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Improvement and Testing of Models for Field Level Evaluation in Urban Environment

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***Abstract*— Through the advent of mobile cellular networks the number of radio base stations installed in urban environments has increased exponentially. As a consequence, the level of the electromagnetic (EM) field has increased at the same pace, sometimes approaching the limits set by the national rules. The first step of a compliance test campaign is the field estimation, mainly close to the base stations. In this article, the estimation of EM field generated by UHF base station is presented. A rephrasing of the COST 231 - Walfisch-Ikegami model is used to evaluate the path loss at distances greater than 20 m from the base station. Then, the knowledge of the full antenna pattern allows to estimate the field level. Since antenna manufacturers measure, and publish, only the patterns on the principal planes, an extrapolation procedure is also presented. A measurement campaign in the specific small urban and irregular environments of Dorgali (NU), Cala Gonone (NU) and Lunamatrona (CA), Italy, done in the context of Onde Chiare project, has been used to assess the approach presented here.**

***Index Terms*— Electromagnetic (EM) field estimation, EM field measurements, propagation models, urban environment.**

I. Introduction

SINCE the beginning of the 80s, characterized by the diffusion of cellular mobile networks, the estimation of loss factors in propagation paths were determinant to predict accurately the electromagnetic (EM) field level produced by one or more radio base station (RBS) installed in an urban environment. This evaluation is actually a problem since it is a complex and expensive task. Therefore, many different techniques have been proposed and assessed to evaluate the path loss [1], aiming at a reliable evaluation of the field level and therefore of the coverage. In parallel with the increase of the number of mobile users, and of their requirements in term of channel capacity, the RBS number in urban environment and the field level has increased at the same, exponential, rate. With the obvious outcome of increased interferences on electronic equipment [2], [3] and increased concerns of the general populations about their safety [4], [5]. The quantitative evaluation of their actual relevance requires the knowledge of the local field level, mainly in the vicinity of RBSs. This field level depends on two factors:

1) the path loss between the RBS and the field point;
2) RBS antenna pattern in all directions.

As a matter of fact, close to the RBS the field can reach a significant level even in the antenna sidelobe region.

It is clear that the assessment of the regulatory compliance requires a measurement campaign. But an effective test campaign needs a quite accurate estimation of the local level of the EM field, to locate the critical points and to design accordingly the tests. This estimation must be based on 1) and 2) listed above, which will be shortly discussed in the following.

As regards the estimation of the path loss, an efficient and reliable prevision model is the COST 231 – Walfisch-Ikegami (COST231-WI) model [6], which has been tested and validated as a (statistical) coverage prediction model. For example, in [7] and [8] the COST 231 - Hata Model [6], [9] and the COST231-WI model [6] were presented and compared to experimental values obtained from a narrowband campaign measurement. In [10] an optimization of the COST231-WI model was performed using the particle swarm optimization (PSO) algorithm. In order to find a standard reliable model to be used in different environments and to provide support for the design of the GSM cells at the frequency of 900 MHz, in [11] the estimated path loss levels using five different models were compared. Further comparisons between path loss levels calculated employing different prevision models were presented in [12]–[18]. In [19] a summary of campaign measurement results in different line of sight (LOS) cases was proposed, all of which showed variations of signal strength with distance. All those models are statistical in nature, and aimed at the coverage calculation. Therefore, they can be used only for distances larger than several tens of meters.

A different approach for the estimation of the path loss is the use of ray-tracing [20]. It could be more accurate, but is computationally heavy and requires a good knowledge of both the environmental geometry and EM properties. In [21]

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the geometrical ray implementation for mobile propagation modeling (GRIMM) model is described. This model was used to estimate signal attenuation levels generated by RBS in a particular environment and to compare experimental and estimated values. Further refinements have been described in [22]–[24], where, in particular, the reflection and scattering effects were analyzed using ray-tracing algorithms and a prevision model based on geometrical optics to calculate path loss levels in street canyon was proposed. The ray-tracing approach can, in principle, be used also for exposure evaluation [25].

Despite the availability of this wealth of different path-loss evaluations, accurate ones, such as ray-tracing, are computationally heavy whereas others aimed at evaluate an "average" level for coverage, such as those developed in the framework of COST231, including the COST231-WI model. Moreover, the latter, like all other empirical/statistical methods, is unable to work close to the source, which is, in our view, another drawback.

As regards the second factor which influences the estimation of the electric field level, the RBS antenna gain patterns [see 26, eq. (27)] are typically measured by the manufactures, and published in the antenna datasheet. However, the aim of these data is to evaluate the RBS coverage, and therefore only the principal planes are measured and shown. As a matter of fact, the antenna coverage area is in the antenna main beam, so the principal planes knowledge is sufficient. In order to estimate the field level for compliance purposes, the whole 4π knowledge of the antenna pattern is required. Since, close to the antenna, even the field in the sidelobe region can be quite strong. Measurement of the antenna pattern over all the 4π solid angle would be the best solution but is it quite expensive, so that several procedures have been proposed to reconstruct the pattern in all directions, starting from the principal planes measurements [27]–[31].

In the last few years, the EM field monitoring in urban area has become a viable way to estimate field exposure. However, such type of monitoring approach is certainly more expensive than the theoretical and predictive way discussed earlier. An innovative monitoring system based on a wireless sensor network able to keep under control the cumulative EM field in the area of interest has been presented in [32] and [33]. The purpose of this system, called Serbian electromagnetic field monitoring network (SEMONT), was the development of a useful tool for national and communal agencies of Serbia for environmental protection, especially to keep under control EM pollution and to assess real-time exposure of population. Other countries, such as Turkey [34] and Italy [35], have launched monitoring programs. In all these cases, however, no previous estimation of the field distribution has been made, though the latter would have allowed a more effective monitoring.

The aim of this article is to describe an integrated approach for the local estimation of RBS EM field in urban environment in the cellular UHF bands, which complements COST231-WI method and adapts it for the case of small (and possibly hilly) towns with irregular street geometry and small houses with different shapes and heights. Such an estimation must be reasonably accurate, but available almost in real-time, in order to be delivered, upon request, to everyone who want to know the EM field level at their location. Eventually it would increase the awareness of the general population to the EM field level present in the environment.

The starting points are, from one side, the path loss prediction methods and, from the other, the knowledge of the RBS antenna gain pattern over the 4π sphere. In both cases, the above discussion shows that substantial modifications or extensions to available approaches are required to get the sought field estimation. Since antenna manufacturers report only the pattern on the principal cuts, Section II will be devoted to the "interpolation" procedure able to reconstruct the pattern in all directions. Then, in Sections III and IV, we discuss how to extend the COST231-WI method to suit our needs. A measurement campaign has been performed in Sardinia, Italy, to assess these improvements. A description of the campaign and of its results are reported in Section V. Finally, some conclusions are drawn in Section VI.

II. ANTENNA PATTERN RECONSTRUCTION

Using the definition of path loss L [see 1, eq. (3.5)], the electric field E(P) produced in any given point P by an RBS is given by

$$E = \sqrt{\frac{8\pi \cdot \zeta_0 \cdot P_t \cdot G(\theta, \phi)}{\lambda^2 \cdot L}} \tag{1}$$

where λ is the wavelength, $\zeta_0 = 377\ \Omega$ the free space impedance, P_t is the input power of the RBS transmitter antenna. The path loss L depends on the relative position of P respect to the RBS antenna and, in an urban environment, takes into account the multipath nature of the propagation [1]. In order to compute (1), we need the gain pattern [see 26, eq. (27)] of the RBS antenna in the direction (θ, φ) of the point P, which can be outside the main lobe of the antenna.

As well known, the antenna manufacturers make available only the gain values associated with the horizontal and vertical planes. This is an effective choice for the coverage computation, since only the main beam is involved in this case. On the other hand, we need the antenna gain also in the side-lobes directions. Before describing how this can be done, a remark is in order. Equation (1) for a multipath environment assumes that the gain for the starting directions of all rays contributing to E(P) is the same. It is however possible that P is in the sidelobe region and a main-beam ray contributes (after a reflection on a building, of course) to E(P). In this case (1) can only give an approximate value for E(P).

Several approaches have been proposed to compute the gain in these directions [27], [29]–[31]. They combine the data in the principal planes by using the angular distances arranged in weight factors, and can be grouped in "Weighted Summing Methods" and "Hybrid Methods." These last use the summing algorithm and a weighted method for the 3-D pattern computation. It is worth nothing that the far-field pattern reconstruction from the principal planes is more an interpolation than an extrapolation problem. As a matter of fact, every pattern is defined on the 4π sphere and so any point is surrounded by curves made of segments of principal planes. Therefore, in order to compute the pattern over the whole 4π sphere, we use the approach proposed in [28], which is built to

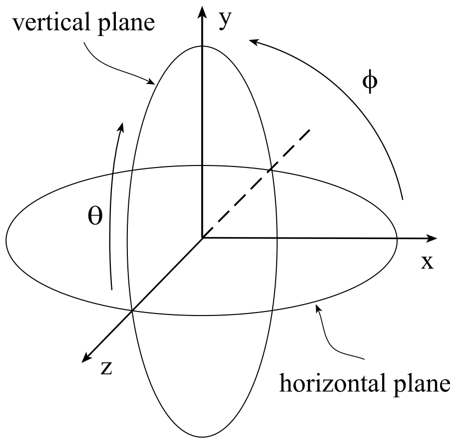


Fig. 1. 3-D geometry of the extrapolation problem.

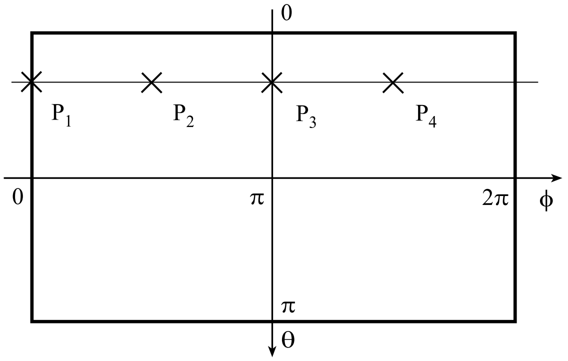


Fig. 2. Map of the far-field spherical surface.

stress, and exploit, this fact. As a matter of fact, the recursive approach proposed in [28] by our group is different from the weighted methods since it is based on the analytic properties of the EM field [36], [37] and uses an interpolation formula which is optimal with respect to the reconstruction error [38].

The knowledge of the horizontal (P_H) and vertical (P_V) radiation patterns of the antenna is assumed as starting point. The above discussion shows that the principal planes are mutually orthogonal and one of their intersection usually coincides with the direction of the maximum radiation intensity. The considered coordinate system is shown in Fig. 1.

According to the geometry, the data in the horizontal plane can be arranged into two functions of θ, namely $P_1(\theta) = P_H(\theta, \phi = 0)$, $P_3(\theta) = P_H(\theta, \phi = \pi)$ for $\theta \in [0, \pi]$.

In analogous way, the data in the vertical plane can be ordered in the functions $P_2(\theta) = P_V(\theta, \phi = \pi/2\ )$ and. $P_4(\theta) = P_V(\theta, \phi = 3\pi/2\ )$. For readers' convenience, it may be useful to map the far-field spherical surface on a planar surface described by the two angular parameters. Fig. 2 shows this representation. The upper (lower) horizontal line corresponds to the north (south) pole at $(\theta = 0)$, $(\theta = \pi)$. The left and right vertical lines are relevant to the same meridian at $\phi = 0, 2\pi$.

The central horizontal line represents the equatorial circumference at $\theta = \pi/2$, whereas the central vertical line corresponds to the meridian at $\phi = \pi$. Crosses in Fig. 2 indicate the points where the data are available for a fixed value of θ.

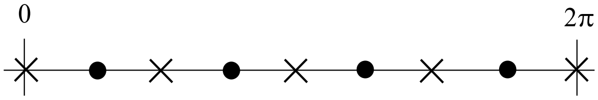


Fig. 3. First step in data reconstruction.

The first step is relevant to the computation of the four data at the middle points (dots in Fig. 3) of the angular distances between the input data. The Cardinal Series (CS) expansion [38] using the Dirichlet function is implemented for assembling the following linear system:

$$P_n = \sum_{i}^{N} P(\phi_i) \frac{\sin(0.5(N-1)(\phi_n - \phi_i))}{N \sin(0.5(\phi_n - \phi_i))}, \quad n = 1, \ldots, N \tag{2}$$

with $N = 4$ and $\phi_i = (2i - 1)\pi/4$. It can be rewritten in matrix form as

$$\underline{\underline{A}}\,\underline{x} = \underline{b} \tag{3}$$

where $\underline{b}$ is the sequence of the known data P_n, $\underline{x}$ is the sequence of the unknown data at the middle points $P(\phi_i)$, and $\underline{\underline{A}}$ is the $N \times N$ real matrix, whose elements are given by

$$A_{ni} = \frac{\sin(0.5(N-1)(\phi_n - \phi_i))}{N \sin(0.5(\phi_n - \phi_i))}. \tag{4}$$

A solution, which is the best approximation in the least squares sense, can be obtained by using the singular value decomposition (SVD) technique, so it results

$$\underline{x} = \underline{\underline{V}}\,\underline{\underline{W}}\,\underline{\underline{U}}^T b \tag{5}$$

wherein $\underline{\underline{V}}$ and $\underline{\underline{U}}$ are $N \times N$ orthogonal matrices, $\underline{\underline{W}}$ is diagonal and its elements are the inverse of the singular values of $\underline{\underline{A}}$.

Eight samples are now available as input data for the second step consisting in the evaluation of the eight data at the middle points. The linear system (2) with $N = 8$ is considered and solved by the applying the SVD technique. Sixteen samples are available as input data for the third step, and so on.

The method used to reconstruct the antenna pattern has been chosen according two criteria.

1) The procedure must provide comparable or better results than those obtained by other methods available in literature.

2) The procedure must be known and available to the research group.

Tests involving typical RBS antennas and dipole arrays have assessed the effectiveness of the chosen procedure and justified its use. Its performance has been compared with those of other methods in literature by taking advantage on the analytical formulation available for dipole arrays. Fig. 4 shows the reconstruction error (exact value – reconstructed value) obtained by applying our approach [28] and the method proposed in [29] to the pattern reconstruction of a simple array formed by two dipoles. They are z-oriented and located on the y-axis at y = 0 and y = 0.8 λ when f = 900 MHz. The reported observation region refers to the parallel at $\theta = 80°$ in

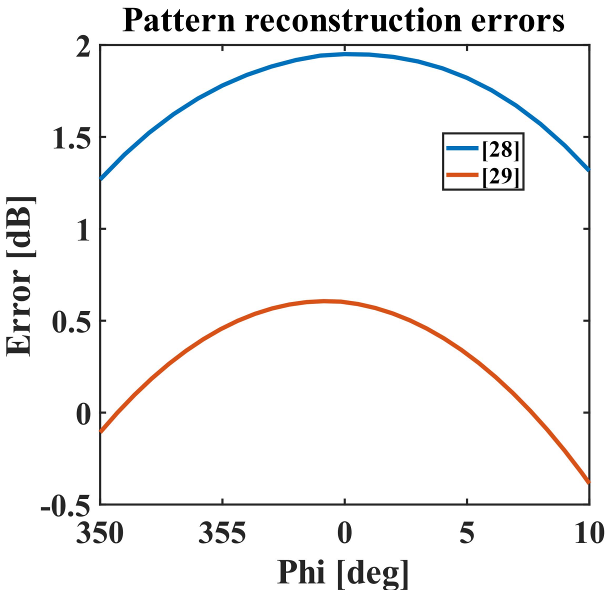


Fig. 4. Reconstruction errors for a two dipole array by applying the moethods from [28] and [29].

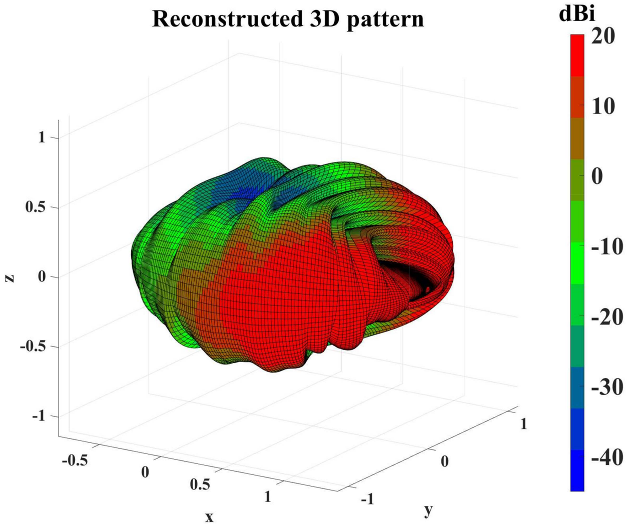


Fig. 5. Reconstructed tridimensional pattern for the Kathrein 730376 antenna using the explained algorithm.

the array reference system. It seems that the above procedure works well when compared with a weighted method.

The pattern reconstruction algorithm has been applied to the data in the horizontal and vertical planes of a commercial antenna for GSM communications, i.e., Kathrein 730376 (Kathrein Inc., Medford, USA), and the resulting tridimensional pattern is shown in Fig. 5.

III. EXTENDED VERSION OF THE COST231-WI

The EU-funded COST 231 project [6] developed and assessed, among other methods, the COST231-WI, an accurate urban path-loss model, based on a combination of Walfisch model [39] and Ikegami model [40]. This is an empiric and statistical model to estimate path-loss and coverage which makes use of an accurate statistical descriptions of urban environment. The description of urban environment is based on roof diffraction and rooftop-to-street propagation. The model allows to estimate the path loss based on several data used to describe the characteristics of the urban environment as follows.

D1) *Height of Buildings* h_{roof}*:* This parameter represents the mean height of buildings in the scenario of study.

D2) *Width of Roads* w*:* This parameter reflects streets mean width in the considered urban environment.

D3) *Building Separation* b*:* This is the mean buildings separation distance in the scenario of interest.

D4) *Road Orientation with Respect to the Direct Radio Path,* φ*:* This parameter describes the angle between the incident wave and the direction of the street where the point is located.

However, this model is not deterministic because no topographical database of the buildings is considered. Rather, these parameters are statistical ones and are representative of the local behavior if we assume a regular urban environment with buildings located on a regular and ordered grid.

The COST231-WI model can be applied to frequencies from 800 to 2000 MHz, distances from 0.02 to 5 km, RBS height from 4 to 50 m and mobile height from 1 to 3 m. Moreover, the COST231-WI model can also cope with RBS below the roof-top-level, improving what the original Walfisch-Bertoni can do [39]. As such, it fulfills, at least in part, our needs.

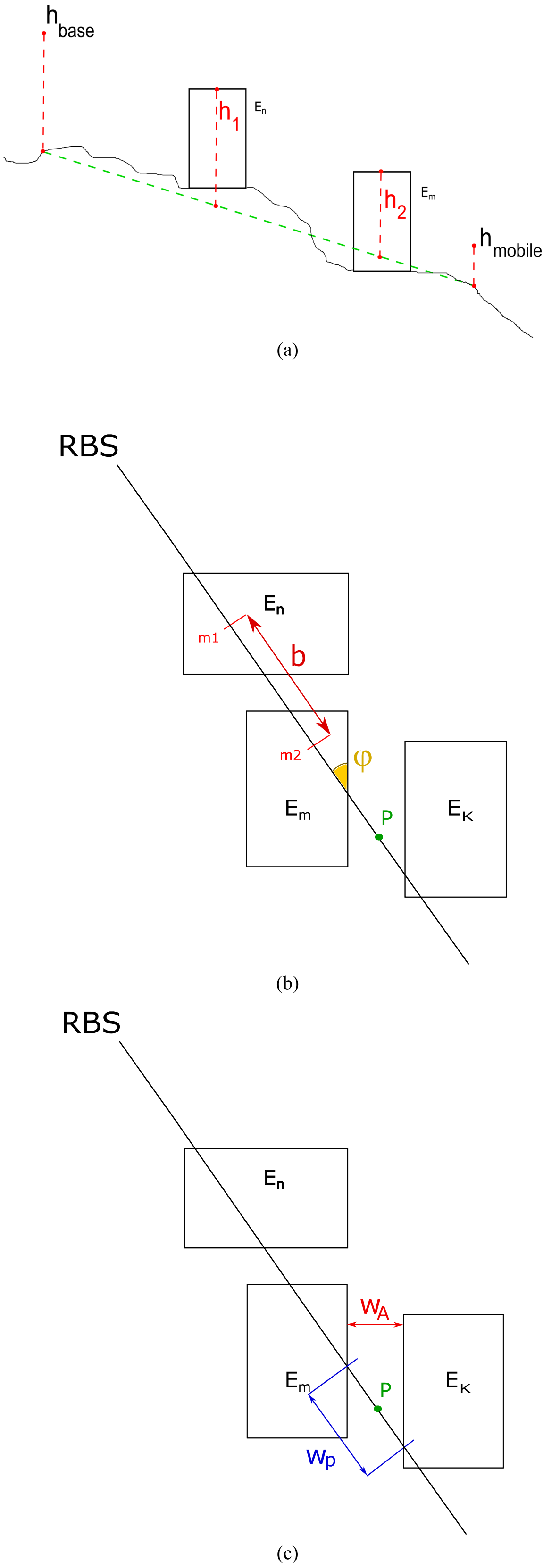
If these conditions are met, the estimation of path loss agrees rather well with measurements for RBS antenna heights above rooftop level. The mean error is in the range of +3 dB and the standard deviation is 4–8 dB [6]. However, the prediction error becomes larger for $\mathrm{h_{base}} \approx \mathrm{h_{Roof}}$ compared to situations where $\mathrm{h_{base}} \gg \mathrm{h_{Roof}}$. Furthermore, the performance of the model is rather poor for $\mathrm{h_{base}} \ll \mathrm{h_{Roof}}$, though some improvements are possible [41].

The COST231-WI model was designed for being utilized in a large urban environment with streets and buildings set in a regular grid (see [6, Figs. 4.4.1 and 4.4.2] or [40], Fig. 2). Since the aim of this article is to estimate accurately path loss and field values in urban environment with irregular grid, the COST231-WI cannot be used "as it is," but requires a suitable extension, based on the ideas behind it [39], [40]. The propagation path between RBS and field point interacts only with the building between these two locations, and with the first building beyond. Therefore, the data D1–D4 will be redefined as follows.

M1) h_{roof} as the arithmetic mean of the heights of buildings crossed by the propagation path, evaluated respect to the segment joining the base of the RBS antenna and the ground below the mobile [see Fig. 6(a)].

M2) w as the width of the street where the receiving mobile is located.

M3) b as the arithmetic mean of the separation distances between buildings that the beam crosses in its propagation path. Each distance is determined as the length of the segment that connects the middle points of the crossing sections related to two consecutive buildings along the propagation path



(a)

(b)

(c)

Fig. 6. Definition of parameters for the COST 231 – Walfisch-Ikami model. (a) Relevant to the definition of h_{roof} in the example $h_{roof}, = (h_1 + h_2)/2$. (b) Definition and representation of the parameters b and φ. (c) Representation of the two possible definition of the w parameter.

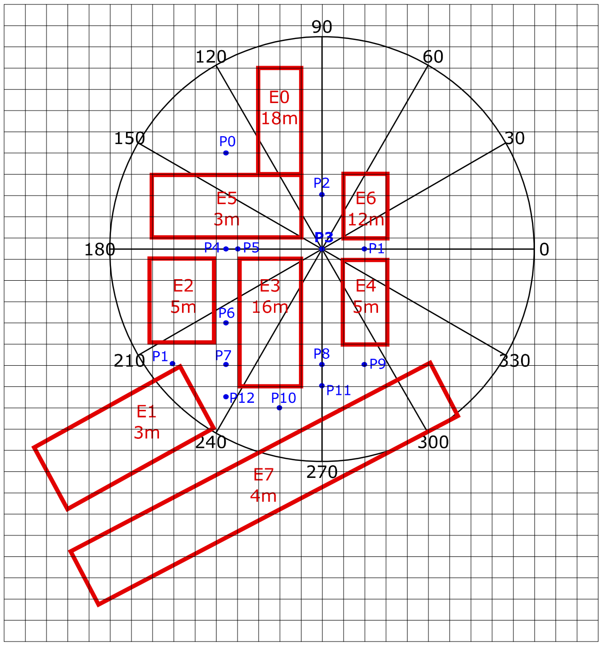


Fig. 7. Virtual city for the test. The antenna positions on the circle of unitary radius considered for the point P3 is reported.

[see b_i in Fig. 6(b)] ($b = 0$ when only one building or none at all are present along the path).

M4) φ as the angle between the propagation path and the last building wall crossed by it before reaching P [see Fig. 6(b)].

The definition M2 is still ambiguous, since it could be interpreted as the actual road width [w_A in Fig. 6(c)], or as the length of the propagation path inside that road [w_p in Fig. 6(c)]. There are good reasons in favor of both definitions. The former, w_A, takes into account that the propagation toward the mobile is inside a parallel-plane waveguide, delimited by the two buildings. The propagation constant and the losses of this "modal" propagation then depends on w_A [41]. On the contrary, in favor of w_p is the ray description of the propagation toward the mobile, which comes out directly from [40], one of the parents of the COST231-WI. Therefore, we have devised the test campaign also to tell between these two definitions of w.

Of course, these new definitions can lead to critical points, where at least one of M1–M4 cannot be defined, or has an unstable value. In order to investigate these critical points, we decided to implement a virtual city in order to establish the applicability conditions. The virtual city, shown in Fig. 7, was designed to get maximum control on physic and geographic parameters to study model performances. In the virtual city there is a group of points P0, P1, ..., P13 for which we computed the relative path loss levels in the hypothesis of positioning a RBS antenna every 30° in a circumference around the point itself with radius equal to 1 km.

Depending on the RBS position, one or the other points P0, ..., P13 can be critical, and this criticality must be overcome. As a matter of fact, the same strategy can be used for

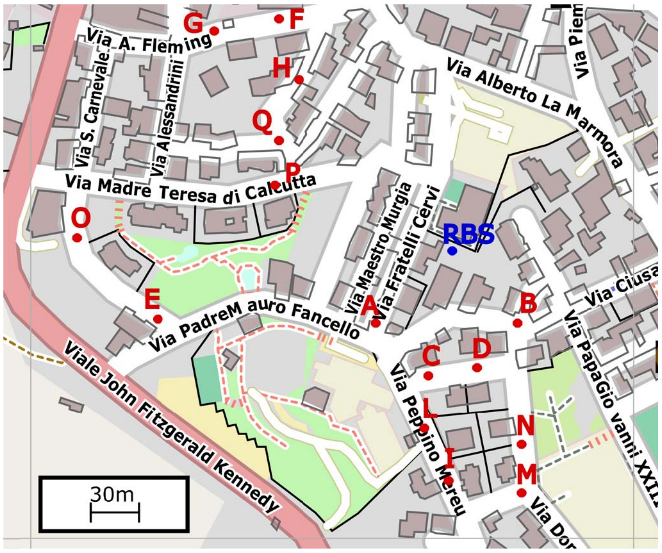


Fig. 8. Geometry of Dorgali measurement campaign at 944.2 MHz. Both the RBS position and the measurement points are shown. The RBS height is 20 m and its pointing direction is 300°.

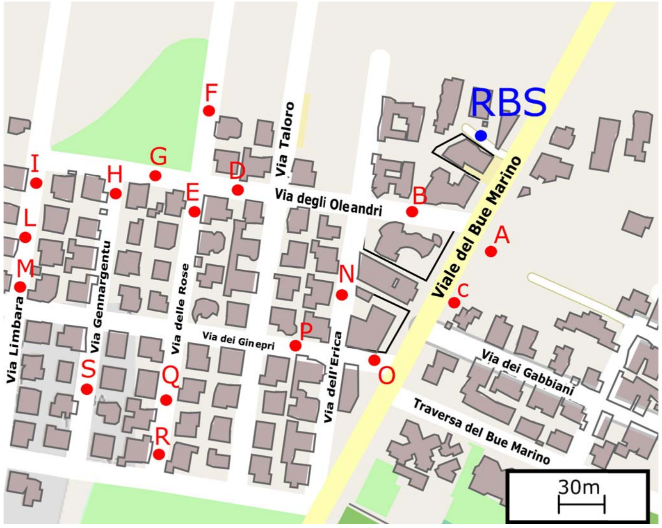


Fig. 9. Geometry of Cala Gonone measurement campaign at 1878.4 MHz. Both the RBS position and the measurement points are shown. The RBS height is 16 m and the RBS pointing direction is 200°.

all kind of critical point, so we describe in detail only one case.

It is clear from Fig. 7 that P3 is a critical point, since for many RBS locations, at least one of the parameters is undefined.

To handle such problem, it must be noticed that the COST231-WI model has been created to consider the mean path loss for mobile stations. Therefore, it is evident that such estimated path loss should vary slowly with position, without discontinuous changes (while actual measurements usually do not [42], [43]). Consequently, we evaluate the path loss and field level in a set of four points, located in the four cardinal directions (East, North, West, South) and distant 1 m (i.e., a few wavelengths) from the critical point. Then the arithmetic mean of these values is assumed as field level in the critical point. This operation has to be repeated for every antenna position and in every similar case to point P3. The dynamical changes have been eliminated by averaging the measured electric field value in V/m over 6 min.

IV. EM FIELD ESTIMATIONS IN THE TOWNS OF DORGALI (NU), CALA GONONE (NU) AND LUNAMATRONA (CA), AND COMPARISON WITH MEASURED VALUES

The definition COST231-WI model parameters, which describe the environment of the mobile radio link, has been suitable extended to cope with Italian small (and possibly hilly) towns of the having irregular building grids and very broad distribution of the geometrical parameters of buildings and roads. Some set of measurements have therefore been performed to assess our proposed extensions in all the frequency bands of interest for cellular communication, namely 900 MHz, 1.8 and 2.15 GHz. Of course, we are fully aware that COST231-WI has a limit frequency of 2 GHz. Nevertheless, we think that this model can allow a good accuracy also at 2.15 GHz, which is less than 10% beyond its maximum frequency. Therefore, thank to the availability of a few 4G RBS in Sardinia, we decided to test this frequency band, too.

All measurements have been made in the small towns of Dorgali (NU), Cala Gonone (NU) and Lunamatrona (CA) in Sardinia (Italy), using a YAGI antenna in the 1.8 and 2.15 GHz band and a Log-periodic antenna (LPDA) in the 900 MHz band as electric field sensor and transducer. A tripod has been used to position the antenna 1.5 m above ground. A Rohde-Schwarz FSH8 spectrum analyzer, operating from 9 kHz to 8 GHz and with an input impedance of 50 Ω has been used to measure the electric field. More than 15 measurement points have been selected for each location and their points have been selected for each location and their position, as well the RBS location, is shown in Figs. 8–10.

The main data of the three measurements campaign are summarized in Table I.

It is well-known that the RBS power has a daily periodic behavior [44], [45], synchronous with the traffic distribution and with variation up to 8–9 dBm between day and night [46]. Therefore we have made our measurement during the peak hours for traffic, when we can safety assume that the RBS power is equal to its nominal value.

The last row of Table I points to the results of each campaign. For each measurement point we have reported, beside the distance from RBS, the measured electric field, the electric field estimated using the approach described here and the estimation error. Coherently with the discussion of Section III about the computation of the width of the street w, we have computed the estimation using both $w = w_{\mathrm{A}}$ and $w = w_{\mathrm{P}}$ [see Fig. 6(b)] and consequently we have reported the two corresponding sets of estimation errors.

From the analysis of Tables II–IV it is clear that the best choice for the street width is to set $w = w_{\mathrm{P}}$ [see Fig. 6(b)]. As a matter of fact, the average error is around 2.4–3.0 dBV/m with this choice in all tested, while it grows to 3.9–5.4 dBV/m using $w = w_{\mathrm{A}}$.

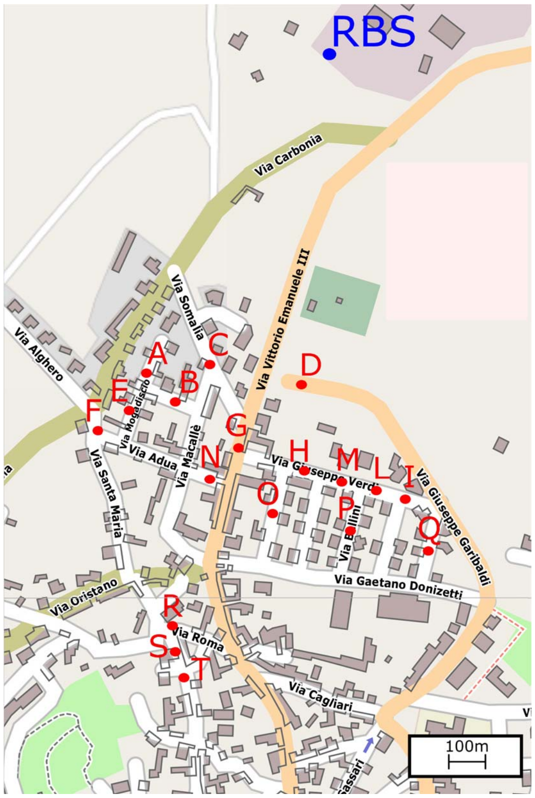


Fig. 10. Geometry of Lunamatrona measurement campaign at 2142.4 MHz. Both the RBS position and the measurement points are shown. The RBS height is 20 m and the RBS pointing direction is 190°.

TABLE I

MAIN DATA OF THE THREE MEASUREMENTS CAMPAIGN

Frequency	944.2 MHz	1847.8 MHz	2142.4 MHz
Site	Dorgali	Cala Gonone	Lunamatrona
RBS antenna	Kathrein 730376	Kathrein 742212	Kathrein 742212
RBS antenna height over local road level	20 m	10 m	30 m
Position of RBS and measurement points	Fig.9	Fig.10	Fig.11
Results	Table 2	Table 3	Table 4

To further support this conclusion, we have computed also the average estimation errors taking into account the sign of the error. In this case the differences between using w_P and w_A are even larger (1.1–1.5 dBV/m for $w = w_P$ versus 2.9–4.4 dBV/m for $w = w_A$).

This latter outcome can also be easily inferred looking at the error columns of the result tables. While for $w = w_P$ the sign of the errors are equally distributed, for $w = w_A$, the estimated field is almost always smaller than the measured one sometimes by more than 10 dBV/m. We want also point out that the definitions of the parameters describing the set of building involved in the propagation between the RBS and the mobile play a significant role when a small, (and possibly hilly) town with a significant variability in the building is considered. Our measurement campaigns were made in such towns and the data collected here show that we can obtain an accuracy equivalent to the one claimed by the COST231-WI [6] for large and almost homogenous cities. Comparing Table IV with Tables II and III we can also conclude that the COST231-WI can be safely extrapolated to the 4G 2.15 GHz band, since the corresponding estimation errors are comparable to the ones found at 900 MHz and 1.8 GHz.

TABLE II

RESULTS OF DORGALI MEASUREMENT CAMPAIGN

Measurement Point	Distance from RBS [m]	Measured Electric Field [dB V/m]	Estimated Electric Field with w = wA [dB V/m]	Estimated Error with w = wA [dB V/m]	Estimated Electric Field with w = wP [dB V/m]	Estimated Error with w = wP [dB V/m]
A	48,5	-32,1	-29,1	3	-28,1	4
B	60	-42	-44,6	-2,6	-44,1	-2,1
C	71,4	-29,6	-44,8	-15,2	-33,1	-3,5
D	67,6	-40,9	-50,9	-10	-44,2	-3,3
E	166,8	-24,4	-29,6	-5,2	-21,1	3,3
F	166	-41,3	-42,1	-0,8	-38,5	2,8
G	188	-40,9	-40,5	0,4	-37,2	3,7
H	135	-40,7	-38,2	2,5	-38,2	2,5
I	131,5	-26,9	-37,3	-10,4	-30,1	-3,9
L	88,4	-27	-35,7	-8,7	-28,7	-1,7
M	145	-40,5	-45,4	-4,9	-43,8	-3,3
N	115	-36,4	-46,1	-9,7	-36,6	-0,2
O	219	-27,2	-30,2	-3,0	-24,3	2,9
P	109	-38,6	-39,5	-0,9	-34,2	4,4
Q	119	-25,8	-30,2	-4,4	-21,6	4,2

TABLE III

RESULTS OF CALA GONONE MEASUREMENT CAMPAIGN

Measurement Point	Distance from RBS [m]	Measured Electric Field [dB V/m]	Estimated Electric Field with w = w_A [dB V/m]	Estimated Error with w = w_A [dB V/m]	Estimated Electric Field with w = w_P [dB V/m]	Estimated Error with w = w_P [dB V/m]
A	79,8	-47,2	-49,8	-2,6	-44,8	2,4
B	62	-59,6	-61,3	-1,7	-59,1	0,5
C	101,5	-48,1	-50,3	-2,2	-44,6	3,5
D	140	-49,7	-50,9	-1,2	-46,9	2,8
E	183	-55	-55,8	-0,8	-53,9	1,1
F	173	-50,8	-54,7	-3,9	-52,6	-1,8
G	203,5	-50,5	-56,7	-6,2	-48,6	1,9
H	228	-57,2	-62,2	-5,0	-58,5	-1,3
I	273,5	-56,1	-62,1	-6,0	-59,4	-3,3
L	281,5	-63,4	-65,5	-2,1	-59,7	3,7
M	300	-52,1	-64,5	-12,4	-53,6	-1,5
N	148,5	-48,8	-48,7	0,1	-45,3	3,5
O	150,6	-55,9	-60,4	-4,5	-60,2	-4,3
P	176	-49,3	-54,5	-5,2	-51,2	-1,9
Q	248,8	-50,4	-55,8	-5,4	-51,7	-1,3
R	282,5	-54,4	-58,5	-4,1	-51	3,4
S	314,8	-54,3	-57,9	-3,6	-51,3	3

We have also experimentally tested our claim that the actual field intensity in a point (critical or not) is the average of the field intensity around that point. This test have been done

TABLE IV
RESULTS OF LUNAMATRONA MEASUREMENT CAMPAIGN

Measurement Point	Distance from RBS [m]	Measured Electric Field [dB V/m]	Estimated Electric Field with w = w_A [dB V/m]	Estimated Error with w = w_A [dB V/m]	Estimated Electric Field with w = w_P [dB V/m]	Estimated Error with w = w_P [dB V/m]
A	438	-53,3	-49,4	3,9	-49,4	3,9
B	437,2	-59,3	-57,3	2	-57,3	2
C	412,7	-53,5	-56,7	-3,2	-54,3	-0,8
D	394,5	-32,9	-39,4	-6,5	-28,3	4,6
E	483,4	-47,3	-46,3	1	-44,7	2,6
F	519,5	-59,2	-58,1	1,1	-54,7	4,5
G	478	-40,6	-56,6	-16	-45,4	-4,8
H	489	-40,5	-50	-9,5	-42,8	-2,3
I	526	-46,6	-51,5	-4,9	-48,1	-1,5
L	519,8	-47,6	-50,4	-2,8	-47,7	-0,1
M	499	-52,4	-50,9	1,5	-48,1	4,3
N	516	-55,7	-55,7	0	-55,7	0
O	540	-44,3	-48	-3,7	-40,6	3,7
P	547	-43,3	-46,4	-3,1	-45	-1,7
Q	587	-44,3	-50,3	-6	-47,3	-3
R	698,3	-49,6	-51,5	-1,9	-51,5	-1,9
S	741	-58,7	-55,9	2,8	-55,2	3,5
T	779	-60,1	-58,2	1,9	-56,9	3,2

TABLE V
RESULTS OF REGULAR GRID MEASUREMENTS IN DORGALI

Measurement Point	Estimated Electric Field with w = w_P [dB V/m]	Measured Electric Field [dB V/m]	Estimated Error with w = w_P [dB V/m]	Averaged Measured Electric Field [dBV/m]	Estimated Error with w = w_P [dB V/m]
P1.1	-28,6	-27,5	-1,1	-29,7	1,1
P1.2	-28,7	-31,5	2,8	-30,2	1,5
P1.3	-29,3	-29	-0,3	-30,2	0,9
P2.1	-29	-30	1	-30,1	1,1
P2.2	-29,6	-32,8	3,2	-31,1	1,5
P2.3	-31,3	-30	-1,3	-30,2	-1,1
P3.1	-29,9	-30,2	0,3	-30,2	0,3
P3.2	-31,6	-31,1	-0,5	-30,6	-1,0
P3.3	-29,6	-28,9	-0,7	-29,3	-0,4
P4.1	-32	-29,4	-2,6	-30,1	-1,9
P4.2	-30	-30,2	0,2	-29,5	-0,5
P4.3	-30,3	-27	-3,3	-29,2	-1,1
P5.1	-30,3	-30,5	0,2	-29,8	-0,5
P5.2	-30,6	-29,6	-1	-30,3	-0,3
P5.3	-31,9	-30,8	-1,1	-29,1	-2,8

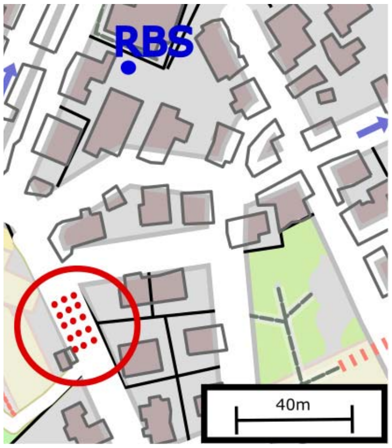


Fig. 11. Regular grid of equally spaced points within a single street in the town of Dorgali.

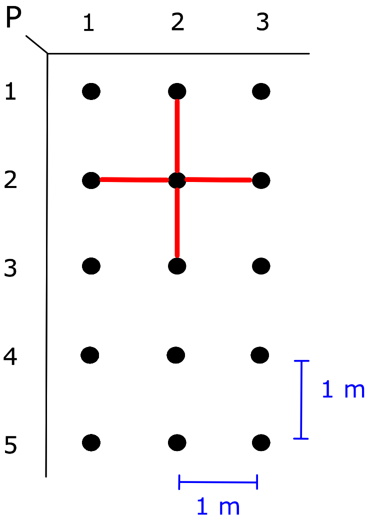


Fig. 12. Labeling of the measurement points of Fig. 10.

by performing a second measurement campaign in Dorgali, on a regular grid of measurement points, shown in Fig. 11 at a distance around 90 m from the base station. In Table V we show the measured field intensity, the estimated one and the measured field after averaging over four points (when available) or less (see Fig. 12) spaced 3 λ apart. It is clear, and expected, that the mean estimation error is around (3 dB) and can be as high as 5.5 dBV/m when the estimation and the point field value are compared. But if we compare the estimation with the averaged field, the differences are significantly lower, even less than 1 dBV/m for the internal points, when the average can be done on four points. The estimation provided by the COST231-WI, suitably modified, is therefore an averaged one, thus supporting our treatment of critical points. However, since the averaging is done on a region not larger than 1 m of diameter, the estimation still be considered local from the user point of view.

V. CONCLUSION

In this article we have shown how we can estimate the RBS EM field in an urban environment with irregular grids of small height buildings, such as small hilly towns, relying on the statistical re-definition of the COST231-WI model parameters. Moreover, using an in-house antenna pattern reconstruction technique which exploits the gain patter over both the horizontal and vertical planes to derive the distribution over the 4π sphere, the full 3-D radiation pattern of the RBS antenna is included to evaluate the EM field values. A measurement campaign was performed at 944.2 (2G), 1878.4 (3G), and 2142.4 MHz (4G) in the small towns of Dorgali (NU), Cala Gonone (NU) and Lunamatrona (CA), respectively. The error of the estimated EM field values, with respect to the measured value, is below 3 dB. The results assess our proposal, based on the COST231-WI model, showing that it can safely be extrapolated beyond its frequency limit of 2 GHz, to cope with the 4G 2.15 GHz band.

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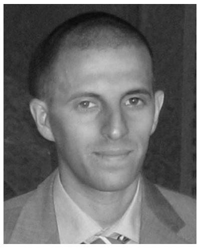

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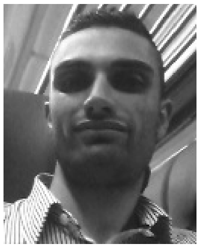

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