In-Situ RF Measurements of EMFs for Human Exposure Assessment Due to Modern Cellular Base Stations

Domenico Capriglione

TC-37–Measurements and Networking (current Chair Prof. Domenico Capriglione, University of Cassino and Southern Lazio, Italy) was built some years ago as an idea of Prof. Leopoldo Angrisani (University of Napoli Federico II, Italy) and Prof. Claudio Narduzzi (University of Padova, Italy), having in mind that given the complexity of modern networks and related systems, a multidisciplinary approach has to be followed for correctly addressing the technological challenges and issues that are arising and will arise in the future in the field of telecommunication systems and networking. So, the TC-37 is actively trying to promote the international cooperation and integration of researchers belonging to the Instrumentation and Measurement Society with ones coming from other areas of telecommunication and information technologies.

The most up-to-date activities of the TC-37 members cover different areas that include methods and techniques for network performance assessment, quality of experience (QoE) and quality of service (QoS) in computer networks, traffic and protocol analysis, in-service testing, networking for measurements as wireless sensor network (WSN) design, implementation and performance assessment of WSNs, indoor positioning, synchronization issues, vehicular networks, cognitive radio, measurements for security in networks, coexistence and interference problems in networks and sensor networks, and standardization in sensor networks [1]–[17].

Among these research activities, due to the fast proliferation and the continued evolution of wireless technologies for short-range and long-range communications in recent years and in the near future great attention will be paid to the evaluation of human exposure to electromagnetic fields (EMFs) [18]. Indeed, depending on the specific application, the sources of EMFs span in a high-frequency range (from a few kHz up to tens of GHz), although a growing interest, today involves radio frequencies and microwave bands, in particular in the range of 100 MHz – 40 GHz. As a consequence, this frequency range is observed with particular care from several points of view: recently the International Commission on Non-Ionizing Radiation (ICNIRP) has provided new guidelines for limiting human exposure [19] while international technical committees and institutes continuously propose and update the relevant technical standards to be followed for assessing human exposure to EMFs [20]–[22]. The importance of this topic is also confirmed by the current European projects in which many metrology institutions are involved [23].

As matter of fact, due to the fast evolution of modern communication technologies, these technical standards are updated also on the basis of many researchers working in this framework, and several members of TC-37 are engaged in this important topic [24]–[26].

Focusing the attention on this theme, this article provides a summary of the main measurement techniques employed for evaluating human exposure to RF EMFs by highlighting some issues and challenges still open in this research area.

Review of Measurement Techniques for RF In-situ EMF Level Estimations

To evaluate human exposure to RF EMFs several measurement techniques can be adopted depending on the purpose of the measurement campaign and accuracy required [20]–[22]. Starting from measurement procedures given in [20], Fig. 1 summarizes the main approaches suggested by the technical standards.

In particular, a suitable site analysis should be carried out first to identify the EMF sources expected, their carrier frequencies and bandwidths, the number of base stations and cells, and the kind of communication technology (2G, 3G, 4G and on) adopted.

The second step deals with the selection of the measurement points: this phase requires particular care because the experimental scenario could include scattering objects and several kinds of obstructions that could significantly affect the reliability of the results. So, this step tries to define the most suitable exposure metric of the measurement points, depending on the particular features of the experimental scenario.

The author received the Instrumentation and Measurement Society's Outstanding Technical Committee Award in 2019.

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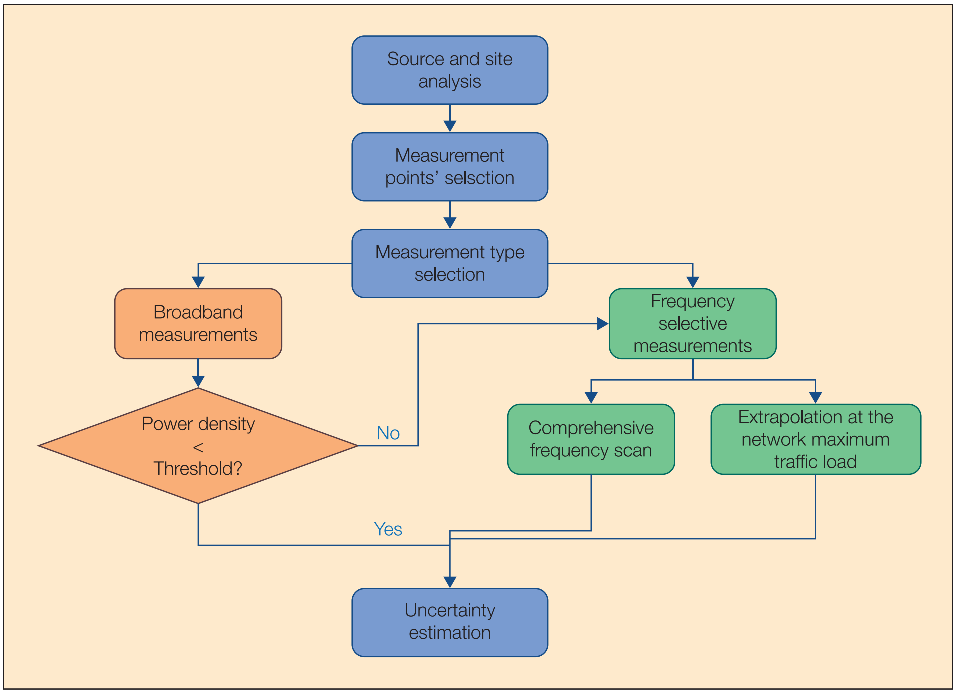

Fig. 1. Alternative approaches to evaluate in-situ RF exposure.

After these preliminary analyses have been accomplished, depending also on the aim of the experimental campaign, the EMF exposure can be estimated according to two main approaches by performing "Broadband measurements" and/or "Narrowband measurements," respectively.

Whatever be the considered approach, a final step dealing with the uncertainty evaluation is required to qualify the reliability of the experimental results. As better detailed in the following, this phase requires particular care in the identification of the uncertainty contributions due to the adopted measurement chain but also due to the intrinsic measurand variability (e.g., mainly due to the traffic loads and operating conditions of the base stations) and to the aleatory effects caused by scattering objects nearby to the measurement probes and antennas.

In the following, the main peculiarities of Broadband and Narrowband measurement approaches are described.

Broadband Measurements

Broadband measurements can provide a comprehensive estimation of EMF exposure over broad frequency bands. These kinds of measurements offer the main advantages of both providing a global evaluation of RF exposure level from all electromagnetic sources simultaneously operating over the whole instrument bandwidth and minimizing the measurement time. In addition, they generally require both less expensive measurement chains and measurement procedures that are less complex compared with those required with the second approach (Narrowband measurements).

Broadband measurements can be adopted if no signal spectrum differentiation over the bandwidth investigated is required for identifying the contribution of each electromagnetic source to the total RF exposure. For these reasons, concerning cellular communications, broadband measurements cannot discriminate between the electric field due to the uplink and downlink bands.

As for the measurement chain, it is generally constituted of a portable datalogger and equipped with an external isotropic broadband probe able to detect electric or magnetic fields or power density levels falling into the probe bandwidth.

Broadband measurements provide the estimation of the RF exposure in a given area during the time interval in which the measurements are collected, and due to the strong time-variant behavior of main EMF sources, they are not able to make forecasts about maximum exposure experienceable in such area but provide reliable information only about the RF exposure measured during the considered time interval.

Then, broadband measurements have to be complemented by narrowband measurements in the case the measured EMF level is approaching or overcoming the applicable limit (suitable threshold defined by a country's legislation).

Narrowband Measurements

Narrowband measurements allow the relevant sources to be identified, thanks to the use of frequency-selective instruments, thus quantifying the contribution to RF exposure due to each EMF source. These kinds of measurements provide more complete information about EMF sources relative to broadband measurements but require more expensive measurement chains and more time-consuming measurement procedures. However, in the case of evaluating the RF exposure to EMFs due to the cellular base stations, they allow implementing some extrapolations to maximum traffic load to provide the estimation of the maximum exposure experienceable. These techniques should allow the results to be independent on the day and the time interval in which the measurements are collected, thus enabling the possibility of making forecasts about maximum exposure experienceable in a given area and also due to the simultaneous operating of several base stations.

Currently, the most widespread technologies for cellular communications are GSM (2G), UMTS (3G) and LTE (4G) [25], [27]. For each of them, specific extrapolation techniques have been defined and further studies are in progress for defining suitable extrapolation techniques for the incoming 5G systems [21], [28].

As for the measurement chain, it includes a frequency selective instrument connected to either an external isotropic or directive broadband antenna. The basic instrument is the spectrum analyzer which can be equipped with dedicated decoding capabilities for specific cellular transmission standards. These features are particularly useful whenever the aim of the measurement campaign is also to identify the contribution of each cell of a cellular system. Indeed, in the case of 3G and 4G systems, more cells operating nearby simultaneously share the same carrier frequency and bandwidth; therefore, it is possible to quantify the contribution due to each cell only if such decoding capabilities are available. Otherwise, the overall contribution is evaluated over a given bandwidth, and the related value will be due to all cells simultaneously covering that area.

Main Uncertainty Causes

The measurement of the RF Electric Fields requires the use of suitable measurement chains and measurement procedures to keep the overall measurement uncertainty relatively low [20]-[22]. Besides the metrological features of the elements constituting the measurement chain, further factors of influence have to be considered and kept under control to avoid unreliable exposure estimations. As an example, the presence of the operator himself and/or other metallic objects or surfaces close to the electric field probe (in the case of broadband instrumentation) or the measurement antenna (in the case of narrowband measurement chains) can significantly affect the measurement results as well as the channel fading caused by moving objects in the measurement scenario and the measurand intrinsic variability. This final factor mainly depends on the data traffic and the number of users during the time interval in which the measurements are performed.

Furthermore, due to the peculiarities of modern communication signals, which are often characterized by spectrum shapes and time evolutions typical of noise-like signals, the response of the probe and the measuring instrument can be considered as a further cause of uncertainty in both broadband and narrowband measurements. Finally, whenever digitally modulated signals have to be analyzed and measured, the instrument settings have to be carefully selected to avoid large measurement errors (in terms of power either overestimations or underestimations).

Narrowband Measurements on LTE Base Stations for Extrapolation to Maximum Traffic Load

In this section, the measurement setup and the experimental results of a measurement campaign carried out on a real LTE base station are reported. In particular, according to guidelines reported in [20], the extrapolation technique at the network maximum traffic load based on the use of spectrum analyzer measurements has been applied for evaluating the maximum expected electric field levels.

The measurement setup includes a directive Rohde & Schwarz HE300A log periodic antenna mounted on a tripod at 1.50 m-height from the floor and connected to a R&S FSH 8 spectrum analyzer (Fig. 2). The directive antenna has been configured to point to an LTE base station placed in the urban area of Cassino, Italy. The spectrum analyzer has been remotely controlled via the ethernet interface and programmed in MatlabTM environment for continuously acquiring and storing the measured electric field levels.

The whole measurement chain assures a total standard uncertainty equal to 1.5 dB [25]. The measurement station has been configured for collecting the electric fields in two bands (800 MHz-frequency and 1800 MHz-frequency bands, respectively) and three mobile operators (designated as OP1, OP2, and OP3).

Although the application of the extrapolation technique should assure that the achieved electric field level estimations will be independent of the time interval in which the measurements are collected, in order to analyze the long-term repeatability of the extrapolated values, the measurement of the electric field has been performed for several days of a week without interruption.

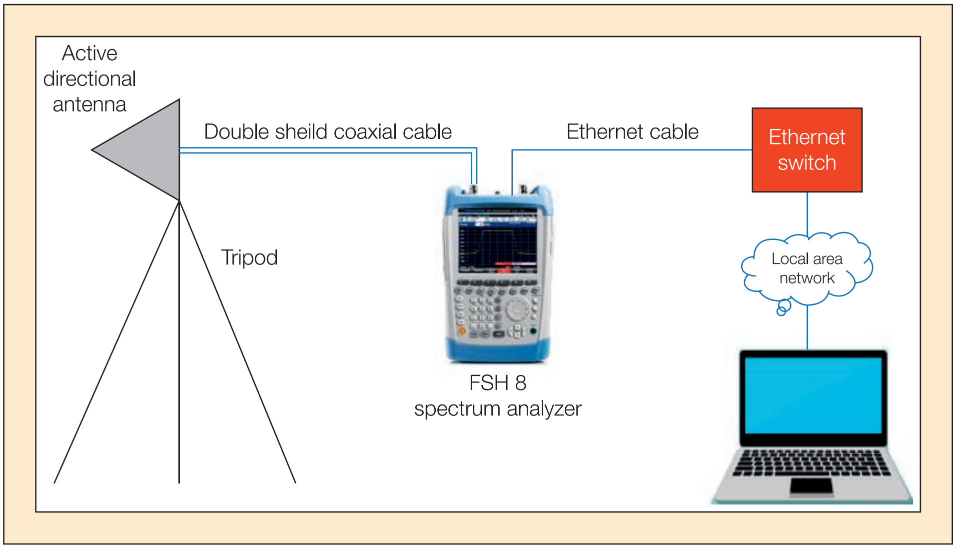

Fig. 2. Measurement set-up for analyzing the long-term repeatability of the electric field due to network maximum traffic load.

In more detail, the extrapolation technique proposed in [20] requires evaluating the maximum electric field magnitude (EMAX) by applying the following formula:

$$E_{MAX} = \sqrt{n_{PBCH}} \cdot E_{PBCH} \qquad (1)$$

where:

- E_{PBCH} is the electric field associated to Physical Broadcast Channel (PBCH), which is a down-link channel used to send information about the cell and the system as a whole and that should be characterized by a constant power level that does not depend on the traffic load;
- n_{PBCH} is the ratio between the maximum power of the cell and power associated with the PBCH. The value for n_{PBCH} can be provided by the network operator or calculated according to the following equation:

$$n_{PBCH} = \frac{n_{RS}}{72} \qquad (2)$$

with n_{RS} denoting the number of subcarriers in the used transmission bandwidth.

The value of E_{PBCH} is evaluated according to the procedure and the measurement settings proposed in [20], summarized as:

- center frequency equal to the center frequency of the LTE signal;
- frequency span equal to 0 Hz (zero-span mode), for measuring the received signal in the time domain;
- resolution bandwidth (RBW) equal to 1 MHz, for assuring to integrate the entire PBCH frequency content;
- sweep time equal to 70 µs times the number of trace points for obtaining an integration approximately close to the symbol duration for each trace point;
- rms detector;
- max-hold functionality selected with a minimum time equal to 20 s.

Fig. 3 shows the evolution of the maximum electric field extrapolated value over a 24-h interval for three mobile operators on the 800 MHz-frequency and 1800 MHz-frequency bands.

It shows different behaviors for the considered mobile operators and frequency bands:

- As for the 800 MHz-frequency band, the extrapolated values for OP1 significantly vary during the day with a variability range of about 5 dB, whereas the extrapolated values of OP2 and OP3 show a variation contained in 2 and 3 dB, respectively. The wider variation range shown in the case of OP1 is due to a significant operating change during the night which is less evident in the case of OP2 and OP3. However, also in daylight intervals OP1 and OP3 show variations approaching 2 dB.
- As for the 1800 MHz-frequency band, OP2 and OP3 show the highest variability ranges (8.6 dB and 5.6 dB, respectively), whereas OP1 shows a variability range approaching 3 dB. Once again, the high values of variability range are due to a significant drop of E_{PBCH} during the

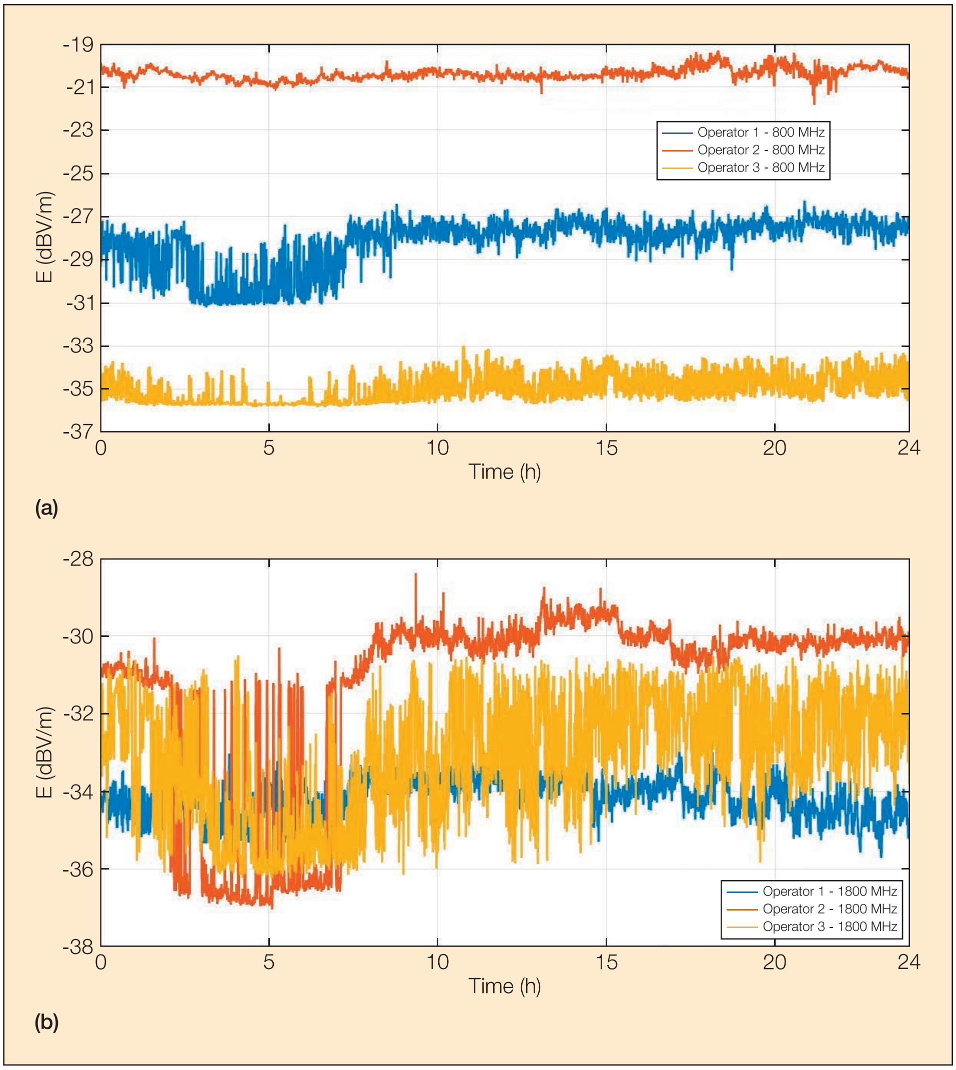

Fig. 3. Evolution of E_{MAX} over a 4-h interval: (a) 800-MHz frequency band, (b) 1800-MHz frequency band. (Day #4 is involved.)

Table 1 – Week analysis of the maximum variability range

Operator – Frequency Band	Maximum Variability range (dB)						
	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
OP1 - B1	4.7	4.6	4.7	4.9	4.6	4.9	7.9
OP2 - B1	2.5	1.3	2.4	2.5	2.8	2.9	2.5
OP3 - B1	2.9	3.3	3.1	2.8	2.9	2.9	2.8
OP1 - B2	3.4	3.5	4.2	3.0	3.7	2.4	2.5
OP2 - B2	9.9	7.9	8.0	8.6	8.4	8.4	8.8
OP3 - B2	6.0	5.9	6.2	5.7	5.9	6.2	5.9

night's hours, but significant variation is clearly visible also in the daytime intervals.

As said, to analyze the long-term repeatability of the results, the experiments were repeated for each day of a week. Table 1 reports the maximum variability ranges evaluated over each day of a week. From the analyses of such results some considerations can be drawn:

- Each analyzed configuration (in terms of operator-band) shows how the extrapolated values generally vary during the day and over the week. As a consequence, the measured values depend on the time interval and day in which the measurements are performed.
- Whatever the operator and the frequency band, the observed variation ranges are not neglectable concerning the typical measurement uncertainty due to the instruments chain (typically the standard uncertainty should be kept less than 2.0 dB). In some circumstances (see OP2-B2 and OP3-B2), the variation ranges are larger than 5 dB and approach 10 dB in the case of OP2-B2.

On the whole, despite that the features of the PBCH signal should assure a value of E_{PBCH} not dependent on time interval and day in which the measurements are collected, the experimental results show that the maximum electric field extrapolated (E_{MAX}) can vary in very wide ranges over the day and the week, thus affecting the reliability of the comparison with the applicable limits on human exposure.

Conclusions and Open Issues

The measurement of human exposure to RF EMFs is a topic of great interest today because of the growing diffusion and fast evolution of communication technologies. Due to the importance of the topic and the technical difficulties arising from the ever-increasing level of complexity of the communication technologies and experimental scenarios, worldwide researchers are involved in designing and fine-tuning measurement methods, standard procedures, and instruments for achieving reliable results of human exposure.

The practical examples in this paper highlight how the research in this field needs continuous updates, and it should involve long-term experimental campaigns for assessing the reliability of measurement techniques and procedures in several experimental conditions and scenarios. These statements are strongly supported by current trends that push to employ DSS (Dynamic Spectrum Sharing) and 5G cellular technologies which will offer new challenges for the measurement of human exposure to EMFs generated by these kinds of sources. In particular, the antenna beamforming and the complexity of 5G technology will require the design of new and effective measurement techniques and protocols able to warrant an adequate tradeoff between accuracy and time needed to completely characterize human exposure in high-density urban scenarios, where several base stations simultaneously operate in the same area. These aspects shall be investigated for both narrowband and broadband approaches.

Furthermore, the estimation of the measurement uncertainty will be an important topic to be addressed, taking into account several quantities of influence among which the response of the antennas, probes, and instruments to the signals generated by modern communication systems, as well as the long-term variability of the power emitted by the related Base Stations in given points of analysis should be examined.

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Domenico Capriglione (S'20) (domenico.capriglione@unicas.it) is currently an Associate Professor of electrical and electronic measurements with the University of Cassino and Southern Lazio, Italy. His current research interests include measurements on RF and telecommunication systems, DSP-based measurement systems, network measurements, and measurement of electromagnetic compatibility. Since 2016, Domenico has served as the Chair of the IEEE I&M Technical Committee TC-37–Measurements and Networking.