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Statistical Characterization of Human Exposure to GSM Electromagnetic Field

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***Abstract* – Statistical characterization of the maximum power received in the GSM band is presented. Results show a large unexpected variability of BCCH channel power over time. Such evidence results in a large uncertainty related to the measurement of the average power through use of the α_{24} parameter as required by the Italian standards to assess average exposure to electromagnetic fields and compliance with limits.**

I. INTRODUCTION

Diffusion of wireless communication devices and evolution in cellular network-based telecommunication systems has results in population paying great attention to exposure to electromagnetic field and its possibly effects. To protect population, in 1999 the European Union has released the 1999/519/CEE recommendation containing the indication of the maximum safe exposure levels in the frequency range of non-ionizing radiation (i.e., from 0 Hz to 300 GHz) [1], distinguishing between *basis restrictions* (based directly on established health effects and biological considerations) and *reference levels* (provided for practical exposure-assessment purposes to determine whether the basic restrictions are likely to be exceeded). In determining the values for basis restrictions (Table 1 in Annex II of [1]) safety factors of about 50 have been applied to the values which are known to cause acute effects. In that sense, the Recommendation implicitly covers possible long-term effects that may arise in the whole frequency range. With the same aim, European Union has also emanated a Directive for the protection of workers [2] whose validity has been postponed until 2018 to take into consideration recent advances in research about exposure to static fields [3].

For better protection against long-term effects, Italy has further decreased exposure limits for population between 100 kHz and 300 GHz to 6 V/m, to be calculated as the root mean square value (*rms*) over 6 minutes [4], because 6 minutes is reported in 1999/519/CEE to be the time constant of human body for thermal effects of high-frequency electromagnetic fields. In 2012 a new decree [5] has set that exposure must be evaluated over 24 hours instead of 6 minutes to better consider variations over the whole day. Moreover, it is suggested that the maximum exposure is measured, so that the measured value refers to the worst case. Because it is impossible to know if the field will ever be at its maximum value and, in that case, when, extrapolation is used. However, extrapolation may be challenging and affected by large uncertainties for GSM, UMTS and LTE system because of the large variability of the electric field due to traffic and propagation conditions [6]-[8].

Focusing on the GSM system, which is still the most widespread cellular system adopted worldwide, the extrapolation technique provided in the EN 50492 standard [9] requires measurement of the electric field related to the BCCH channel, which is always transmitted at the maximum power, multiplied by the square root of the total number of carrier frequencies of the same BTS. Papers [10] and [11] show results of maximum exposure evaluation by application of such technique. It is apparent that extrapolation overestimates exposure because it assumes that all carrier frequencies operate at the maximum power at the same time over the entire measurement interval, which is a very low probability event.

The Italian Electrotechnical Committee (CEI, Comitato Elettrotecnico Italiano) has released Appendix E to CEI 211-7 [12] in which a different extrapolation technique is suggested, consisting in multiplying the maximum measured field E_{max} by the square root of a parameter named α_{24}, defined as:

$$\alpha_{24}=\frac{P_{avg}}{P_{max}} \tag{1}$$

where P_{avg} is the average power over 24 hours and P_{max} the maximum power. The standard sets that α_{24} must be provided by the service provider upon request of a public authority, so that the average electric field can be determined straightforwardly after measuring E_{max}, usually obtained by measurement of the field generated by the BCCH channel.

The papers deals with the statistical characterization of the maximum power P_{max} (as it is directly related to E_{max}) to validate the assumption that it is constant over time for the BCCH frequency. Should this assumption turn out to be uncertain, then the minimum measurement time to obtain P_{max} must be determined.

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II. MEASUREMENT SETUP

Measurements were carried out within the premises of the Electromagnetic Compatibility Lab (emcLab) of the Department of Electrical Engineering and Information Technologies at the University of Naples Federico II, 20 thru 30 December 2013. The setup (shown in Fig. 1) consisted of an EM 6568 omnidirectional biconical antenna by ElectroMetrics placed on a dielectric tripod and located further than 2 meters from walls and metal objects; an FHS6 spectrum analyzer by Rohde & Schwarz; a PC for remote control of instrumentation and data storage. The spectrum analyzer was set according to Appendix E of CEI 211/7 standard reccomendations: 10 MHz span, 100 kHz resolution bandwidth and 100 ms sweep time. Center frequency of 949.3 MHz was chosen in order to acquire all channels active in the area for a specific GSM-900 service provider within a single sweep. With these settings it was possible to cover the channels from 47 (944.4 MHz) to 96 (954.2 MHz). Sweep repetition time was set to 2 seconds, and after 1800 scans (i.e., approximately one hour) a 1 minute MAX HOLD measurement was obtained. To avoid possible interference the area was forbidden to people and the number of moving obstacles in the close proximity on the lab reduced as much as possible.

Fig. 1. Measurement setup

III. EXPERIMENTAL RESULTS

In this section we present results of the statistical characterization of P_{max} obtained by measurements over 10 days from 20 to 30 December 2013.

A. Time and channel type dependence

The first analysis is about the variation with time shown by P_{max}. Such quantity has been obtained by two different approaches. While power measurements on wireless transmitters data channels can be affected by repeatability issues [13], [14], P_{max} can be assumed to be constant if measured at the BCCH frequency, so standards usually suggest that the spectrum analyzer be set with the MAXHOLD detector so to have a clear reading of the maximum value after a few scans. The first methodology we used requires that MAXHOLD detector is set for 60 seconds at the end every measurement hour and the measured value stored as P_{mMH}. Therefore, in each day a set of about 24 samples of P_{mMH} is collected. The second methodology evaluates P_{max} as the maximum sample P_{m1H} of all those obtained over a one hour measurement interval.

Fig. 2 shows a box plot of P_{mMH} and P_{m1H} grouped according to the measurement day for the four BCCH channels monitored. For channels 54 and 94 power levels are much lower than channels 69 and 79, possibly due to a different location of the BTS with respect to the measurement point or to a different direction of the main lobe.

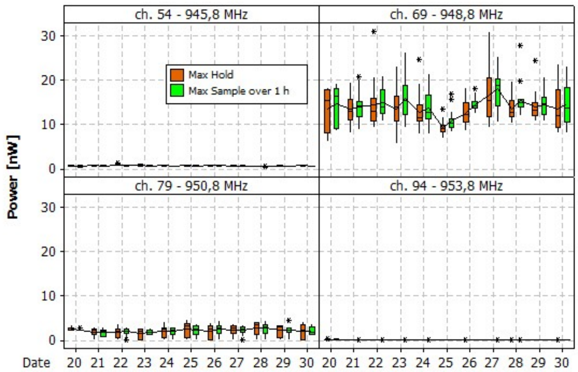

Fig. 2. Comparison of P_{mMH} *and* P_{m1H} *for* the BCCH channels.

Focusing on the latter channels, we can see that mean, median and interquartile range (which is strictly related to the standard deviation) values do change daily, although in a similar manner for both methods. To verify such claim, Fig. 3 shows the percentage relative error between the two methods, defined as:

$$\Delta P=\frac{P_{mMH}-P_{m1H}}{P_{mMH}} \tag{2}$$

Channel 69 and both channel 54 and 94 have ΔP close to zero, which confirms equivalence of the two methods in spotting the maximum value within an hour.

We highlight that values of ΔP close to zero may also show when noise only is measured. Fig. 4 shows, however, that this is not the case as the signal at channels 54 and 94, yet weak, can be seen on top of the background noise. A peculiar behavior can be observed for channel 79, where ΔP shows mostly negative and with mean percentage values up to about -300%, proving that the maximum power sample over one hour P_{m1H} is constantly larger than the MAXHOLD power P_{mMH}. This outcome can be interpreted by considering that measured power is possibly affected by slow variations that can be detected only by measuring over large time intervals, like in the case of P_{m1H}. In this sense channels 54, 69 and 94 have a much better BCCH behavior as their power keeps more constant over one day.

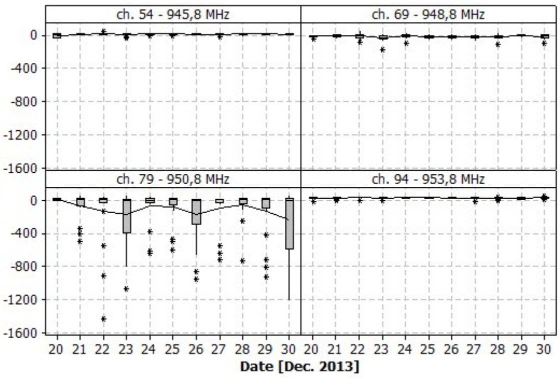

Fig. 3. Relative error between the two measurements methods for the BCCH channels.

Slow variability can in principle be given by two contributions: one by the power radiated by the BTS antenna, and another one by the propagation path, the latter resulting in long-term fading. Given the functional characteristics of the GSM system, we must assume that the observed phenomenon is an indicator of the time dependence of the propagation channel.

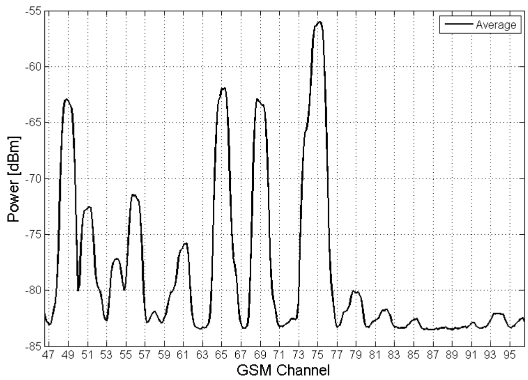

Fig. 4. Frequency spectrum

Given the just highlighted dis-uniformity in the behavior, we also analyzed the four non-BCCH (TCH) highest-peak channels, i.e. 49, 65, 74 and 75 for comparison purposes. In Fig. 4, and by comparing Fig. 2 and Fig. 5, we can see that all four channels have powers that on average are higher than BCCH channels, which is not expected at all. For all of them, mean, median and interquartile range values for both measurement methods do change daily, although percentage relative error in Fig. 6 has much smaller values than those obtained for BCCH channels. Such result may be explained by considering that the one minute MAXHOLD measurement is enough to sample the whole system's time dynamics. To investigate further on time dependence of P_{mMH} and P_{m1H}, Fig. 7 shows a boxplot for the BCCH channels grouped by the hour of the day in which the acquisition was made. Similar behaviors to those shown in Fig. 2 are observed because P_{mMH} and P_{m1H} do vary on an hourly basis. Furthermore, by inspection of Fig. 8 we can get a closer insight into the behavior of channel 79 shown in Fig. 3 and conclude that the values of the relative error between the two methods other than zero are mostly concentrated in the time interval between 0 AM and 8 AM.

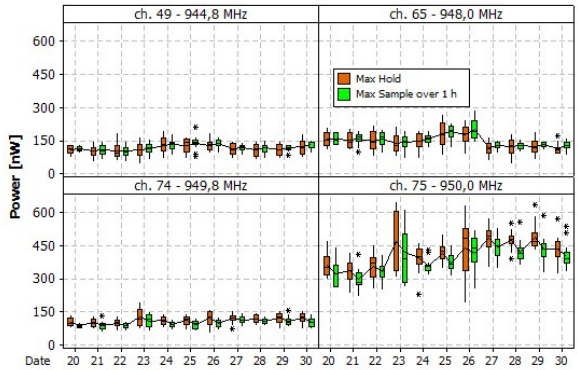

Fig. 5. Comparison of P_{mMH} *and* P_{m1H} *f*or the TCH channels.

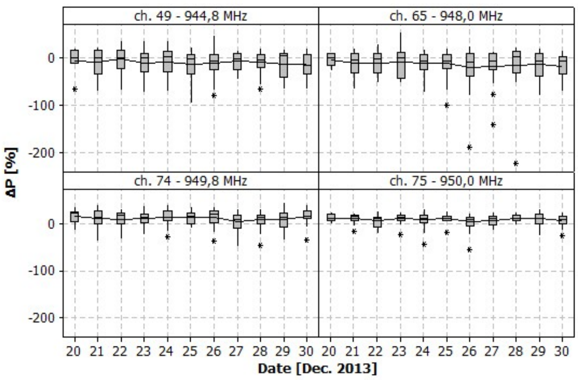

Fig. 6. Relative error between the two measurements methods for the TCH channels.

B. Traffic condition dependence

Although a tight bond between hour of the day and traffic condition exists, we investigated the quantities of interest according to two specific traffic conditions and whether a day was a working or non-working one. In Fig. 9, P_{mMH} and P_{m1H} are grouped by channel type (BCCH and TCH channels), working (monday thru friday) and non-working day and peak/off-peak time, where peak time is between 8:30 am and 5:30 pm. The figure shows that power for BCCH channels present much larger variations in P_{mMH} and P_{m1H} values than TCH channels, and that the latter have typically much larger values, although the difference between them keeps around zero, like shown in Fig. 10.

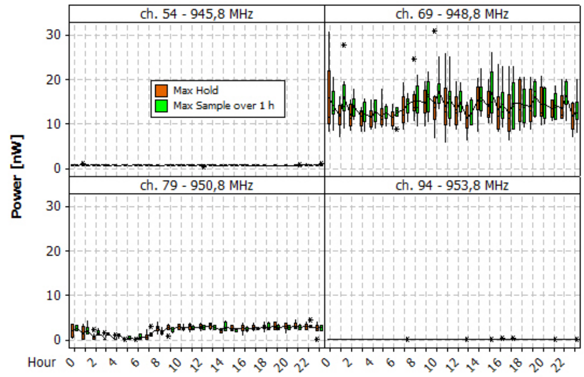

Fig. 7. Comparison of P_{mMH} and P_{m1H} for the BCCH channels grouped by hour of the day.

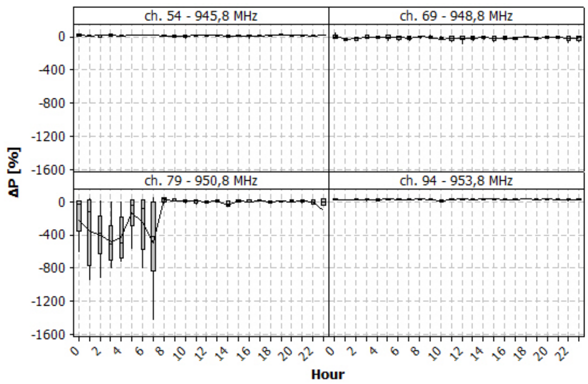

Fig. 8. Relative error between the two measurements methods for the BCCH channels grouped by the hour of the day.

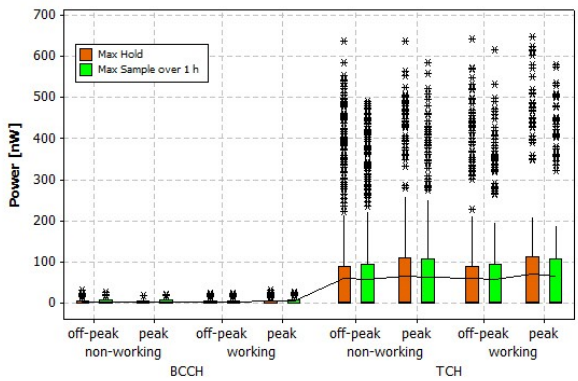

Fig. 9. Comparison of peak and off-peak hour for BCCH and TCH channels.

In the same figure, it can also be seen that the median value of the difference (represented by the horizontal segment within the box) is above zero and almost constant in all scenarios, the average (represented by the dot connected by the solid line) is close to the median for peak hours in both BCCH and TCH channels, while it differs significantly from it for off-peak hours in BCCH channels and is close to the first quartile for off-peak TCH channels. This means that typically P_{m1H} is larger than P_{mMH} which can be explained by the same token as in Sect. III.A.

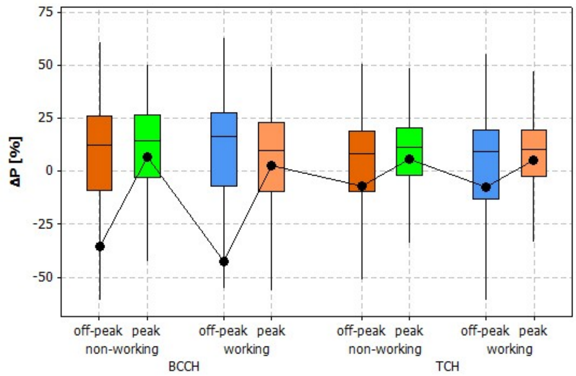

Fig. 10. Percent relative error.

C. Determination of α_{24} and its estimates α_x

The α_{24} parameter was determined for each BCCH channels by evaluating the average power P_{avg} and maximum power P_{max} from power samples P acquired in each measurement day at 0.5 S/s. Results are reported in Table I for days December 21 thru 29, as measurements in the first and last day do not extend over a whole 24 hour period.

Table I. α_{24} for the four BCCH channels.

	ch. 54	ch. 69	ch. 79	ch. 94
Dec. 21	0.4414	0.4060	0.0532	0.4695
Dec. 22	0.4538	0.4322	0.0536	0.4878
Dec. 23	0.4330	0.3415	0.0653	0.4485
Dec. 24	0.5309	0.3809	0.0490	0.4944
Dec. 25	0.5149	0.3697	0.0464	0.5685
Dec. 26	0.4843	0.4370	0.0349	0.5046
Dec. 27	0.4339	0.4402	0.0566	0.4609
Dec. 28	0.4182	0.3461	0.0435	0.4711
Dec. 29	0.5629	0.4414	0.0377	0.4318

As expected from the statistical analysis shown in the previous sections, yet not expected given the nominal behavior of BCCH channels, α_{24} values do vary over days. Since α_{24} requires 24 hours measurements to be evaluated, we want now to investigate whether shorter-time α_x, for x = 1, 2, 3, 4 and so on, can be used as estimates of α_{24}. To do that we need to test the hypothesis that the expected value of the distribution of α_x for each day is equal to the α_{24} obtained for the same day versus the hypothesis that it is not (two-tailed test), assuming a 5% I type error probability. Results are reported in Table II. Each cell shows the minimum value of hours x for which we fail to reject the null hypothesis that the observed α_x are drawn from a distribution whose mean is α_{24}, so assuming that α_x is an unbiased estimator of α_{24}.

Table II. Hypothesis testing H_0: $\mu_{\alpha 1} = \alpha_{24}$ *vs.* H_a: $\mu_{\alpha 1} \neq \alpha_{24}$.

	ch. 54	ch. 69	ch. 79	ch. 94
Dec. 21	*8*	*6*	*4 (*)*	*4*
Dec. 22	*6*	*5 (*)*	*3*	*5*
Dec. 23	*5*	*4*	*3*	*5*
Dec. 24	*5*	*6*	*3*	*5*
Dec. 25	*8*	*4*	*3*	*4*
Dec. 26	*8*	*3*	*2*	*4*
Dec. 27	*5*	*4*	*2*	*5*
Dec. 28	*6*	*5*	*1*	*4*
Dec. 29	*3*	*6 (*)*	*4*	*5*

It can be seen from the table that the α_x becomes more reliable an estimator as x increases. It must be noted, however, that larger values for x, i.e. larger time intervals used to estimate α_{24}, imply that the sample number decreases, causing the test statistic to have less degrees of freedom. For the starred items in the Table, for example, for some values of x larger than that indicated, the test turns out to reject the null hypothesis again, possibly as a consequence of the aforesaid mentioned decrease in the sample size. It must be noted, however, that use of only one observation of α_x will be made in practice not the sample mean of a larger set. Therefore the efficiency of α_x as an estimate of α_{24} must be investigated further.

IV. CONCLUSIONS

Results presented in the paper show that the assumption that P_{max} for the BCCH channels is constant with time may be misleading and may thus return erroneous evaluations of the average exposure when procedure indicated in the Italian norm is used. Furthermore, it is shown that α_{24} can be estimated by shorter time interval estimators, although further investigations are due to assess dependence of bias on sample size.

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