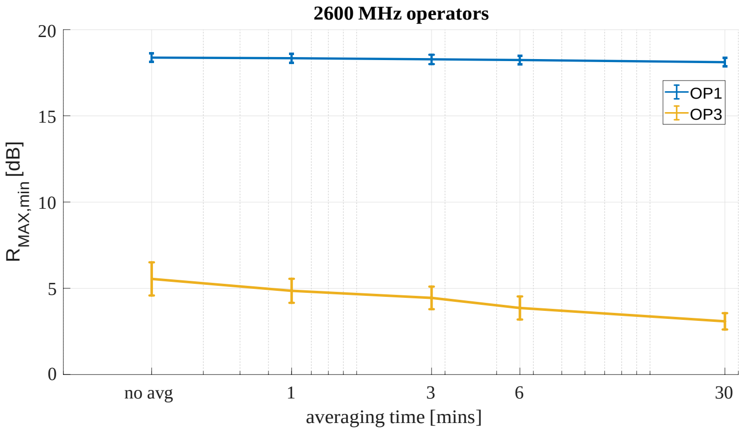

Figure 11. $R_{MAX,min}$ values at 2600 MHz band: the averaging effect

Most of these frequency bands are allocated on a technology-neutral basis, considering the fact that different technologies can be used within one frequency band. However, this was not the case in the past. For example, the 900 MHz and 1800 MHz frequency bands were used exclusively for 2G and the 2100 MHz frequency band for 3G only. When 4G was first introduced, the frequency ranges of 800 MHz and 2600 MHz were only used for LTE. Nowadays it is quite common that 4G and 5G technologies started using frequency bands previously occupied by 2G and 3G, whereas 3G is using frequency bands previously occupied by 2G. Under realistic conditions, it is, therefore, possible for a RBS to have LTE at 800 MHz, GSM with one or more channels at 900 MHz, UMTS with two channels at 900 MHz, LTE with two channels at 1800 MHz, UMTS with one or more channels at 2100 MHz, LTE with two channels in 2600 MHz and also 5G at 2100 MHz and 3400 MHz. This corresponds to a total of 11 or more individual channels.

According to the normative specifications [16], each channel would have to be measured for 6 minutes. The measurement of more than one frequency band at the same time is only possible when performing a frequency-selective measurement. To decode the stable signal of UMTS, LTE, or 5G it is necessary to perform single measurements at every channel with special measurement equipment that can decode these parts of the signals, such as VNA or NARDA SRM-3006 SA using the appropriate operating modes and software upgrades necessary for decoding the signal. For the exact evaluation, it is necessary to measure, i.e. 11 6 min = 66 min. This represents the pure measurement time per measuring point without any post-processing. Since the spatial averaging over at least three points is required according to [12], this time is tripled again. In addition, there may be several operators at the same location, which must be taken into account as relevant sources. As a result, the pure measurement time at one location can extend up to one day. This represents a huge effort that is performed very rarely in practice. Since the accessibility of the measurement points is often not possible, a simulation in such cases must be used. Simulations must also be used if the site is still in the planning phase and measurements cannot yet be carried out as a result. However, in both cases the effort is considerable, so both can be evaluated in several steps, as mentioned above. Having that in mind, the number of measurements in some situations should be kept as low as possible to reduce the effort for the EMF assessment per site. As a consequence, the measurement time could be reduced to optimize the time necessary for the EMF exposure evaluation.

3.4. Aspects toward improving the reliability of the measurement results

New guidelines for limiting exposure to EMFs (100 kHz to 300 GHz) [21] define the reference levels for exposure, averaged over 30 min. Until now, it is unclear how this recommendation will be implemented in the standards for measurements such as [12]. If it will be necessary to apply such an approach, then 30-min measurement time could be very long in the real-life situations, and especially in the compliance boundary determination cases. The same issue according to measurement time and effort also arises for the measurements that are located further away from the RBSs. In the case of measurements for local residents or concerned citizens, the question often arises about the maximum possible exposure, or at what range of values the exposure can fluctuate within a day. For these reasons, if the question of safe compliance with the limit values is not the top priority case, then the measurements (frequency- or band-selective) could be made over shorter periods, and these results could be presented with the corresponding uncertainties. From all these aspects, the necessity to reduce the duration of measurements to be able to carry out them quickly and cost-efficiently are obvious.

Of course, on the other hand, the accuracy of such measurements must not suffer considering its ability to prove compliance with the reference levels. In a few cases, however, the measurements will be unavoidable. Since the accessibility to private areas generally represents a problem, in such cases simulations have to be used as well as in the planning phase of the RBSs. Although spatial representation of the real exposure situation could make calculation time running for several hours, they could, in many cases, represent very efficient evaluation method.

4. Conclusion

Measurements of human exposure to RF-EMFs generated by the 4th generation of cellular networks in urban environments is a very important topic in today’s world since human life is heavily influenced by many technologies exploiting the 4G assigned frequencies. In that sense, the higher the number of RBSs, especially in complex urban environments, the more difficult the realistic exposure assessment. Despite specific guidelines used for the measurements of EMFs, there are still several issues to be discussed regarding the reliability of the measurement procedures and the evaluation of the measurement uncertainty. In general, to assess human exposure, some easier and faster approaches have been proposed in the literature and technical standards, among which Extrapolation Techniques (ETs) play the central role. They are thought to overestimate the maximum channel power on the basis of the supposed constancy of the level of a suitable pilot signal in the measurement point of interest, thus warranting a conservative approach concerning human exposure at that point. However, several experimental campaigns have proved how the hypotheses of the pilot signal power constancy cannot always be kept. Having that in mind, in some cases, supposed overestimation can turn into underestimation, thus losing the “conservative” feature and making the power measurement unreliable. For that reason, it is of great importance to achieve better stability of the pilot signals power as much as possible to have reliable and comparable results that are not heavily influenced by the time of measurement on a day or a week time scale.

Following the guidelines provided by the relevant technical standards in force, this paper describes the experimental results achieved by performing a long-term analysis for several days and weeks on three network operators and three frequency bands adopted in Italy for 4G communications.

The effects of the averaging time on raw data were evaluated to observe such an effect on reducing the variability of the PBCH power levels during the 24 h period per day. To these aims, a suitable figure of merit has been defined, namely $R_{MAX,min}$. In particular, as for the experimental tests related to the PBCH signal power measurements, two kinds of analyses were described: the former showed the behavior of $R_{MAX,min}$ when applied on row data (collected each 20 s), whereas, the latter showed the effects of different averaging times on such a figure of merit. The variation ranges of $R_{MAX,min}$ parameters evaluated over raw data sets of up to 18.40 dB found in the case of OP1-B3 (Table 1) justified the conducted analysis aimed at refining the measurement procedures and post-processing techniques given by the technical standards. Considering these effects, the results generally, significantly improved but in some situations, also high values of averaging time cannot assure an adequate smoothing of the collected traces. Therefore, these results suggest to further investigate on the possibility of improving the measurement procedures provided by the technical standards in force and their correct application on the field.

Another important issue that has been discussed in this paper was related to exposure safety requirements regarding the determination of compliance boundaries from RBS transmitting antennas, mainly estimated by measurements and calculations (simulations). Illustrated examples described the measurement and simulation approaches at two different locations in Austria for a roof terrace exposure condition. These procedures must be done for every new RBS and relevant upgrade.

As for the measurement approach, EMF exposure can be determined by measuring the actual value of exposure and calculating the possible theoretical or actual maximum exposure as defined in IEC 62232, whereas calculating the maximum usually includes post-processing.

As for the calculation (simulation) approach, a multi-stage procedure is often used (calculation of the compliance distance with the far-field formula, calculation of the compliance distances according to the box-shaped compliance boundary, simulation of the compliance boundary as an iso-surface for the RBS site). In any case, it must be ensured that the RBS is complied with the safety limits at any time of the day (taking into account the averaging time of the relevant guideline or standard) and in any possible operating state of the RBS. If this goal is not achieved, reconstruction will be necessary or access restrictions will have to be implemented. Considering the determination of compliance boundary in this paper, the measurement results were significantly below the reference values with a maximum of 19.38% of the Austrian reference level. In addition, the results of the simulation at the second location have shown that a reference value exceedance is only given at a height of 3.5 m above the viewing terrace.

Because the standards (international and national ones) that limit the RF-EMF exposure are recently redefined, it is still unclear how some steps such as 30-min measurement and averaging time will be implemented in real-life situations, especially in compliance boundary determination cases. The same issue according to measurement time and effort also arises for the measurements that are located further away from the RBSs.

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