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Electromagnetic Field Levels in Built-up Areas with an Irregular Grid of Buildings: Modeling and Integrated Software

Luca Schirru [1] , Filippo Ledda [2], Matteo Bruno Lodi [3],*, Alessandro Fanti [3],*, Katiuscia Mannaro [4] , Marco Ortu [3] and Giuseppe Mazzarella [3]

[1] National Institute for Astrophysics (INAF), Cagliari Astronomical Observatory, Via della Scienza 5, 09047 Selargius, Italy; luca.schirru@inaf.it

[2] MetaCell Ltd., LLC, Boston, MA 02142, USA; filippo@metacell.us

[3] Department of Electric and Electronic Engineering, University of Cagliari, 09123 Cagliari, Italy; marco.ortu@unica.it (M.O.); mazzarella@unica.it (G.M.)

[4] Department of Mathematics and Computer Science, University of Cagliari, 09123 Cagliari, Italy; katiuscia.mannaro@unica.it

* Correspondence: matteob.lodi@unica.it (M.B.L.); alessandro.fanti@unica.it (A.F.)

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Abstract: The knowledge of the electromagnetic field levels generated by radio base stations present in an urban environment is a relevant aspect for propagations and coverage issues, as well as for the compliance to national regulations. Despite the growing interest in the novel fifth generation (5G) technology, several aspects related to the investigation of the urban propagation of the Global System of Mobile Communication (GSM), third generation (3G), and fourth generation (4G) mobile systems in peculiar non-rural environments may be improved. To account for irregular geometries and to deal with the propagation in hilly towns, in this work we present an enhanced version of the COST231-Walfisch–Ikegami model, whose parameters have been modified to evaluate the path loss at distances greater than 20 meters from the radio base station. This work addressed the problem of providing an effective, reliable, and quantitative model for the estimation of electromagnetic field levels in built-up areas. In addition, we also developed and tested a pre-industrial software prototype whose aim is to make the estimated electromagnetic field levels available to the key players in the telecom industry, the local authorities, and the general population. We validated the proposed model with a measurement campaign in the small urban and irregular built-up areas of Dorgali (Nuoro), Cala Gonone (Nuoro), and Lunamatrona (Cagliari) in Sardinia (Italy).

Keywords: radio propagation in an urban environment; electromagnetic field level; narrow band measurements; software prototype

1. Introduction

From the early 1980s, worldwide urban environments have witnessed a thorough technological innovation driven by telecommunication systems development. The contemporary users demand a high-quality experience, supplied by a continuous improvement of the services in order to ensure new mobile network functionalities. This results in an overwhelming diffusion of commercial cellular mobile networks, especially those operating in built-up environments in the cellular ultra-high frequency (UHF) bands [1]. Hence, the accurate prediction of the electromagnetic (EM) field levels produced by one or more radio base stations (RBSs) installed in a given urban area, the quantitative assessment of the coverage, and the estimation of loss factors in propagation paths, from the transmitter to the receiver, became determinant aspects for the design of the mobile network or for the evaluation of

the EM pollution in any urban environment of interest. Indeed, it is possible to verify if inhabitants are exposed to physical parameters in the limit prescribed by current regulations [2,3]. Moreover, today scientists must communicate scientific evidence clearly. The government agencies must inform people about safety regulations and policy measures, and concerned citizens must decide to what extent they are willing to accept such risk. In this process, it is important that communication among the stakeholders be done clearly and effectively [3]. In order to respond to the needs of mobile network design and the requirements of exposure regulations, theoretical models are able to predict efficiently how EM signal propagates represent valuable and reliable tools for these aims.

It is possible to obtain evaluations of path loss and interference considerations with a suitable propagation model [4,5]. Such a model for propagation in urban environments allows us to avoid long and expansive measuring campaigns, thus constituting a valuable tool for both coverage and exposure assessment. The propagation model must be chosen depending on the peculiar ambient to characterize. Hence, it can be utilized in both the planning and the design phase of the radio systems or when verifying the coverage aims and quality of the service (QoS). To define the model as valid, it is necessary to account for the essential features (e.g., altimetry, characteristics of buildings and streets) of the propagation scenario in an effective and accurate way, i.e., by summarizing the pivotal aspects of specific parameters.

Moreover, the mechanism of propagation for the selected environment has to be correctly described and modeled [4,5]. On the other hand, it is worth noting that the features of the linked antennas deployed in the given scenario must be included in the mathematical description of the types of urban propagation.

In the literature, several propagation models have been proposed. Depending on the descriptive approach of the selected urban environment, the numerical tools for the evaluation of field levels, these models are classified into two types. The former class contains statistical models, which makes use of parameters expressed as average values. The statistical models are used to study wide areas, where the exact evaluation of parameters is expansive. The second model type refers to the so-called deterministic models, which, on the other hand, make use of parameters with exact values, thus being useful for narrow urban areas. From the analysis of the state-of-the-art, it is possible to highlight that several studies were performed with the aim of achieving a correct description of the evaluation of the EM field produced by an RBS together with validation based on an adequate measuring campaign to efficiently monitor the exposure to the EM source. Indeed, a comparison between the EM field values derived from empirical–statistical models, namely, the COST231-Hata model and the COST231–Walfisch–Ikegami (C231WI) model [4,5], and experimental validation through a narrowband measurement campaign was carried out [1]. An interesting and useful study was conducted for the case of the city of Turin (Italy) [6], where the exposure of the population to EM fields generated by RBSs was assessed by comparing measured values with appropriate instrumentations and theoretical values derived from a model which did not consider attenuation and reflection from buildings. Furthermore, a thorough analysis was performed in the city of Monselice (Padova, Italy) with the aim of predicting field levels, considering the alteration due to the presence of buildings (attenuation and reflection), using two different approaches: the former through the expression of the far-field, the latter with the ray-tracing technique [7]. Reference [8] presented work about a comparison of the theoretical evaluation and measured values of power nearby a specific RBS.

The interest of the scientific community is also addressed in the monitoring of EMF levels in urban environments in order to assess the degree of population exposure to UHF EM fields. In the literature, several works focused on the use and description of peculiar and specific measurement systems, and experimental protocols can be found, as shown in Table 1. In Reference [9,10], the authors proposed an innovative monitoring system based on a wireless sensor network (WSN) able to keep under constant control the overall and cumulative EM field in the area of interest. The purpose of the system called SEMONT (Serbian ElectroMagnetic field MOnitoring Network) was the development of a useful tool for national and local agencies of Serbia for environmental protection, especially

to keep under control electromagnetic pollution and to asses real-time exposure of the population. In Reference [11,12], the authors presented a study based on the RF radiation levels produced by radio base stations in Serbia and focused the attention on the antennas set at roof height, which are the most common in the analyzed area. These studies [11,12] led to the valuable result of verifying that exposure levels were within limits prescribed by international standards. The problem of field estimation and EM monitoring is a worldwide issue and hence in other countries similar research was performed. For instance, in Turkey the concerns about EM exposure resulted in an indoor and outdoor measuring campaign to assess safety conditions for several inhabitants of a specific area in proximity to a GSM radio base station [13]. In Reference [14], it is possible to observe the results of a study carried out in the rural area of Bari (Italy) focused on the quantification of the effects of exposure to EM, generated by an RBS, on agricultural workers. With reference to the same topic, in [15–17] the results derived from the measurement of power density were compared with EM exposure levels in public areas in Nigeria, in a metropolitan zone in India, and in several areas of China, respectively. The monitoring of electromagnetic field strength from RBSs in urban environments was validated with narrowband measurement campaigns using a spectrum analyzer [17]. As a matter of fact, from this discussion, the experimental monitoring approach is certainly more expansive from an economical and temporal point of view compared with the theoretical and predictive way discussed previously. Therefore, for both the coverage assessment and the exposure concerns, a validated theoretical model constitutes a valuable tool.

Besides the model development and accuracy, as reported in Table 1, in the literature, relevant attention is paid to the translation of the propagation scheme into integrated software for displaying and sharing the field levels in a given area. Indeed, by using optical geometry and the geometric theory of diffraction, hence describing field propagation in terms of beams, a deterministic model was used to design software able to evaluate field levels in urban environments [18]. From the simplified model of antennas transmitting in free space, Windows-based software to predict EM field levels was developed [19].

Among the most relevant models used to predict radio signal propagation in urban environments, the COST 231 Hata model [4,5,20,21] and the COST 231 Walisch-Ikegami model [4,5,22–24] are used for any prediction at distances greater than 20 m from the RBS, as can be seen in Table 1. The COST 231 Hata model, which is an empirical and statistical technique, considers as main parameters the height of the RBS and of the terminal mobile, as well as the distance to the observation point. Therefore, the C231WI model results are more accurate, with respect to other models results. In fact, it can be classified as an empirical–statistical model (see Table 1), which makes use of a better and more careful description of the urban environment, thanks to the different approach to the propagation mechanism by diffraction by roofs and the roof–street linking/coupling [23]. Descriptive parameters for the environment are the average height and distance of separation between adjacent buildings, the width of the street, and the angle between the street and the line of conjunction of the RBS and the mobile station. These are all statistical parameters, and they assume that buildings in an urban center are arranged in a regular grid.

The fundamental working hypotheses of the C231WI can be considered acceptable in medium-sized and large cities; whereas, for the highly recurrent case of irregular, variable, hilly cities and small towns, the C231WI model would surely lose accuracy and effectiveness. The aim of this work is the development, validation, and use of a theoretical model which can describe the propagation of EM fields generated by GSM, 3 G, and 4 G RBSs (at frequencies of 944.2 MHz, 1847.8 MHz, and 2142.4 MHz) in urban scenarios of small, hilly towns with irregular street geometry and small houses with different shapes and heights. In this way, by modifying the definition of the propagation model parameters, it is possible to take into account the plethora of configurations and cases of interest for the coverage estimation and exposure assessment.

This estimation of EM fields from RBSs, using a propagation model based on a modified version of the C231WI, is used to develop an integrated software system with a dedicated mobile application

in order to share and visualize the estimated EM fields in a given area, thus informing the telecom companies, the local authorities, and the general population.

Table 1. Summary table of the state-of-the-art of propagation models and field level estimation.

Name	Category	Coverage	Scenario	Country	Year	Ref.
COST231-Hata Mode	Empirical	150 MHz–1.5 GHz d > 20 m	Urban	-	1980	[4,21]
COST231-Walfisch–Ikegami	Empirical	900 MHz–1.8 GHz d > 20 m	Urban	-	1999	[4,5,23,24]
Prasad et al.	Statistical Deterministic Statistical Empirical	1.8 GHz d > 20 m	Urban Suburban	India	2011	[1]
Anglesio et al.	Deterministic	100 kHz–3 GHz d > 20 m	Urban	Italy	2001	[6]
Giliberti et al.	Deterministic (Ray tracing)	3 MHz–3 GHz	Urban Suburban	Italy	2009	[7]
Miclaus and Bechet	Deterministic	900 MHz d > 20 m	Urban	Romania	2007	[8]
SEMONT	Empirical	700 MHz–2.6 GHz	Suburban	Serbia	2014–2020	[9–12]
Çerezci et al.	Empirical	900 MHz–2.1 GHz	Urban	Turkey	2015	[13]
Pascuzzi and Santoro	Deterministic	900 MHz–1.8 GHz d > 20 m	Urban Suburban	Italy	2015	[14]
Ojuh et al.	Deterministic	900 MHz	Rural	Nigeria	2015	[15]
Saravanamuttu et al.	Statistical Empirical	540 kHz–2.6 GHz d > 20 m	Urban	India	2015	[16]
Zheng and Zhigang	Deterministic	30 MHz–3 GHz	Urban	China	2015	[17]

In light of these premises, our work aims to develop a theoretical model for describing the propagation of UHF EM fields produced by one or more radio base stations in specific urban scenarios and at the same time increase awareness of the population at the EM field level in the interested zones. Originally, our research was initiated under an umbrella project called "Onde Chiare" and was supported by the Regione Autonoma Sardegna. This project aimed to answer the need of information about EM fields by the general public while satisfying the requirement of lowering the monitoring efforts of regulatory and local agencies. Accordingly, the first objective of our work was to develop a mathematical framework serving as a design tool for cellular networks and to predict coverage performances. Furthermore, the second objective was the development of a Web-based platform of mobile phone base stations and their emissions and simultaneously of a mobile application linked to this in order to give direct access to data in a user-friendly, reliable, up-to-date, and timely way. Our system aims to provide a common information basis for decision makers and the public and therefore presents the values of EM field levels to the interested population and checks whether the exposure to EMF is likely to be exceeded. In this way, it would be possible to activate procedures to reduce levels when they exceed the attention thresholds.

This paper makes the following contributions to the literature. First, it focuses on relevant models used to predict radio signal propagation in urban environments and then defines an enhanced model for the estimation of loss factors in propagation paths in order to predict accurately the EM field level produced by one or more radio base stations installed in specific urban environments. Secondly, it presents our pre-industrial software prototype called the Onde Chiare System (OCS) oriented to support the knowledge in the electromagnetic field and obtain general information about antennas and regulations. Then, it demonstrates with an experimental validation that the modified version of the COST231-WI model can deal with the built-up scenarios of hilly, largely variable, and small, irregularly arranged towns. The experimental validation is fundamental in order to use the proposed model and test the developed software system. Finally, a discussion of its implications and the conclusions are presented.

2. The Estimation of EM Field Levels

Basically, the field level depends on two factors, namely, the path loss between the RBS and the field point, and the RBS antenna gain in all directions. To calculate the electric field levels in any desired position, the following far-field equation was used [25]

$$E = \sqrt{\frac{8\pi\eta_0 P_t G(\theta,\varphi)}{\lambda^2 L}} \tag{1}$$

where E is the far field in V/m, η_0 is the vacuum impedance, P_t is the transmission power of the RBS transmitter antenna expressed in Watts, $G(\theta,\varphi)$ is the transmitter antenna gain as a function of vertical and horizontal angles in degrees, and L is the attenuation path loss of the electromagnetic signal.

In an urban scenario, there is more than one active RBS. For this reason, we must compute the field amplitude Ep for each RBS using the previous formula and then add the corresponding power density, since the fields of different RBSs are uncorrelated. Therefore, the total EM field is obtained using [25]

$$E_{Tot} = \sqrt{\sum_{p=1}^{n} E_p^2} \tag{2}$$

where n is the number of active RBSs. Regarding the transmitter antenna gain, it must be included in the model. In this work, the term $G(\theta,\varphi)$ was derived with the knowledge of the horizontal and vertical radiation patterns, which are provided by the manufacturers in the datasheets. Typically, the fields for the main E- and H-planes are known. However, the estimation of the electric field should be performed for a given arbitrary point. It is therefore necessary to derive the entire radiation pattern. Among the available methods, in this work, the gain of the transmitting antenna is used as input to the 3D interpolation algorithm from [25,26] in order to derive the full pattern and hence calculate the field levels in a given point. An explicative scheme of the reconstruction procedure is shown in Figure 1 for the case of a Kathrein 742212 antenna.

Modified Version of the COST 231– Walfisch–Ikegami Model

As discussed in the Introduction, a statistical and empirical model is preferable in order to respect and account for the actual topology of the built-up area under analysis in the model. Furthermore, in this work, a model valid for the UHF frequency range and for distances greater than 20 m from the RBS would be considered for coping with hilly and irregular built-up environments. The model which fulfills all these requirements is the C231WI model [4,5,23,24]. Indeed, for the frequency range from 800 MHz to 2000 MHz, for a set of mobile-to-RBS distances from 0.02 km to 5 km, RBS height from 4 m to 50 m, and for mobile height from 1m to 3 m, the COST231WI model allows the path loss evaluation considering the following parameters [4]:

- the height of the buildings in the given scenario (h_{roof});
- the width of the roads in the built-up area (w);
- the building separation (b);
- the road orientation with respect to the radio path (φ).

Therefore, the term L in Equation (1) is a function of these parameters, i.e., $L = L (h_{roof}, w, b, \varphi)$ [4]. A remark is in order. Indeed, in their classical form, the C231WI parameters could be representative of the local field behavior only for a regular urban environment with almost similar buildings having similar features, located in a regular and ordered grid [4]. This is a relevant limitation, considering that the majority of cases, especially in the Italian scenario, are represented by small, hilly towns with irregular arrangements of buildings having significant variability in their height [7,11–19]. When the best, regular configuration is analyzed, the theoretical estimation of the path loss differs by about +3 dB ± 4–8 dB from the measured values, in the case of RBS antennas with heights above the rooftop level [23,24]. Since, in the literature, the analysis of C231WI performances for the cases of non-regular grids, buildings with largely variable height, and set in a non-plane, hilly area has been poorly investigated, to date the error and the deviation of the predicted field levels with respect to measurements are not known. Therefore, employing the C231WI model would lead to unreliable theoretical predictions of EM field values, thus implying a noticeable bias in coverage prediction or

in the exposure assessment. Furthermore, for the C231WI model, it is known that the error becomes larger when $h_{base} \approx h_{roof}$, especially with respect to the case when $h_{base} >> h_{roof}$. Moreover, the C231WI has the shortcoming of dealing for distances very close to the source, i.e., the model effectiveness is scarce for $h_{base} << h_{roof}$. Therefore, there is room for improvement.
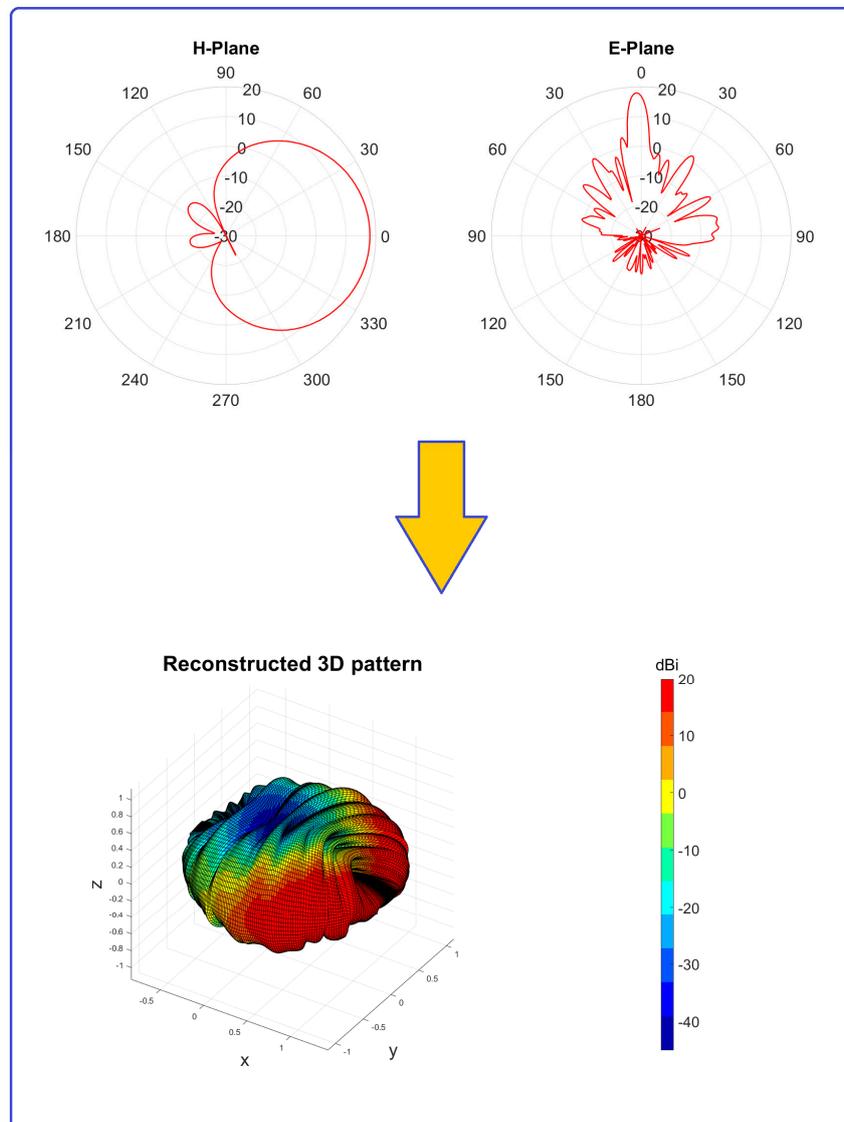

Figure 1. Example of the inputs and output of the algorithm for the 3D reconstruction of the antenna gain [25,26]. The case of the Kathrein 742212 antenna is presented.

It is possible to overcome the aforementioned limitations of the C231WI model by rephrasing and redefining the model parameters, as done in [25]. Instead of using the mean value of the buildings in the grid of interest, h_{roof} should be defined as the mean of the height of the buildings which are crossed by the propagation path, considering the segment which joins the RBS antenna and the ground below the mobile, as shown in Figure 2a [4]. This new definition of the roof height allows us to account for a hilly built-up environment [25], while ensuring the possibility of describing flat cities [5]. This is the built-up environment. Then, parameter w should be assumed to be equal to the width of the street where the receiving mobile is located. A clarification is in order. It is possible to interpret w as the actual road width (w_A) or as the length of the propagation path inside that road (w_p), as shown in Figure 2b [4]. Both possible definitions were tested and verified [25]. Indeed, w can be interpreted as the equivalent ray description of the propagation path (w_p) or as the length of propagation toward

the mobile inside a parallel-plane waveguide, with the two buildings as walls, which as the outcome that the dispersion of such a "modal" propagation is an unknown function of w_A [25]. The findings from [25] demonstrated that an actual road with ($w = w_p$) is the modeling strategy for which the prediction error is lower, with respect to the other w parameter evaluations. As regards the term b, in the proposed rephrased model, the arithmetic mean of the separation distances between buildings that are crossed by the beam in its propagation path is a more appropriate definition, as shown in Figure 2c. Finally, φ is redefined as the angle between the propagation path and the last building wall crossed by it before reaching the observation point (see Figure 2c). With these new set of parameters, it is possible to estimate the electric field level in a given urban area using Equation (1).

The modified version of the C231WI model is used to derive the field values in a given urban area. In this study, the model is validated and then used for the irregular and hilly towns of Dorgali (NU), Cala Gonone (NU), and Lunamatrona (CA), Italy. The Onde Chiare software uses the proposed model to derive by request the EM field value at the user location. In this way it is possible to monitor the electromagnetic field levels produced RBSs in urban environments and share this information with the interested stakeholders.
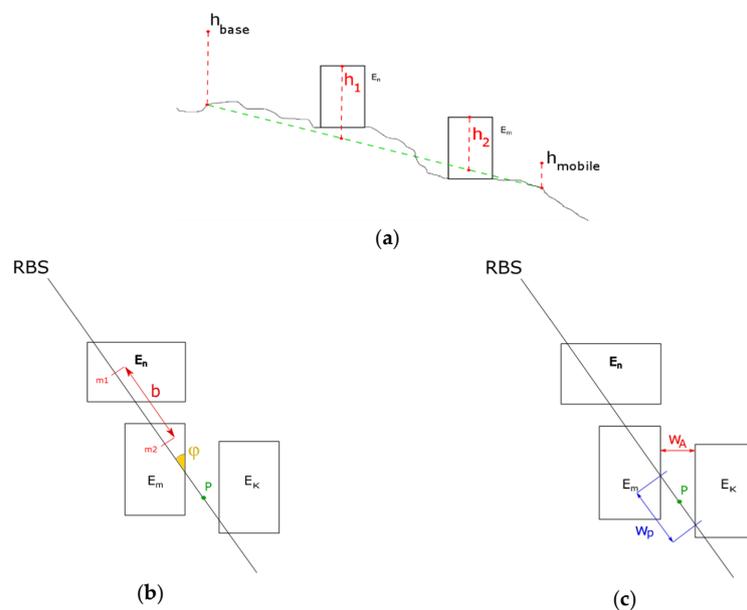
Figure 2. New definition of parameters for the COST231–Walfisch–Ikegami model [24]: (**a**) Schematic drawing of the re-defined parameter hroof to account for the hilliness of a given urban scenario; (**b**) Representation of the two possible definitions of parameter w. In this work, the definition $w = w_p$ is used [24]. (**c**) Definition and representation of the parameters b and φ. The rectangular boxes, named respectively, En, Em, and Ek, are the buildings crossed by the electromagnetic field during its propagation path from the RBS (see label in black) to the point P (see label in green). In addition, h_{base}, h_{mobile}, and $h_{1,2}$ represent the RBS height, the point P height, and the building height, respectively. Finally, the w, b, and φ parameters are the width of the roads in the built-up area, the building separation, and the road orientation with respect to the radio path, respectively

3. Onde Chiare Project

As introduced previously, the "Onde Chiare" project aimed to implement a model for the estimation of loss factors in propagation paths in order to accurately predict EM field levels produced by one or more RBSs installed in particular urban environments. Moreover, it had the goal of developing a regional database of mobile phone base stations and their emissions, while presenting to the public the values of EM field levels in order to show that the exposure to EM fields is below the prescribed limits. In this way it would be possible to activate procedures to reduce levels when they exceed the attention thresholds.

In the context of non-ionizing radiation, data communication as well as its acquisition has a significant importance. The acquired data may help in several functions. They can describe the environment quality and provide information to the local government for urban and territorial planning, but also to the public about the exposure to radio frequency, thus also reducing the concern about upgrades and reconfigurations of mobile phone RBSs. In this direction the project developed a Web-based platform in order to give direct access to data in a user-friendly, reliable, up-to-date, and timely way, providing a common information basis to decision makers and the public.

3.1. System Design

In detail, the software system named Onde Chiare System (OCS) is a pre-industrial prototype setting up a collaborative software platform of services oriented to support the knowledge in the electromagnetic field and obtain general information about antennas and regulations. The general functioning scheme of OCS is shown in Figure 3.
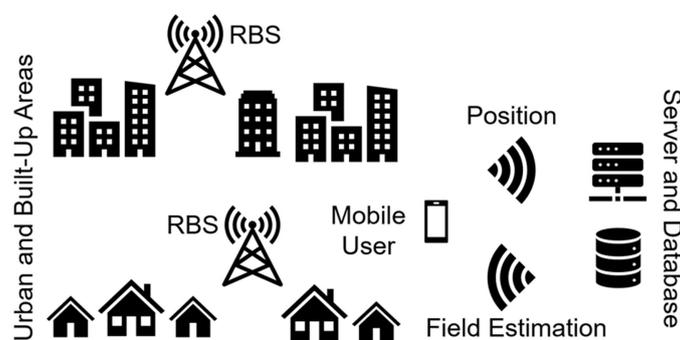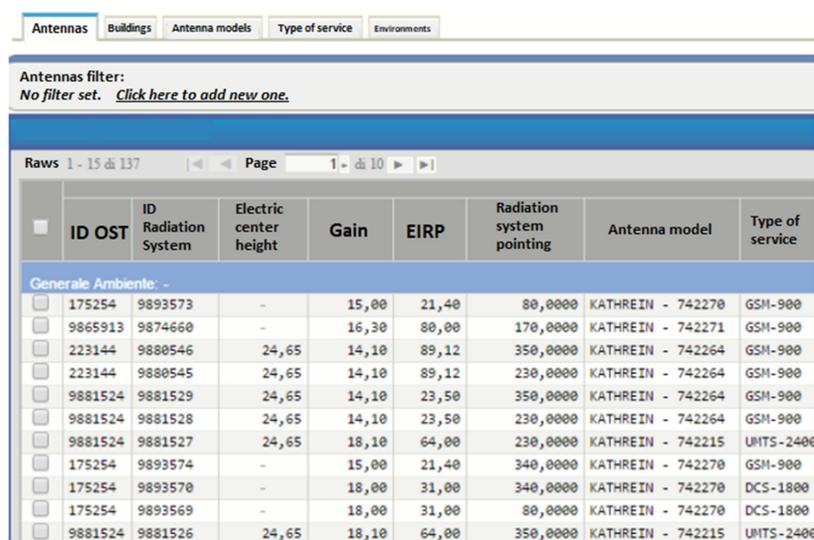

Figure 3. General scheme for the Onde Chiare system. The user can access the database, using an Android device, to check geolocalized information in order to recover the set of surrounding RBSs. The server elaborates the electric field estimation using the modified version of the C231WI model with the geographical and topological data and then sends the output to the user.

OCS has an online register containing the data of the cellular RBS (GSM, 3G, and 4G) installed over the regional territory of Sardinia (Italy). The system aims to support the planning of actions for administrative and regulatory purposes, both for the estimation of the electromagnetic field levels and the evaluation of the population exposure conditions. To address these requirements, the OCS provides a Web application (web app) and a mobile application (mobile app). The Onde Chiare web app maps the geographical distribution of the authorized radio transmitters in Sardinia and provides an information sheet for each of these stations. The map is based on the data supplied by Arpa Sardegna [27]—the regional public service agency responsible for environmental monitoring. This public agency supports the competent authorities in the planning, authorization, and sanctions in the environmental field and it has been tasked with collecting information about health concerns in relation to exposure from EM fields. In particular, the Onde Chiare web app is not only a data register that collects information of mobile phone base stations submitted by the telecommunication operators to the authorities, it also allows the users to observe the results of EM field levels estimated using the model described in the previous section, Section 2. Data are displayed on the map, but they can also be downloaded in various formats for further elaboration. The web app enables the government to manage the territorial and urban transformation processes from the environmental and social perspectives and citizens to gain valuable information about health risks of mobile communications.

OCS provides different access levels: public and private. For privacy and data protection issues, the private problem has different levels of accessibility: for example, restricted areas have been created for the municipalities and the mobile operators with password-controlled access. In practice, the local authority in its area of expertise can view the full specifications of the plants in its territory and can have only public data, not belonging to the municipality itself. An example of the information available

using the Onde Chiare system is shown in Figure 4. The database is based on a geographic information system (GIS) giving the antenna mast positions on a normal geographic map. To access the data, the user can type a specific address or the city, and once this is entered, the database will display the map showing an icon marker for each cellular base station in that area. Users can click on the icon and some information will be displayed, as shown in Figure 4b. The Onde Chiare system displays a map that includes both the location of the mobile antennas with technical information and the measurement performed to assess levels of exposure in the surrounding of the masts. Further information on mobile communications technologies and regulations, potential health risks, and research investigations about exposure to radiation are available in .pdf format. The data register can be visualized on mobile devices via a mobile app called the Onde Chiare app [28].

(**a**)

(**b**)

Figure 4. Examples of the web app of the Onde Chiare system. (**a**) The register of antennas contains information related to the position, the identification number, the height, the gain, the nominal power, the pointing direction, the antenna type, and the working frequency band. (**b**) The web app provides the actual location of the RBS in the region of interest, with the full set of information.

3.2. Onde Chiare App

The Onde Chiare app is a prototype designed for Android devices that was tested internally at the University of Cagliari [28]. Figure 5a shows the app main screen; it offers the possibility for each mobile device owner to become part of a network of distributed information made up of citizens interested in environmental issues. Indeed, the active participation of citizens has a fundamental role. The Onde Chiare app is an application that enables the community to promote a proper form of active involvement of citizens and real-time information sharing of electromagnetic field levels in a given geographical area. This mobile application provides some services such as:

1. Information about the geographic location and the input power of the antenna on the map, as shown in Figure 5b;
2. Geolocation of the electromagnetic field measurements;
3. Sending of geo-localized reports (i.e., broken antennas), as shown in Figure 5d.

(a)　　　　　　　(b)　　　　　　　(c)　　　　　　　(d)
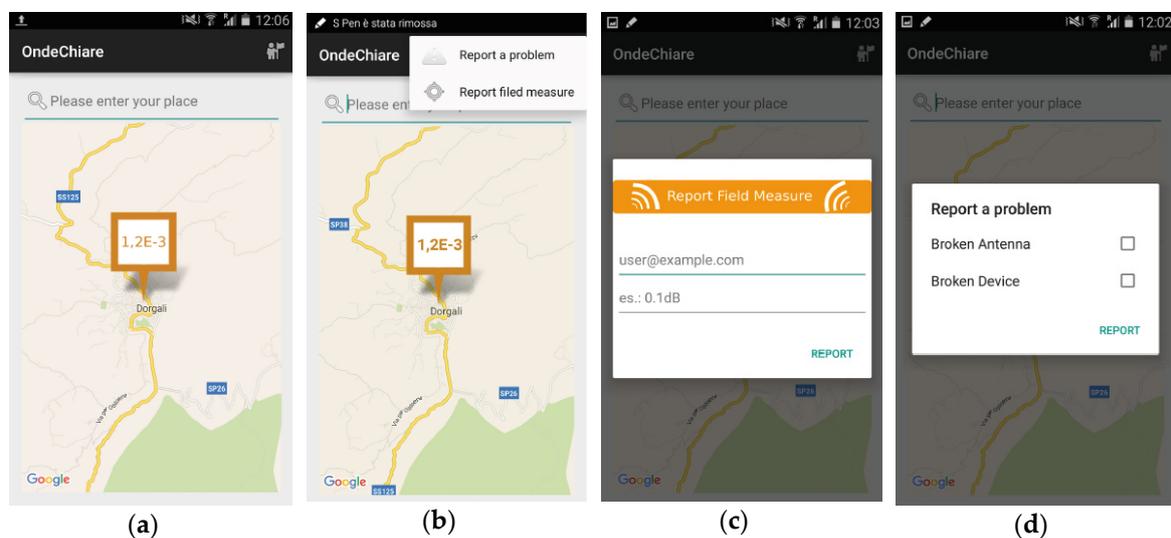
Figure 5. Examples of the app functionalities. (**a**) Main screen: the mobile user position is presented in the Google maps environment. (**b**) Report Menu. (**c**) User-suggested field measures for enhanced feedback. (**d**) Screen of the reported diagnostic tool.

The application allows a user to collect specific information directly from the system. Originally, we created our application in an Android development environment based on the Java Software Development Kit (SDK) 4 and Android 6.0. The application was developed using state-of-the-art frameworks, such as RoboGuice [29] for dependency injection [30] and Roboletric [31] for automated testing. Google Maps SDK was used to draw locations on a map in real time. The application places an informative marker on the user's current position on the map, as shown in Figure 5a. The user can also type a specific address, and the map shows all existing antenna masts. Each antenna mast is represented by an icon and by double-clicking on a specific antenna on the map, the basic technical information for the mast is displayed as in Figure 4b. The register includes information about the geographic location and the input power of the antenna and transmits to a centralized database via an unencrypted channel by stakeholders obliged to disclose information. This information is a set of organized technical data related to all transmission systems operating in the telecommunications sector, and the structured data are stored in a well-defined database. This system allows us to use our modified version of the COST 231 Walfisch–Ikegami model to estimate the field level in a given point within an urban area of interest. The OCS can be considered an effective tool for supporting regional actions in terms of planning, control, and supervision of the entire telecommunications system, while enabling us to assess the adherence to national obligations from the EM exposure point of view.

4. Model and System Validation: Measurement Campaign

To demonstrate that the modified version of the C231WI model can deal with the built-up scenarios of hilly, largely variable, and small, irregularly arranged towns, such as those often encountered in Italy, an experimental validation was carried out. The experimental validation is fundamental in order to use the proposed model to develop the software system.

The measurements were performed in the three UHF bands of interest. In particular, in the town of Dorgali (NU), the electric field levels were measured in the GSM band, at 944.2 MHz in the set of points shown in Figure 6a. For the frequency of 1847.8 MHz, the site of Cala Gonone (NU), presented in Figure 6b, was considered. Finally, the 4G coverage (2142.4 MHz) and exposure were assessed in the town of Lunamatrona (CA) in Sardinia (Italy), as shown in Figure 6c. Regarding the highest frequency band, a remark is in order. The C231WI model is known to be limited to an upper frequency bound of 2 GHz. This is a nominal constraint, but, in this work, relying on the method of [24], we corroborated the possibility of using the C231WI model at 2150 GHz with reasonable accuracy. At each site, the measurements were carried out using a YAGI antenna for both the 1.8 GHz and 2.15 GHz bands. On the other hand, a log-periodic antenna (LPDA) was used for the 900 MHz band. A tripod was 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 Ohm, was used to measure the electric field. Given the daily periodic pattern of the transmitted RBS power [32,33], which follows the traffic load and present variations of about 8–9 dBm between day and night [34], all the measurements were performed during the traffic peak hours [32]. At least 15 measurement points were selected for each location, and their position, as well the RBS location.

Figure 6. Topology of the three sites for the measurement campaigns. (**a**) Dorgali (NU, Italy): the working frequency of the RBS is 944.2 MHz, for a Kathrein 730376 antenna located 20 m above the road level. Fifteen measurement points were selected (A–Q). (**b**) Cala Gonone (NU, Italy): the working frequency of the RBS is 1878.4 MHz, for a Kathrein 742212 antenna located 10 m above the road level. Seventeen measurement points were selected (A–S). (**c**) Lunamatrona (CA, Italy): the working frequency of the RBS is 2142.4 MHz, for a Kathrein 742212 antenna located 30 m above the road level. Eighteen measurement points were selected (A–T).

5. Results

The extended version of the C231WI model [24] and the Onde Chiare system were experimentally validated, and their effectiveness in the estimation of electric field levels was assessed, as described in Section 4. The first urban scenario was the town of Dorgali (NU, Italy), as shown in Figure 6a. The measured electric field values are reported in Table 2. To derive the related estimated EM field levels, for each of the fifteen measurement points, using the new definition of the model parameters

given in Section 2 (see Figure 2), the OCS is accessed to retrieve the information about the nearest RBS. Then, the 3D pattern of the antenna gain is derived using the reconstruction algorithm [25,26]; hence by applying Equation (1), the resulting theoretical electric field value is derived, as reported in Table 2. It can be noticed that at the frequency of 944.2 MHz (2G), for distances from the RBS which range from 48.5 m to 166.8 m, the maximum error is about 4.5 dB V/m, which is coherent with the original version of the model [4] and previous literature results [25]. When the frequency increases to 1847.4 MHz (3G), in the case of Cala Gonone (NU, Italy), i.e., Figure 6b, the Onde Chiare application, following the aforementioned steps, returns estimated values of the electric field levels very close to the measured ones, as reported in Table 3. Indeed, for a range of distances from the RBS greater than the previous case (i.e., from 62 m to 314.8 m) the average error is about 0.61 dB V/m, with a maximum error 10% lower than that found for 944.2 MHz. For the highest frequency band, i.e., 2142.4 MHz, at the site of Lunamatrona (CA, Italy) presented in Figure 6c, the modified C231WI model and the OCS can provide an estimated electric field level very similar (from −4.8 dB V/m to 4.5 dB V/m, for RBS distances from 412.7 m to 779 m) to the measured one, as shown in Table 4.

Table 2. Results of the Dorgali measurement campaign (944.2 MHz, Kathrein 730376).

Point	Distance from the RBS (m)	Measured (dB V/m)	Estimated (dB V/m)	Error (dB V/m)
A	48.5	−32.1	−28.1	4
B	60	−42	−44.1	−2.1
C	71.4	−29.6	−33.1	−3.5
D	67.6	−40.9	−44.2	−3.3
E	166.8	−24.4	−21.1	3.3
F	166	−41.3	−38.5	2.8
G	188	−40.9	−37.2	3.7
H	135	−40.7	−38.2	2.5
I	131.5	−26.9	−30.1	−3.9
L	88.4	−27	−28.7	−1.7
M	145	−40.5	−43.8	−3.3
N	115	−36.4	−36.6	−0.2
O	219	−27.2	−24.3	2.9
P	109	−38.6	−34.2	4.4
Q	119	−25.8	−21.6	4.2

Table 3. Results of the Cala Gonone measurement campaign (1847.8 MHz, Kathrein 742212).

Point	Distance from the RBS (m)	Measured (dB V/m)	Estimated (dB V/m)	Error (dB V/m)
A	79.8	−47.2	−44.8	2.4
B	62	−59.6	−59.1	0.5
C	101.5	−48.1	−44.6	3.5
D	140	−49.7	−46.9	2.8
E	183	−55	−53.9	1.1
F	173	−50.8	−52.6	−1.8
G	203.5	−50.5	−48.6	1.9
H	228	−57.2	−58.5	−1.3
I	273.5	−56.1	−59.4	−3.3
L	281.5	−63.4	−59.7	3.7
M	300	−52.1	−53.6	−1.5
N	148.5	−48.8	−45.3	3.5
O	150.6	−55.9	−60.2	−4.3
P	176	−49.3	−51.2	−1.9
Q	248.8	−50.4	−51.7	−1.3
R	282.5	−54.4	−51	3.4
S	314.8	−54.3	−51.3	3

In order to highlight that the new definitions of the model parameters which describe the set of buildings involved in the propagation between the RBS and the mobile are pivotal for the case of small, hilly towns with a significant variability in the topology and environment, it is worth noting that an accuracy equivalent to the one claimed by the original C231WI in the case of large and almost homogenous cities is obtained [4]. In other words, with the results from Table 2 to 4, it is demonstrated that the modified version of the C231WI model and the OCS perform similarly to the original model, but for a worst and complex case. We have summarized these findings in Figure 7 in order to present

the model and system performances against the distance from the RBS and the working frequency. The error of the estimated field level oscillates randomly with the distance from the RBS. However, from Figure 7 it can be noticed that for the three sites, the distribution of the error is similar for the three built-up areas of interest. This implies that the prediction error is similar across the UHF frequency band considered in this work. By remembering that the original C231WI model was developed to work at a maximum frequency of 2 GHz [4,25], the findings from Figure 7 corroborate the possibility of extending the model to higher frequency as long as its parameters are modified, as explained in Section 2. As a conclusion, the validation campaign demonstrated that the modified version of the C231WI model and the Onde Chiare system are effective, accurate, and reliable tools for the prediction of EM field levels in irregular, hilly built-up areas, thus being a technological solution for companies from the telecommunication system or for local regulatory agencies.

Table 4. Results of the Lunamatrona measurement campaign (2142.4 MHz, Kathrein 742212).

Point	Distance from the RBS (m)	Measured (dB V/m)	Estimated (dB V/m)	Error (dB V/m)
A	438	−53.3	−49.4	3.9
B	437.2	−59.3	−57.3	2
C	412.7	−53.5	−54.3	−0.8
D	394.5	−32.9	−28.3	4.6
E	483.4	−47.3	−44.7	2.6
F	519.5	−59.2	−54.7	4.5
G	478	−40.6	−45.4	−4.8
H	489	−40.5	−42.8	−2.3
I	526	−46.6	−48.1	−1.5
L	519.8	−47.6	−47.7	−0.1
M	499	−52.4	−48,.1	4.3
N	516	−55.7	−55.7	0
O	540	−44.3	−40.6	3.7
P	547	−43.3	−45	−1.7
Q	587	−44.3	−47.3	−3
R	698.3	−49.6	−51.5	−1.9
S	741	−58.7	−55.2	3.5
T	779	−60.1	−56.9	3.2
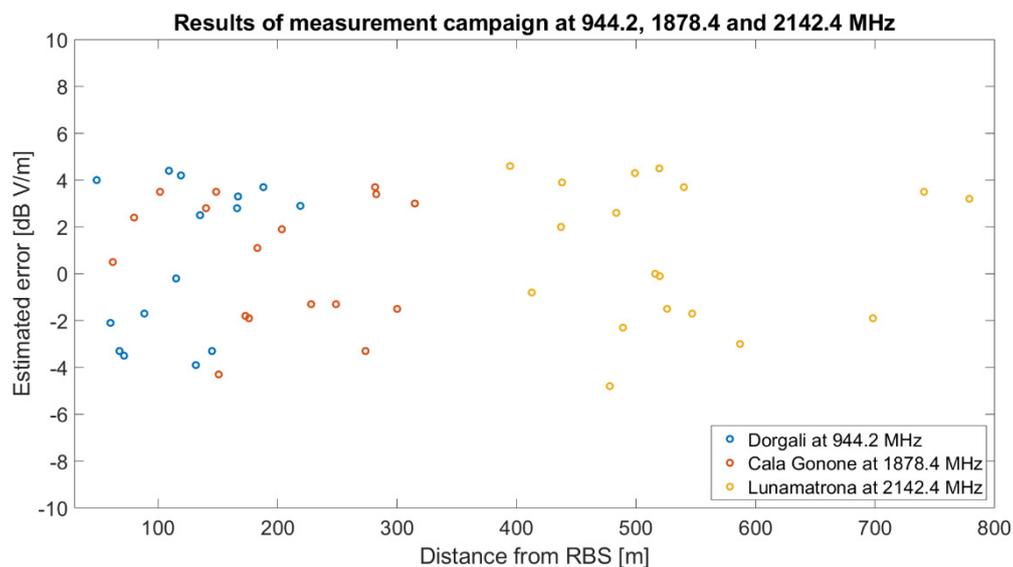
Figure 7. Comparison of the estimated error with our modified version of the C231WI model for the three built-up scenarios of Dorgali (NU, Italy), Cala Gonone (NU, Italy), Lunamatrona (CA, Italy) at the UHF frequencies of 944.2 MHz, 1878.4 MHz and 2142.4 MHz.

6. Conclusion and Future Work

In line with our research work, we addressed the problem of providing an effective, reliable, and quantitative model for the estimation of electromagnetic field levels in built-up areas. In particular, the COST 231 Walfisch–Ikegami model was re-phrased and modified in order to allow the description of small, hilly towns with buildings of largely variable height, arranged in irregular grids. The novel methodology was validated by performing a measurement campaign in three different sites for the three different GSM, 3G, and 4G frequencies, namely, 944.2 MHz, 1878.4 MHz, 2142.4 MHz. The values of the estimated electric field differed by a maximum of about 5 dB relative to measured ones, for a large set of distances from the RBS and for all frequencies. These findings corroborate the possibility of using the modified C231WI model for urban environments which are significantly different from those for which it was initially developed [25]. Furthermore, our results support the feasibility of extending the use of this model up to 2.5 GHz with reasonable accuracy. Given this experimental evidence, and since the development of 5G technology already resulted in the deployment of RBS stations, it is questionable if our modified C231WI model could be extended to the 3.6–3.8 GHz band, for both monitoring and coverage issues [35–37]. Indeed, in the literature, there is a lack of models and experimental strategies for EM propagation in urban environments [38], such as those investigated in this work, even though several studies which cover the synthesis of antennas, protocols, and systems for 5G exist [39–41]. Future work may deal with the definition and correction of the model parameters for EM signals of higher frequency, with the goal of ensuring the same accuracy and reliability of the estimated electric field levels.

Moreover, our research work aimed to answer the information needs of citizens about EM fields while satisfying the requirement of lowering the monitoring efforts of regulatory and local agencies. Accordingly, we developed a pre-industrial software prototype called the Onde Chiare System oriented to provide real-time knowledge of electric field levels in a given area. It is a valuable tool to improve the communication efforts by local authorities and facilitate the policy makers to make careful planning decisions and inform the citizens on environmental issues.

This technological solution may be further refined to develop a commercial product that could be of interest for telecommunication industries to speed-up the coverage assessment or setup a user-driven diagnostic system based on the app feedbacks. Furthermore, the Onde Chiare system may be used as a platform for regulatory agencies and entities for the environmental monitoring of general public exposure to electromagnetic radiation, while serving as an informative tool for citizens concerned about EM pollution-connected risks.

Conflicts of Interest: The authors declare no conflict of interest.

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