Birth and Development of the "Electromagnetic Fields" Group

Graziano Cerri, Marco Farina, Luca Pierantoni, Antonio Morini, Franco Moglie, Valter Mariani Primiani, Leonardo Zappelli, Andrea Di Donato, Alfredo De Leo and Paola Russo

Abstract It is a popular opinion that the electromagnetic fields are only related to telecommunication systems as a carrier of the information. This is certainly true, but it is also in some way misleading because it excludes a lot of applications of paramount interest both from a research and a technological point of view. In this sense the research activity of the "Electromagnetic fields" group is exemplary. In fact, without disowning telecommunication applications, the research has been increasingly oriented towards new and original aspects, not strictly related to ICT. This new point of view led to deepening more and more topics related to physical aspects of the interaction between the electromagnetic fields and matter. As a consequence, models describing the behaviour of the electromagnetic fields in non-conventional environments were developed. For example, models combining Maxwell and Boltzmann equations to treat the non-linear effect of the plasma ignition were introduced; by the same token a multi-physical approach Maxwell-Schrödinger/Dirac to characterize the problem of the quantistic transport in nano-structured materials was developed. In the paper the most important research topics, their developments, applications and their evolution will be presented.

1 Early Development

The activity of the "Electromagnetic Fields" research team (simply 'group' hereinafter) started at the beginning of the 80s of the last century, when Prof. Roberto De Leo, full professor of "Electromagnetic Fields", moved from Università di Bari to Università di Ancona. He immediately was aware of the development possibility offered by a new university and contacted Prof. Tullio Rozzi, full professor of "Microwaves" at the University of Bath (UK), who soon thereafter moved from England to Ancona. So, the development of the two main research lines that have always characterized the activity of the group can be dated back at the first half of the 80s.

G. Cerri (✉) · M. Farina · L. Pierantoni · A. Morini · F. Moglie · V. M. Primiani · L. Zappelli · A. Di Donato · A. De Leo · P. Russo
Dipartimento Di Ingegneria Dell'Informazione, Via Brecce Bianche, Ancona, Italy
e-mail: g.cerri@univpm.it

S. Longhi et al. (eds.), *The First Outstanding 50 Years of "Università Politecnica delle Marche"*, https://doi.org/10.1007/978-3-030-32762-0_2

One of the most important research topic investigated by Prof. De Leo group was the study of the environmental impact of the electromagnetic fields, a subject that allowed the Ancona research unit to become one of the most relevant at national level in this field, anticipating problems who would have gained the attention of the scientific community and common people many years later.

In the very general context of the environmental impact, we consider both the interaction between electromagnetic fields and human body, and the coexistence of electronic devices and equipments in the same space. The first topic concerns the safety aspects of the electromagnetic fields, the second electromagnetic compatibility (EMC) problems.

The dosimetry studies aimed to evaluate the power deposition into human tissues when exposed to electromagnetic fields allowed to develop original models and experimental techniques, that were progressively applied to investigate the problem of the therapeutic use of the electromagnetic fields. In particular, hyperthermia treatments, that is the possibility to nurse tumoral tissues with temperature enhancement through electromagnetic radiation, were intensively investigated. The key point was the design of the applicator, the antenna to be placed on the patient skin to radiate the cancer region. The challenging aspects were the design of the radiating structure in the very near field of the antenna, especially for the problem of the matching conditions varying from a patient to another, and the capability to focus radiation into the tumor, avoiding temperature increase of the healthy tissues. These studies led to cooperate with other academic institutions and with industrial partners: in the first case cooperation resulted in an European Project, and in the second one it gave rise to the realization of a device for hyperthermia treatment successfully tested in hospitals [1–7].

In the same time the group investigated the problem of the brain cortex stimulation with pulsed magnetic fields, showing a capability to anticipate forthcoming scenarios, because this technique is currently investigated as possible treatment of some neurological disorders as depression and Parkinson. In Ancona the research was essentially addressed to study the possibility of replacing the electrical brain stimulation, painful and uncomfortable for the patient, with the magnetic stimulation, without any inconvenience for the patient, aimed to check damages of the motor area of the brain cortex. Also in this case the research activity, in cooperation with some neurologists of the regional hospital, was at first directed to develop a realistic model to evaluate the interaction between a magnetic pulse and a human brain, in particular the current density distribution into the brain, and then to the design of applicators able to focus the currents in specific regions [8–10].

Ancona was also one of the first Italian university to deeply take care of the EMC aspects, both as a research topic and as an educational matter. In fact the University of Ancona was the first in Italy to insert a class of 'Electromagnetic Compatibility' in the degree course of 'Electronic Engineering', so fostering the change of philosophy in modern engineering design, in the sense that EMC should not be considered an accidental trouble, but an important aspect of the design constraints, because EMC phenomena have a rigorous electromagnetic support and can be accurately modelled. In the early 90s, on behalf of the Italian branch office of Hewlett Packard, the group gave many lectures in different Italian locations to engineers coming from Italian industries. From a research point of view the group investigated aspects concerning both external and internal compatibility. In the first case the focus was the shielding effectiveness of enclosures with particular concern to apertures and resonance effects, whereas, in second case, crosstalk effects among traces of PCBs were theoretically and experimentally characterized [11–15]. However the topic that had not been deeply studied yet in the literature, and that gave the group the maximum international visibility was the systematic approach to the study of fast and intense transient fields, mainly due to ESDs events or generated during EFT tests. Accurate models, experimentally validated, in the time and frequency domain, for linear and non-linear devices were developed, and allowed to show direct and indirect effects, excitation of dangerous resonances [16–20].

In early 90's group headed by Prof. Rozzi started works on advanced electromagnetic models of several kind of waveguides, in particular planar structures. The research was aimed to obtain numerically efficient and accurate models of, e.g., microstrip and coplanar waveguide accounting for actual thickness and losses of conductors, in contrast to what available at the time, where finite thickness and losses were addressed by approximate perturbative approaches. This way a new technique was discovered, the so called "Generalized Transverse Diffraction Resonance" (GTRD) approach. At the end of 90's this was applied not only passive waveguides but also to active devices, such as Field Effect Transistors, in order to model a new class of distributed amplifiers (Travelling Wave FET), and principles were discussed in-depth in a book [35] edited by the IEE (currently IET), London. While the approach was conceived for 2D, namely waveguide, in so called eigenvalue problems, there were initial ideas to extend it to a fully arbitrary 3D circuit (deterministic problem). As matter of fact this process was later accomplished between the end of 90's and early years of the new millennium, and a software, called Electromagnetic 3D Simulation (EM3DS) was developed as result of such theories. EM3DS was among the very few general purpose simulation software available at that time—likely one out of 10 or slightly more- and gained popularity being used by many relevant institution and companies (e.g. NASA,[1] Intel,[2] L3 comm[3] etc.), and integrated in commercial software by Intellisense[4] (Corning) and Coventor,[5] while being able to work seamlessly with software like Microwave Office (AWR,[6] currently National Instruments). Further studies involved coupled acoustic waves and electromagnetic waves for integrated resonators like BAW and TFBAR.

[1] https://www.nasa.gov/centers/glenn/home/index.html.

[2] https://www.intel.com/.

[3] https://www.l3t.com/.

[4] http://www.intellisense.com/.

[5] https://www.coventor.com/.

[6] https://www.awrcorp.com/.

2 From the Old to the New Millennium

We have to consider that in these years an extraordinary growth of the mobile telecommunication systems led to a dramatic increase of the number of base stations in urban areas: as a consequence the problem of the exposition of the population to electromagnetic fields became a matter of discussion on the media, in public meeting, at the central and local parliaments. As a consequence, the study of the electromagnetic environmental impact was the natural evolution of the previous studies concerning the interaction of the fields and the human body. A further motivation to approach the problem came from the continuous requests of many local governments to participate to the writing of the 'antenna planning' for cellular networks. The group decided to face the problem with a very general approach, consisting in an innovative philosophy, where the electromagnetic impact should have been a constraint of the network, as other telecommunication requests. More specifically, the problem concerns the choice of the RBS positions, antenna tilts and heights, and radiated powers for a specified number of RBSs serving the interested area. The proposed solution is based on an optimization procedure that carries out the following principal requirements: (1) minimization of the radiated electromagnetic field, (2) maximization of the C/I ratio, (3) minimization of the distance between RBSs and the area with more traffic, (4) maximization of the coverage percentage, and (5) maximization of the efficiency of the base station system. Original techniques based on artificial neural networks were developed to efficiently evaluate the path loss of the electromagnetic waves in urban environment, and, in the framework of a project of the national agency for environmental protection, a method was proposed to compare the environmental impact of different base stations [21–24].

In the EMC research domain, new topics specifically related to measurements were developed. In particular the characterization of field sensors in a wide frequency range allowed to perform measurements of fields generated by fast transient currents, and the study of the reverberating chambers allowed to characterize this particular measurement test site. In these years the group developed a new idea to stir the field inside the chamber, called source stirring, whose advantage with respect the more common mechanical stirring is the lack of heavy and bulky mechanical paddles. The technique and the array to perform the electronic stirring were patented [25–31]. It worth noting that in these years the plasma antenna was also theoretically studied [32] and experimentally characterized: this was the first self-consistent model of this kind of device, based on a multi-physic approach consisting in a mathematical system formed by the Maxwell and Boltzmann equations: the model allows to accurately describe the non-linear effects of the plasma ignition through an external field, describing all the transient behaviour of the physical quantities till steady state condition [33–35].

In the new millennium most of Rozzi's group shifted toward nanotechnology, in both theoretical and experimental studies. Nanotechnology is a technological field covering all aspects of nanoscale science and technology from a multidisciplinary perspective. It characterizes the understanding and control of matter at nanoscale dimensions, that is from few hundreds nm down to atomic dimensions. Nanotechnology not only yields miniaturization of devices and enhancement of integration density, but also features unusual physical, chemical, and biological device properties. Since many nano-structured materials exhibit their most interesting properties in a wide spectrum, from the microwave up into the optical frequency range, the concept and realization of nanoelectronic devices is a challenge also for the microwave/RF engineering community. At the nanoscale, both the charged particles and electromagnetic fields must obey the laws of quantum mechanics, which leads to quantum electrodynamics. Therefore, by the theoretical point of view, intense work was devoted to exploit the machinery developed to solve Maxwell's equations into the framework of quantum mechanics, and later using relativistic quantum mechanical equations (Dirac formulation) to express alternatively Maxwell's equations [36, 37]. Starting from well-known numerical techniques (e.g. TLM, FEM, Scattering Matrix Method), full-wave solvers for the multiphysics modeling of the combined Maxwell-Schrödinger/Dirac problem have been developed [38, 39]. A core concept relies in the fact that the electromagnetic field provides source terms for the quantum transport equations, that, in turn, provide charges and currents for the electromagnetic field. The main research topics can be summarized as: (i) the modeling of nano-structures/devices/systems based on low-dimensional materials, e.g. carbon-nanotubes (CNT), graphene, 2D materials beyond graphene, nanoparticles; (ii) the analysis of complex systems, ranging from nano- to meso-scale, and including quantum transport, electromagnetics, opto-mechanics, thermal effects, opto-mechanics, opto-electronics.

On the experimental side, the group pioneered a new approach into the framework of Scanning Probe Microscopes (SPM), namely the Scanning Microwave Microscopy (SMM) [40]. In this approach a probe is brought in close proximity to the surface of a sample, and current scanning probe microscope are able to image single molecules; in SMM a microwave signal is injected in the probe, and scanned while detecting changes in the reflected microwave signal. Imaging resolution can be sub-nanometric or even atomic, in spite of centimetric wavelength, due to the behaviour of evanescent waves produced by the sharp tip. This way a map of differences in local electromagnetic properties (e.g. dielectric constant, conductivity) can be obtained; a set of calibration techniques was developed [41] enabling local quantitative measurements. SMM, with respect to other techniques, allows to obtain quantitative data (electromagnetic properties) and at the same time to probe below surfaces also samples that are optically opaque. At the same time it was discovered that some principle of Time Domain Reflectometry could be exploited to improve the quality of images [42] and to obtain further calibration approaches [43]. Incidentally, during a set of experiments on semiconductor polymers, a new phenomenon was discovered [44], that could lead to a new generation of mass storing devices, where the interaction between a probe and a semiconductor could permanently lower locally the polymer conductivity, by changing the degree of disorder at molecular scale (Fig. 1). Microwave microscopy could be also a new device to investigate non-invasively, without the need of labelling, biological samples, and as matter of fact the group is focusing in performing measurements on cells, mitochondria and small

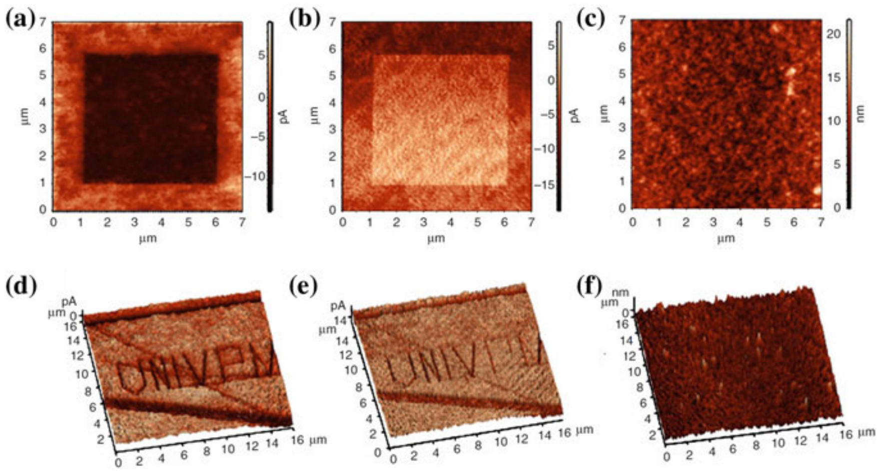

Fig. 1 Comparison between current maps, lateral force and topographic images in scanning probe microscopy (conductive Atomic Force Microscopy). A square, 5 µm of side, was written; reading is performed in an area 7 µm × 7 µm in P3HT: [70] PCBM (1:1) annealed at 100 °C for 15 min. **a** Current map (0.5 V) **b** lateral force image: the written square appears as a region with increased molecular disorder **c** topography: no topographic change is visible. The above images were obtained simultaneously. Also, the acronym "UNIVPM" is written and represented in 3D: **d** current map, **e** Lateral force (inverted for clarity) and **f** topography (Reprinted from [44])

nanometric vesicles, called exosomes, that could be the mean by which some chemical signal spreads among cells; recent theories also suggest a role of exosomes in spreading of metastases in cancer. Mitochondria are on the other hand implied in a process, called apoptosis (cell suicide), whose role is being investigated for cancer, while being at the basis of cell metabolism and, consequently, potentially underlying degenerative diseases. Microwave microscopy could become a tool to compare electrical properties of organelles in both healthy and disrupted or ageing cells [45].

Following the same concepts introduced in SMM, novel imaging techniques, based on scanning probe microscopy, were implemented in the range of optical frequencies by merging together in a lens-free system different methods, such as: Contrast-Phase Microscopy [46], Optical Tomography [47] and Synthetic Holography [48]. These systems exploit the principle of low temporal coherence combined with the high spatial coherence propriety of light confined inside a scanning optical micro-cavity. These approaches are well suitable to work in liquid environment, for biological applications, and integrable with the actual SPM systems to achieve nanometric resolution.

In the last years, some properties of the scattering matrix for non-uniform radial waveguides were analysed in order to simplify the evaluation of the e.m. fields in such structures [49]. The results were applied not only to e.m fields but also to acoustic applications. The analysis of the properties of the scattering matrix were used to define a new kind of equivalent circuit, able to represent N-ports microwave devices, in presence of guided and/or evanescent modes [50, 51]. The new circuit is based on a polygon with N sides, as the number of ports, and N(N − 3)/2 diagonals. Moreover, N transmission lines are connected to the N sides. Each side and diagonal are loaded with susceptances that represent the “kernel” of the microwave device. The circuital properties of the device (filter, coupler, multiplexer, …) are contained in the “kernel” of the circuit. The polygon equivalent network can be used for example in the measurement of N-port device [52] and in the synthesis of hybrid coupler [53].

3 Nowadays and Beyond

3.1 Reverberation Chamber

Reverberation chamber (RC) theory and applications remain hot topics in the current and future activity planning of the EMC group. This research activity led to international cooperation with other Universities as the University of Nottingham (UK), the College Park (USA), the Queen Mary of London (UK) [54]. From an industrial point of view, the RC finds application in traditional electromagnetic compatibility tests (immunity and emissions) and power electromagnetic applications, like the microwave heating processes. In all these fields of application, the Ancona activity was characterized by a strong interaction with industries (ELASIS-FIAT, Emitech, Tornati Forni, Unibind). The future trend in theoretical aspects will be focused on the necessity to properly combine deterministic and stochastic electromagnetic methods of analysis [55–58]. The necessity of stochastic methods becomes more evident when the RC is transformed into a chaotic environment [59, 60]. Another interesting RC application is the characterization of shielding materials in aerospace and building construction applications [61–64]. The advantage is the random field excitation of the material more adherent to real life situations, w.r.t traditional deterministic methods [65]. Recently, the application of RCs has been extended to the testing of wireless devices and systems [66]. In fact, the RC is able to provide a rich multipath propagation environment, very similar to real life situations where these devices (access points, smartphones, IoT devices, etc.) may operate in presence of strong reflections having random behavior. This last activity opened other research topics and led to the built-up of a joint laboratory TIM[7]-UNIVPM for testing real live LTE base stations in 4G technology provided by NOKIA[8] [67–70]. Strong research and application activities are expected in the future for the extension to the emerging 5G technology.

[7] https://www.telecomitalia.com/tit/it.html.

[8] https://www.nokia.com/it_it/.

3.2 Electromagnetic Sensors

European and national research policies have, among their priorities, initiatives that will contribute to build a healthy and active population for the future, as well to enhance inclusion of people with disabilities. In line with this topics, the research group also focused on the development of sensors to monitor vital parameters (breathing and heart rate) that can be used in domestic environments, as well as sensors that can be used by blind or visually impaired people both in everyday life (sensors for mobility) and in sport.

The monitoring of vital parameters through electromagnetic sensors developed by the team is non-contact and allows the subject to remain dressed and covered if the monitoring takes place during sleep [71]. This reduces the invasiveness of the system and increases its acceptance and ease of use.

This application activity has led the research team to work alongside companies that belong to the Marche territory with strong attitude to innovation. This collaboration leads to an exchange of know-how between companies and university that has allowed to address problems of implementation and design not common in daily academic activity. The realization of demonstration prototypes was the result of this synergy [72].

The activity on electronic travel aids for the autonomous walking of visually impaired person has turned to the planning and realization of a system based on a obstacle detection radar [73, 74]. The system has been miniaturized to allow the placement of the antenna on the white stick [75]. In parallel to this activity, two prototypes of systems have been designed and built to assist blind people in running: one to be inserted into an athletics track [76, 77], and another for road training [78], again for running. For these projects the group collaborated with a Paralympic champion who resides in our Region: Andrea Cionna, who offered his advice on the implementation of the systems, as well as tested them. Some short videos of the systems realized are available on [79].

3.3 Electromagnetics at Nanoscale

Nowadays, nanotechnology is one of the core research area of the group. The development of modern devices based on nanostructured materials and nanotechnologies, for a wide area of applications ranging from microwave to photonics, relies on an electromagnetic computational platform defined by new general modelling and simulation routes. Accordingly, programs and simulations are developed and optimized for specific issues and challenges. The latter are related to the low-dimensionality of novel materials and to the possible coexistence of multiphysics phenomena, e.g. electromagnetic (EM), charge propagation and quantum transport [80–87], In particular, quantum phenomena like ballistic transport, tunneling, many-body correlations, carrier confinement and interface effects overlap with classical physical effects, which make traditional circuit design unsuitable to nanoelectronics. To this purpose, we developed appropriated models based on the solution of coupled systems of equations dealing with combined electromagnetic-transport phenomena i.e. Schrödinger/Dirac, Maxwell-Boltzmann, etc. The above e.m. platform takes into account the different aspect-ratio between nano-structured materials and device environment, bridging from the atomistic to the continuum scale (extreme multi-scale analysis). The key-issue is the coupling of quantum models and electromagnetic models, that acts at discrete level, but, in some case, as for ballistic regime, also at continuum level [80]. Other physics can also include, e.g. coupling to phonons (thermal effects), in opto-mechanical cavities, [87, 88]. In order to support semiclassical modelling, ab initio methods for high-frequency simulations of atomic-thick materials/surfaces need to be considered, as the Density Functional Theory (DFT). A key development is that the aforementioned discrete, ab initio methods (atomistic level) transfer/integrate the results into/with the larger scale models by constitutive equations/relations [80], in order to incorporate all necessary physics towards the continuum, full-wave method (device/sub-module level).

Constitutive equations must result in constitutive relations, eventually in integral form, which are usually numerically easier to handle. Exploiting constitutive parameters extraction from models may also lead to a compact representation, like the one provided a by complex, dispersive: (i) electric permittivity/conductivity; (ii) magnetic permeability, possibly in tensorial form. Standard solvers usually can simulate either quantum transport or full-wave electromagnetics, but a simultaneous solution is very hard to be achieved at a large scale. There is therefore a strong need to link the atomistic scale up to the continuous world, in order to characterize practical macroscopic elements, like micro-antennas, terahertz and plasmonic devices, periodic and aperiodic metamaterials. The combined solution of quantum transport and electromagnetic wave propagation features: different partial differential equation systems (PDE-S); different propagation/diffusive nature of the PDE-S; non-linear coupling; large geometrical/electrical aspect ratios.

Nano-structured materials and electromagnetic (EM) smart surfaces are also the target for innovative industrial products for antenna, radar and sensing application at microwave frequencies and in photonics. These are micro- to nano- structured artificial surface materials (2D or 2.5D), where: (a) the working principles exploit extreme sub- wavelength features already for passive (linear) operation; (b) the material need to encompass an overall size of hundreds of wavelengths; (c) localized or distributed active non-linear micro- to nano-scale inclusions are deployed densely in the underlying textured surface. The latter include constructs comprising carbon nanotubes (CNT), metal nanowires and nanoparticles, graphene, or more conventional semiconductor-based devices.

The activities described above are now at a final stage, but new ideas and potential applications have arisen from them. Nowadays, studies are already underway to verify the feasibility of using the monitoring system of vital parameters to monitor the energy expenditure of a person at home, even in this case without the use of bulky and annoying electrodes connected to the person. At the same time, the experience of autonomous mobility of blind people could be borrowed for applications in the field of civil protection where there is a need to use drones with autonomous driving.

References

1. Cerri G, De Leo R, Francescangeli O (1985) Microstrip disk antenna radiation into biological-like media. Alta Freq LIV(5):302–311. Premio A.E.I. “Bonazzi” 1985
2. Antolini R, Cerri G, Cristoforetti L, De Leo R (1986) Absorbed power distributions from single or multiple waveguide applicators during microwave hyperthermia. Phys Med Biol 31(9):1005–1019
3. Cerri G, Chiaraluce F, De Leo R (1987) Microstrip applicators for therapy. Mikrowellen Mag 13(5):452–461
4. Cerri G (1990) The microstrip spiral antenna. Eur Trans Telecommun Relat Technol 1(5):549–555
5. Cerri G, De Leo R, Primiani VM ‘Thermic end-fire’ interstitial applicator for microwave hyperthermia. IEEE Trans MTT 41(6/7):1135–1142
6. Cerri G, De Leo R, Rosellini G (1997) Evaluation of electromagnetic power deposition in a spherical multilayer head in the near field of a linear antenna. Wirel Netw J 3:499–510
7. Nikita KS, Cavagnaro M, Bernardi P, Uzunoglu NK, Pisa S, Piuzzi E, Sahalos JN, Krikelas GI, Vaul JA, Excell PS, Cerri G, Chiarandini S, De Leo R, Russo P (2000) A study of uncertainties in modeling antenna performance and power absorption in the head of a cellular phone user. IEEE Trans MTT 48(12):2676–2685
8. Cerri G, De Leo R, Francescangeli O, Melone S (1991) Accurate evaluation of electrical current excitation in brain cortex by magnetic field pulses. Phys Med 7(3):99–105
9. De Leo R, Cerri G, Balducci D, Moglie F, Scarpino O, Guidi M (1992) Computer modelling of brain cortex excitation by magnetic field pulses. J Med Eng Technol 16(4):149–156
10. Cerri G, De Leo R, Moglie F, Schiavoni A (1995) An accurate 3-D model for magnetic stimulation of the brain cortex. J Med Eng Technol 19(1):7–16
11. Cerri G, De Leo R, Primiani VM (1992) Theoretical and experimental evaluation of the electromagnetic radiation from apertures in shielded enclosures. IEEE Trans EMC 34(4):423–432
12. Cerri G, De Leo R, Primiani VM (1993) A rigorous model for radiated emission prediction in PCB circuits. IEEE Trans EMC 35(1):102–109
13. Cerri G, De Leo R, Primiani VM, Schiavoni A (1994) FDTD analysis of crosstalk in multilayer printed circuits. Int J Numer Model Electr Netw Devices Fields 7:209–221
14. De Leo R, Cerri G, Primiani VM (1995) Scattering matrix approach for frequency and time domain crosstalk analysis in multilayer PCBs. IEE Proc Sci Meas Technol 142(3):206–212
15. De Leo R, Cerri G, Mariani Primiani V, Botticelli R (1999) A simple but effective way for cable shielding measurements. IEEE Trans EMC 41(3):175–179
16. Cerri G, De Leo R, Primiani VM, Righetti M (1994) Field penetration into metallic enclosures through slots excited by ESD. IEEE Trans EMC 36(2):110–116
17. Cerri G, De Leo R, Primiani VM (1996) ESD indirect coupling modelling. IEEE Trans EMC 38(3):274–281. Special Issue on ‘EMC research in Italy’
18. Cerri G, De Leo R, Primiani VM.(1997) Investigation of radiated susceptibility during eft tests. IEEE Trans EMC 39(4):298–303
19. Cerri G, De Leo R, De Rentiis R, Primiani VM (1997) ESD field penetration through slots into shielded enclosures: a time domain approach. IEEE Trans EMC 39(4):377–386
20. Cerri G, De Leo R, Primiani VM, Russo P, Tribellini G (1999) Development of a hybrid MOMTD/FDTD technique for EMC problems: analysis of the coupling between ESD transient fields and slotted enclosures. Int J Numer Model Electron Netw Devices Fields 12:245–256
21. Cerri G, De Leo R, Micheli D, Russo P (2004) Base station network planning including environmental impact control. IEEE Proc Commun 151(3):197–203
22. Cerri G, Cinalli M, Michetti F, Russo P (2004) Feed forward neural networks for path loss prediction in urban environment. IEEE Trans Antennas Propag 52(11):3137–3139
23. Cerri G, Russo P (2006) Application of an automatic tool for the planning of a cellular network in a real town. IEEE Trans Antennas Propag 54(10):2890–2901

24. Russo P, Cerri G, Vespasiani V (2010) A numerical coefficient for evaluation of the environmental impact of electromagnetic fields radiated by base stations for mibile communications. Bioelectromagnetics 31(8):613–621. ISSN 0197–8462
25. Cerri G, Coacci F, Fenucci L, Primiani VM (2001) Measurement of magnetic fields radiated from ESD using field sensors. IEEE Trans EMC 43(2):187–196
26. Cerri G, De Leo R, Primiani VM, Pennesi S, Russo P (2003) Wide band characterization of current probes. IEEE Trans EMC. 45(4):616–625
27. Cerri G, Primiani VM, Pennesi S, Russo P (2005) Source stirring mode for reverberation chambers. IEEE Trans EMC 47(4):815–823
28. Cerri G, De Leo R, Moglie F, Primiani VM (2006) Theoretical and experimental analysis of the field-to-line coupling in a reverberation chamber. IEEE Proc Sci Meas Technol 153(5):201–207
29. Cerri G, Herlemann H, Primiani VM, Garbe H (2007) Short pulse measurements by field sensors with arbitrary frequency response. In: Sabath F (ed) Ultra - wideband short-pulse, electromagnetics 7. Springer, pp 552–560
30. Cerri G, Primiani VM, Monteverde C, Russo P (2008) Investigation of the antenna factor behaviour of a dipole operating inside a resonant cavity. IEEE Trans EMC 50(1):89–96
31. Cerri G, Primiani VM, Monteverde C, Russo P () A theoretical feasibility study of a source stirring reverberation chamber. IEEE Trans EMC 51(1):3–11
32. Cerri G, Russo P, Vecchioni E (2010) Self-consistent model for the characterization of plasma ignition by propagation of an electromagnetic wave to be used for plasma antennas design. IET Microws Antennas Propag 4(12):2256–2264
33. Russo P, Primiani V.M, Cerri G, De Leo R, Vecchioni E (2011) Experimental characterization of surfaguide fed plasma antenna. IEEE Trans Antennas Propag 59(2):425–433
34. Russo P, Cerri G, Vecchioni E (2011) Self-consistent analysis of cylindrical plasma antennas. IEEE Trans Antennas Propag 59(2):425–433
35. Rozzi T, Farin M (1999) Advanced electromagnetic analysis of passive and active planar structures. The Institution of Electrical Engineers, UK, London
36. Mencarelli D et al (2007) Electronic properties of carbon nanotubes investigated by means of standard electromagnetic simulators. Phys Rev B 75:0854021–0854028 Condensed Matter and Materials Physics
37. Rozzi T, Mencarelli D, Pierantoni L (2009) Deriving electromagnetic fields from the spinor solution of the massless dirac equation. IEEE Trans Microw Theory Tech 57(12):2907–2913. https://doi.org/10.1109/TMTT.2009.2034225
38. Pierantoni L, Mencarelli D, Rozzi T (2008) A new 3d- transmission line matrix scheme for the combined schrödinger-maxwell problem in the electronic/electromagnetic characterization of nanodevices. IEEE Trans Microw Theory Tech 56(3):654–662
39. Mencarelli D, Rozzi T, Pierantoni L (2008) Coherent carrier transport and scattering by lattice defects in single- and multi-branch carbon nanoribbons. Phys Rev B 77:1954351–1954411. https://doi.org/10.1103/PhysRevB.77.195435
40. Farina M, Di Donato A, Mencarelli D, Venanzoni G, Morini A (2012) High resolution scanning microwave microscopy for applications in liquid environment. IEEE Microw Wirel Compon Lett 22(11):595–597
41. Farina M, Mencarelli D, Di Donato A, Venanzoni G, Morini A (2011) Calibration protocol for broadband near-field microwave microscopy. IEEE Microw Wirel Compon Lett 59(10):2769–2776
42. Farina M et al (2011) Disentangling time in a near-field approach to scanning probe microscopy. Nanoscale 3(9):3589
43. Farina M et al (2016) Investigation of fullerene exposure of breast cancer cells by time-gated scanning microwave microscopy. IEEE Trans Microw Theory Tech 64(12):4823–4831
44. Farina M et al (2013) Fast ultrahigh-density writing of low conductivity patterns on semiconducting polymers. Nature Commun
45. Farina M et al (2018) Imaging of sub-cellular structures and organelles by an stm-assisted scanning microwave microscope at mm-waves. In: 2018 IEEE/MTT-S international microwave symposium—IMS. Philadelphia, PA, pp 111–114

46. Di Donato A et al (2013) Infrared imaging in liquid through an extrinsic optical microcavity. Opt Lett 38(23):5094–5097
47. Di Donato A et al (2014) Optical microcavity scanning 3D tomography. Opt Lett 39(19):5495–5498
48. Di Donato A et al (2015) Synthetic holography based on scanning microcavity. AIP Adv 5:117125
49. Zappelli L (2004) On the definition of the generalized scattering matrix of a lossless radial line. IEEE Trans Microw Theory Tech 52(6):1654–1662
50. Zappelli L (2012) An Equivalent Circuit for Discontinuities Exciting Evanescent Accessible Modes. IEEE Trans Microw Theory Tech 60(5):1197–1209
51. Zappelli L (2015) Simple, fast, and effective identification of an equivalent circuit of a waveguide junction with n ports. IEEE Trans Microw Theory Tech 63(1):48–55
52. Zappelli L (2017) Reconstruction of the S-matrix of N-port waveguide reciprocal devices from 2-port VNA measurements. Prog Electromagn Res B 72(1):129–148
53. Zappelli L (2018) Optimization Procedure of Four-Port and Six-Port Directional Couplers Based on Polygon Equivalent Circuit. IEEE Trans Microw Theory Tech 66(10):4471–4481
54. Serra R, Marvin AC, Moglie F, Primiani MV, Cozza A, Arnaut LR, Huang Y, Hatfield MO, Klingler M, Leferink F (2017) Reverberation chambers a la carte: An overview of the different mode-stirring techniques. IEEE Electromagn Compat Mag 6:63–78. ISSN: 2162-2264 https://doi.org/10.1109/memc.2017.7931986
55. Arnaut LR, Moglie F, Bastianelli L, Primiani VM (2017) Helical stirring for enhanced low-frequency performance of reverberation chambers. IEEE Trans Electromagn Compat 59:1–11. ISSN: 0018-9375
56. Gifuni A, Bastianelli L, Moglie F, Primiani VM, Gradoni G (2017) Base-case model for measurement uncertainty in a reverberation chamber including frequency stirring. IEEE Trans Electromagn Compat 60:1–9. ISSN: 0018-9375 https://doi.org/10.1109/temc.2017.2763627
57. De Leo A, Cerri G, Russo P, Primiani VM (2017) Experimental validation of an analytical model for the design of source-stirred chambers. IEEE Trans Electromagn Compat 60:540–543. ISSN: 0018-9375 https://doi.org/10.1109/temc.2017.2723804
58. De Leo A, Primiani VM, Russo P, Cerri G (2017) Low-frequency theoretical analysis of a source-stirred reverberation chamber. IEEE Trans Electromagn Compat 59:315–324. ISSN: 0018-9375 https://doi.org/10.1109/temc.2016.2613402
59. Gagliardi L, Micheli D, Gradoni G, Moglie F, Primiani VM (2015) Coupling between multipath environments through a large aperture. IEEE Antennas Wirel Propag Lett 14:1463–1466. ISSN: 1536-1225 https://doi.org/10.1109/lawp.2015.241162
60. Primiani VM, Moglie F (2012) Numerical simulation of reverberation chamber parameters affecting the received power statistics. IEEE Trans Electromagn Compat 54:522–532. ISSN: 0018-9375 https://doi.org/10.1109/temc.2011.2167337
61. Micheli D, Pastore R, Apollo C, Marchetti M, Gradoni G, Primiani VM, Moglie F (2011) Broadband electromagnetic absorbers using carbon nanostructure-based composites. IEEE Trans Microw Theory Tech 59:2633–2646. ISSN: 0018-9480 https://doi.org/10.1109/tmtt.2011.2160198
62. Albano M, Micheli D, Gradoni G, Morles R.B, Marchetti M, Moglie F, Primiani VM (2013) Electromagnetic shielding of thermal protection system for hypersonic vehicles. Acta Astronaut 87:30–39. ISSN: 0094-5765 https://doi.org/10.1016/j.actaastro.2013.02.003
63. Mazzoli A, Corinaldesi V, Moglie F, Primiani VM, Favoni O (2016) Electrically conductive DSP cement composites. J Appl Biomater Funct Mater 14:e357–e358. ISSN: 2280-8000 https://doi.org/10.5301/jabfm.5000321
64. Mazzoli A, Corinaldesi V, Donnini J, Di Perna C, Micheli D, Vricella A, Pastore R, Bastianelli L, Moglie F, Primiani VM (2018) Effect of graphene oxide and metallic fibers on the electromagnetic shielding effect of engineered cementitious composites. J Appl Biomater Funct Mater 18:33–39. ISSN: 2352-7102 https://doi.org/10.1016/j.jobe.2018.02.019
65. Moglie F, Micheli D, Laurenzi S, Marchetti M, Primiani VM (2012) Electromagnetic shielding performance of carbon foams. carbon. 50:1972–1980. ISSN: 0008-6223 https://doi.org/10.1016/j.carbon.2011.12.053

66. Recanatini R, Moglie F, Primiani VM (2013) Performance and immunity evaluation of complete WLAN systems in a large reverberation chamber. IEEE Trans Electromagn Compat 55:806–815. ISSN: 0018-9375 https://doi.org/10.1109/temc.2013.2239636
67. Micheli D, Barazzetta M, Moglie F, Primiani VM (2015) Power boosting and compensation during OTA testing of a real 4 g LTE base station in reverberation chamber. IEEE Trans Electromagn Compat 57:623–634. ISSN: 0018-9375 https://doi.org/10.1109/temc.2015.2434277
68. Barazzetta M, Micheli D, Bastianelli L, Diamanti R, Totta M, Obino P, Lattanzi R, Moglie F, Primiani VM (2017) A comparison between different reception diversity schemes of a 4G-LTE base station in reverberation chamber: a deployment in a live cellular network. IEEE Trans Electromagn Compat 59:1–9. ISSN: 0018-9375 https://doi.org/10.1109/temc.2017.2657122
69. Micheli D, Barazzetta M, Diamanti R, Obino P, Lattanzi R, Bastianelli L, Primiani VM, Moglie F (2018) Over-the-air tests of high-speed moving LTE users in a reverberation chamber. IEEE Trans Veh Technol 1–10. ISSN: 0018-9545 https://doi.org/10.1109/tvt.2018.2795650
70. Micheli D, Barazzetta M, Carlini C, Diamanti R, Primiani VM, Moglie F (2017) Testing of the carrier aggregation mode for a live LTE base station in reverberation chamber. IEEE Trans Veh Technol 66:3024–3033. ISSN: 0018-9545, https://doi.org/10.1109/tvt.2016.2587662
71. Scalise L, Primiani VM, Russo, P, De Leo A, Shahu D, Cerri G (2013) Wireless sensing for the respiratory activity of human beings: measurements and wide-band numerical analysis. Int J Antennas Propag. Article no 396459
72. Frontoni E, Pollini R, Russo P, Zingaretti P, Cerri G (2017) HDOMO: smart sensor integration for an active and independent longevity of the elderly Sensors (Switzerland) 17(11). Article no 2610
73. Scalise L, Primiani, VM, Russo P, Shahu D, Di Mattia V, De Leo A, Cerri G (2012) Experimental investigation of electromagnetic obstacle detection for visually impaired users: a comparison with ultrasonic sensing. IEEE Trans Instrum Meas 61(11):3047–3057. Article no 6222333
74. Di Mattia V, Russo P, De Leo A, Scalise L, Primiani VM, Cerri G (2014) Efficient numerical-analytical tool for time domain obstacles detection. IET Sci Meas Technol 8(2):69–73
75. Cardillo E, Di Mattia V, Manfredi G, Russo P, De Leo A, Caddemi A, Cerri G (2018) An electromagnetic sensor prototype to assist visually impaired and blind people in autonomous walking. IEEE Sens J 18(6):2568–2576
76. Pieralisi M, Di Mattia V, Petrini V, de Leo A, Manfredi G, Russo P, Scalise L, Cerri G (2017) An electromagnetic sensor for the autonomous running of visually impaired and blind athletes (Part I: The fixed infrastructure). Sensors (Switzerland) 17(2). Article no 364
77. Pieralisi M, Di Mattia V, Petrini V, De Leo A, Manfredi G, Russo P, Scalise L, Cerri G (2017) An electromagnetic sensor for the autonomous running of visually impaired and blind athletes (Part II: The wearable device). Sensors (Switzerland) 17(2). Article no 381
78. Pieralisi M, Petrini V, Di Mattia V, Manfredi G, De Leo A, Scalise L, Russo P, Cerri G (2015) Design and realization of an electromagnetic guiding system for blind running athletes. Sensors (Switzerland) 15(7):16466–16483
79. https://www.youtube.com/channel/UCr3dqvBqN4svZoSAvjf1oiw
80. Pierantoni L, Mencarelli D, Rozzi T (2009) Boundary Immittance Operator for the Combined Schrödinger-Maxwell Problem of Carrier Dynamics in Nanodevices. IEEE Trans Microw Theory Tech 57(5):1147–1155. https://doi.org/10.1109/TMTT.2009.2017351
81. Mencarelli D, Rozzi T, Pierantoni L (2010) Scattering matrix approach to multichannel transport in many lead graphene nanoribbons. IOP Sci Nanotechnol 21(15):5570–15580. https://doi.org/10.1088/0957-4484/21/15/155701
82. Mencarelli D, Pierantoni L, Farina M, Di Donato A, Rozzi T (2011) A multi-channel model for the self-consistent analysis of coherent transport in graphene nanoribbons. ACS Nano 5(8):6109–6128. https://doi.org/10.1021/nn2011333
83. Mencarelli D, Bellucci S, Sindona A, Pierantoni L (2015) Spatial dispersion effects upon local excitation of extrinsic plasmons in graphene micro-discs. J Phys D: Appl Phys 48(46):1–9. Article no 465104, arXiv:1507.07090, https://doi.org/10.1088/0022-3727/48/46/465104
84. Mencarelli D, Pierantoni L, Stocchi M, Bellucci S (2016) Efficient and versatile graphene-based multilayers for EM field absorption. Appl Phys Lett (AIP). https://doi.org/10.1063/1.4962148

85. Pierantoni L, Mencarelli D, Bozzi M, Moro R, Moscato S, Perregrini L, Micciulla F, Cataldo A, Bellucci S (2015) Broadband microwave attenuator based on few layer graphene flakes. IEEE Trans Microw Theory Tech 63(8):2491–2497. https://doi.org/10.1109/TMTT.2015.2441062,Aug
86. Dragoman M, Neculoiu D, Bunea AC, Deligeorgis G, Aldrigo M, Vasilache D, Dinescu A, Konstantinidis G, Mencarelli D, Pierantoni L, Modreanu M (2015) A tunable microwave slot antenna based on graphene. Appl Phys Lett (AIP) 106(15). 13 April 2015, Article no 153101 https://doi.org/10.1063/1.4917564
87. Mencarelli D, Stocchi M, Pierantoni L (2018) Electromagnetic amplification of microwave phonons in nonlinear resonant microcavities. IEEE Trans Microw Theory Tech 66:3603–3610
88. Mencarelli D, Djafari B, Pennec Y, Pitanti A, Zanotto S, Stocchi M, Pierantoni L (2018) Numerical emulation of thru-reflection-line calibration for the de-embedding of surface acoustic wave devices. Scientific reports (Nature Publishing Group), https://www.nature.com/articles/s41598-018-27511-0, https://doi.org/10.1038/s41598-018-27511-0