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Empirical and Modeling Approach for Environmental Indoor RF-EMF Assessment in Complex High-Node Density Scenarios: Public Shopping Malls Case Study

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ABSTRACT This work provides an intensive and comprehensive in-depth study from an empirical and modeling approach of the environmental radiofrequency electromagnetic fields (RF-EMF) radiation exposure in public shopping malls, as an example of an indoor high-node user density context aware environment, where multiple wireless communication systems coexist. For that purpose, current personal mobile communications (2G-5G FR 1) as well as Wi-Fi services (IEEE 802.11n/ac) have been precisely analyzed in order to provide clear RF-EMF assessment insight and to verify compliance with established regulation limits. In this sense, a complete measurements campaign has been performed in different countries, with frequency-selective exposimeters (PEMs), providing real empirical datasets for statistical analysis and allowing discussion and comparison regarding current health effects and safety issues between some of the most common RF-EMF exposure safety standards: ICNIRP 2020 (Spain), IEEE 2019 (Mexico) and a more restrictive regulation (Poland). In addition, environmental RF-EMF exposure assessment simulation results, in terms of spatial E-field characterization and Cumulative Distribution Function (CDF) probabilities, have been provided for challenging incremental high-node user dense scenarios in worst case conditions, by means of a deterministic in-house 3D Ray-Launching (3D-RL) RF-EMF safety simulation technique, showing good agreement with the experimental measurements. Finally, discussion highlighting the contribution and effects of the coexistence of multiple heterogenous networks and services for the environmental RF-EMF radiation exposure assessment has been included, showing that for all measured results and simulated cases, the obtained E-Field levels are well below the exposure limits established in the internationally accepted standards and guidelines. In consequence, the obtained results and the presented methodology could become a starting point to stablish the RF-EMF assessment basis of future complex heterogeneous 5G FR 2 developments on the millimeter wave (mmWave) frequency range, where massive high-node user density networks are expected.

INDEX TERMS Radiofrequency electromagnetic fields (RF-EMF), personal exposimeter (PEM), electromagnetic safety, E-field strength distribution, 3D ray launching (3D-RL), 5G, high-node density, public shopping malls.

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I. INTRODUCTION

The level and frequency pattern of environmental radiofrequency electromagnetic fields (RF-EMF) exposure is

continuously changing as technological innovation advances. From new wireless communication technologies and infrastructure deployments (i.e., Fifth-Generation (5G), Internet of Things (IoT)), to new wireless services and applications (autonomous vehicles, wireless sensor networks (WSN) for security monitoring, smart metering, networks access, etc.), their corresponding environmental RF-EMF exposure assessment is pivotal in order to warrant compliance with international EMF thresholds and regulation limits. Therefore, public environments, where both, occupational and general public coexist, require RF-EMF exposure characterization, monitoring and evaluation, due to the influence of the multiple wireless communication technologies interconnections, behaviors, dynamic condition changes and cumulative exposures in terms of spatial and technical features (transmitter TX and receiver RX locations, scatterers involved, interference, frequency of operation, types of antenna, transmitted power or data transmission, among others) as well as the different user densities, distributions and communication link requirements. This is particularly needed in indoor environments, in which it was estimated that people spend at least about 70% of their daily time [1], from domestic household to public environments such as administrative, commercial centers and healthcare environments [2]–[6]. The pervasive use of wireless communication devices, the growing demand of accessibility to audio, video on demand or in general, personal wireless communications including or requiring Internet access, in each aspect of everyone daily life and various professional activities, has emphasized the need for assessing RF-EMF exposure, with great interest in ensuring safe RF-EMF exposure conditions considering the health impact and/or potential malfunctions in electronic devices caused by the RF-EMF emissions from the combination of all the available wireless communication systems [7]–[18]. It can be a serious problem for any electronic device, but working with medical devices can have life-threatening consequences, particularly in sensible environments such as healthcare facilities.

All these aspects cause RF-EMF exposure assessment to be affected by dynamic uncertainties and therefore, represent a challenging task in order to attend the increasing complexity of the RF-EMF spatial-temporal exposure, aggravated with the rapid evolution of the next generation of 5G cellular communication systems. In the last years, small cells, microcells, picocells or femtocells, i.e., miniature base stations specifically designed for the enhancement of the coverage and capacity of a cellular service in indoor environments, have been deployed to overcome the power attenuation from outdoor to indoor locations. In this sense, this phenomenon is and will be intensified in crowded areas, such as public shopping malls, libraries or the city central business districts where systems involve sensors, computing and communication devices working in increasingly dense electromagnetic environments, giving rise to context aware scenarios, with multiple heterogenous networks and high node user densities. Currently, 5G related WSN and 5G Frequency Range 1 (5G FR1) system deployments are operating close to the 2G-4G previous generation cellular frequency bands, below 6 GHz (i.e., 700 and 3700 MHz) and some reduced experimental deployments have been implemented near the millimeter wave (mmWave) frequency range (26-28 GHz) [19]. This expansion has started in 2018-2019, but it is expected in a large-scale worldwide for 2021-2022 (5G Frequency Range 2 / 5G FR2) and in a near future on the mmWave spectrum (i.e., 28 and 39 GHz) [19]. At the same time, new concerns for the compliance of RF-EMF assessments will arise and the evaluation of health and safety issues concerning exposure of occupational and general public will be required. Thus, and because of all the aforementioned circumstances general public concern over EMF health hazards still remains high nowadays, including both, the citizens' level and the authorities' level, leading to regulation/legislation revisions in order to warrant health and security conditions [20], particularly over the new wireless communication system developments.

A. TECHNICAL BACKGROUND

In order to enable interactive environments, mobility and ubiquity are mandatory requirements in order to provide information exchange between a wide range of locations, devices and time frames. In this way, heterogeneous network operation relies on the combined and cooperative use of multiple wireless communication systems. Depending on coverage/capacity requirements, which are given by traffic demands, mobility conditions, user densities and locations and overall interference levels (which can be further classified as intra-system, inter-system or external interference sources, with specific characteristics and distributions in each case), among other factors. Depending on these requirements as well as on network conditions, connection from terminals and devices to the serving cells of the different systems will be given by the corresponding access/hand over mechanisms. In this way, connectivity can be provided by Public Land Mobile Networks (PLMN), spanning from 2G to 5G systems (i.e., GSM, GPRS, UMTS, HSPA, LTE and 5G NR in FR1 and/or FR2, all of them operating in licensed spectrum bands). Mobile systems are characterized in general by employing variable cell size architectures in which different duplexing mechanism (mainly FDD and also TDD in the case of 4G and 5G), adaptive modulation and coding schemes, access methods (evolving from classical FDMA/TDMA towards OFDMA and exploring more flexible non-orthogonal NOMA based schemes) and different frequency ranges (mainly from UHF to the 6 GHz frequency bands) may be present [21] , [22]. Interference control is compulsory, given by increase in transmission bit rates and reduced latency values, aided by mechanisms such as bidirectional power control, discontinuous transmission (with vocal activity detection in the case of legacy circuit switched voice connections) and the use of beamforming and spatial streams, among the multiple radio resource allocation and management features. Specific solutions have also been proposed in order to provide machine to machine (M2M)

or device to device (D2D) connectivity, such as LTE Cat. M1 and Cat. M2 or NB-IoT in the case of 4G systems and D2D communication capabilities in the case of 5G systems, mainly within 5G NR FR1 bands. High speed data traffic can be also handled by means of wireless local area networks, providing infrastructure, extended service (i.e., campus area network applications), meshing transport solutions or purpose-specific vehicular connectivity [23], [24]. Interference control is a key element in order to guarantee coverage/capacity relations, which is achieved by the use of functionalities such as Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), beamforming or multiple spatial streams. The frequency ranges span from sub 1 GHz (future 802.11ah intended for IoT applications) to 6 GHz, with the majority of systems operating in the 2.4 GHz and the 5.5 GHz to 5.9 GHz, mainly within unlicensed frequency spectrum bands (including 802.11p, WAVE and C-ITS systems, intended for vehicular communications). Millimeter wave bands have also been allocated (within the 60 GHz frequency range), focused on principle for high capacity, short range indoor applications. Additionally, the evolution and adoption of interactive context-aware environments has led to the development of multiple WSN technologies, mainly in the framework of 802.15 standard, implemented considering variable network topologies (mainly star, mesh and chain topologies), low processing power and reduced energy consumption, among others. Frequency ranges span from low UHF bands to 2.4 GHz, with small to moderate channel bandwidth allocations [25], [26].

In order to comply with coverage/capacity, mobility, wide area deployment needs and energy consumption requirements, simultaneous operation of PLMN (licensed spectrum bands), WLAN and WSN (mainly unlicensed frequency bands) systems is required. Therefore, the resulting indoor electromagnetic environment is going to exhibit extensive use within the frequency ranges from low UHF to 6 GHz, moreover with the advent of massive device communication predicted in IoT applications.

B. ENVIRONMENTAL EXPOSURE

Today, environmental RF-EMF exposure in indoor environments depends on both outdoor sources such as the signals from broadcast transmitters in the area (radio or television broadcasting) or downlink (DL) signals from cellular base stations (BS) and indoor sources, such as uplink (UL) signals from mobile phone terminals (also recognized as handsets), DL signals from indoor BS (i.e., 5G femtocells) or other wireless communication services as Wi-Fi or local WSNs, among others [19]. While radio and television transmitters have a large coverage area and therefore operate at relatively high-power levels, the EMF power level inside a building can be up to at least 100 times lower, depending on the structure and the composition of the walls and on the number and dimension of windows per wall. In addition, the exposure caused by outdoor sources varies from floor to floor. As to the indoor RF-EMF sources, their number and their locations, as well as the structure of the rooms and their furniture, are affected by a lack of information especially for private environments [7]. Depending on local circumstances, in general, personal wireless cellular communications (UL or DL signals usually for voice or communication or data exchange), cellular BS general exposure DL signals and Wi-Fi Access Points (access to Internet) are the main contributions to total RF-EMF exposure when analyzing indoor environments [18], [27], [28].

With the introduction of new generation of wireless communication technologies and the Smart Concept worldwide, an expanding demand with huge increase in data transmission has presented, mostly, in the last decade, outpacing current capacity and increasing the RF-EMF exposure associated [29]–[31]. Nevertheless, communication technology systems have become more efficient and effective at the same time [32]–[35]. Consequently, personal RF-EMF exposure assessment is influenced by many variables which in turn, contribute to a complex and challenging characterization and evaluation where generalization do not apply [29], [36]–[41].

In general, concerns regarding general public exposure from cellular BS must be addressed considering basically, two different aspects: transmitting facilities compliance with their corresponding regulatory RF-EMF exposure limits and the distribution of exposure across general population [19]. Since the presence of cellular BS has increased constantly in last years, and it is expected to grow even more with the new 5G development, the potential public health impact in the vicinity of the antennas has been a vigorous research topic at the same time. Relevant scientific results have been published assessing general exposure from cellular BS with similar conclusions: RF exposure, measured in public accessible locations nearby or in the vicinity of the cellular BS antennas, are only a small fraction of international EMF exposure limits when transmitting facilities comply with regulatory limits [7], [42]–[48]. Accordingly, recent analyses have evaluated the influence of the growing proliferation of 5G small cells deployments, concluding that generally, overall RF-EMF exposure will be reduced to the active user or the nearby bystanders [49], [50] and environmental total exposure will be lower due to a decreasing EMF needs of each cell [51]. Currently, 5G base station exposure levels are under analysis in order to provide clear health and safety insight [50], [52]–[55].

From an environmental point of view, several recent surveys, reviews and meta-analysis studies can be found in the literature, where RF-EMF exposure levels are discussed [6]–[11], [18], [28], [56]–[60], usually performing dynamic campaigns of measurements with RF-EMF frequency-selective exposimeters (PEM) and volunteers' help.

As in the previous research works, similar conclusions have been obtained: generally, RF-EMF exposure levels over a broad frequency range are very low in a general life context (with exposure levels well below 1 V/m) when compared with current established international RF-EMF exposure limits [33], [48], [28], [61], [61]–[63] presenting higher mean

exposure levels for public transportation systems environments (considered complex heterogeneous environments in terms of radio wave propagation) [58], [59], [64], [65]. In this sense, worst exposure average levels are obtained for rail transportation wagon cars scenarios, where the metal structure influence, the supplying electric lines and towers and particularly their huge passenger affluence (high density cellular use environments), involves much more challenging propagation phenomena [59], [66]–[68]. From the results, it must be pointed out that there is lack of clear evidence when analyzing the relative contribution of UL and DL signals in the total cumulative exposure [18] , [48], [61]. Considerable sources' variability is obtained due to several key factors that must be carefully analyzed: environmental characteristics, propagation conditions, user density, quantity and technical characteristics of heterogeneous networks coexisting or type of measurement procedures among others. Thus, further studies are required in order to precisely characterize the composition of the total RF-EMF exposure considering dynamic conditions.

In summary, from all the environmental general public exposure well-done rigorous and serious research works (reliable, with multiple samples, replicable, etc.) up to date, the only conclusion that can be stated is: the RF-EMF exposure levels obtained are far below (even for worst-case scenarios) the current EMF thresholds and regulation limits, mainly based on thermal effects [69], [70], with on-going discussions in relation with assessment of potential non-thermal effects.

It is worth-noting that scientific knowledge on long-term (multi years) exposure, particularly in chronic environments, is limited and still inconclusive [12]–[17]. In addition, occupational RF-EMF exposure assessment in worst-case conditions needs attention and must be precisely analyzed [19] as well as special situations in the context of safety of EMF vulnerable population [18]. Hence, precautionary principles in order to prevent adverse health effects and safety issues of RF-EMF exposure are welcome, as well as further studies are required [71], especially considering the fact that 5G wireless communication systems have different exposure modes compared to legacy systems and the fact that at the moment the trend is towards the use of increasingly higher frequencies, particularly deployed in the mmWave frequency range [72], [75] . However, taking together all the serious epidemiological studies and reviews of published literature, there is insufficient evidence and a lack of clear causal evidence, that RF-EMF radiation exposure induce harmful health hazards considering current established RF-EMF exposure limits [74]–[78].

C. LEGISLATION BACKGROUND

In most countries, EMF regulations and legislation and thus, RF-EMF radiation exposure limits, are based generally on the two most international adopted guidelines and standards [79], [80], the International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines (ICNIRP 2020) [69], or the Institute of Electrical and Electronics Engineers (IEEE) standard C95.1-2019 by the IEEE International Committee on Electromagnetic Safety [70]. In general, EMF exposure limits are adequately established in order to attend two main different group of population: occupational and general public, with independency of the selected EMF standard or guideline. Occupational exposure limits are normally in the order of five times higher than those set for the general public. Overall, reduction based on a safety factor is established for a higher occupational exposure limit in contrast with a more stringent restriction exposure limits for general public [69], [70], due to the assumption in which occupational exposition is generated under known RF-EMF conditions and workers must be trained to identify RF-EMF radiation/emissions and mitigate or reduce potential RF-EMF health hazards. On the other hand, general public can include EMF vulnerable or susceptible population, to which special attention in the context of health and safety should be provided.

It must be remarked that these guidelines and standards must be periodically revised and updated in order to attend the arise of new RF-EMF challenges (i.e. 5G cellular networks development on the mmWave frequency range) and to precisely evaluate their corresponding exposure, providing valid and accurate reference thresholds, exposure limits and restrictions for the new frequency bands, considering their inherent technical characteristics (transmission power, UL/DL operation, frame features and structure, energy consumption, time domain behavior, etc.). Consequently, the new version of the IEEE (IEEE standard C95.1-2019) [70] and ICNIRP (ICNIRP 2020) [69] limits were last updated in 2019 and 2020 respectively, accordingly with the health agencies and official entities (i.e., RF regulation exposures in USA correspond to the Federal Communications Commission (FCC) and FCC limits were approved in 1996 [81] and after a formal in-deep revision in 2019, they have not been updated and are still valid), as well as, with the current EMF scientific knowledge available. Nevertheless, both standards have been updated with the adoption of new methodologies concerning the assessment of potential 5G exposure scenarios. For example, in the new released version of the ICNIRP 2020 guidelines [69], special emphasis has been given to: local (reference levels averaged over 6 minutes interval) or localized exposures (less than 6 minutes) for non-continuous signals exposure (i.e. 5G MIMO beamforming), the reference levels delimitation from 2 GHz (now defined in terms of power density) instead of the previous 10 GHz, appropriate EMF assessment in far-field and near field conditions by means of specific limits and rules or EMF assessment specification for simultaneous exposure from multiple EMF frequency sources (i.e. context aware or heterogeneous network environments), among others. In general, it can be stated that the new aforementioned EMF exposure limits are now expressed as a function of the frequency range, the exposure duration and also the spatial characterization [59].

From a worldwide perspective, RF-EMF regulatory frameworks differences have motivated a lack of harmonized

RF-EMF exposure limits adoption due to mainly the following concern factors: precautionary principle application [82]–[84] and specific and local socio-political contexts. [85].

In the European Union (EU), health protection against non-ionizing radiation for occupational and general public was established with the European Recommendation 1999/519/EC [85], following the international ICNIRP guidelines [86], as well as the World Health Organization (WHO) [71] and the International Labour Organization (ILO) recommendations. Accordingly, several European countries transposed this Recommendation in their own legislation, mostly following the EU Directive 2013/35/CE. [87]. As an example, Spain adopted this recommendation into its independent legal system, by means of the publication of the RD 1066/2001 [88]. Nevertheless, clear differences are appreciated between Eastern European countries (EE) and Western European countries (WE) [89], [90]. On the one hand, in the majority of WE countries [91] safety standards, which served to address community concerns and stablish protection about the known health hazards or consequences from RF-EMF exposure [80], are based on the protection against biological effects, mainly thermal, which can occur when tissues temperature rises too much or too fast, and thermoregulatory system compensation capacity is defeated [92]–[94]. In general, these WE countries EMF exposure limits (based on ICNIRP guidelines) are crossly aligned with the ones established in USA (IEEE), Canada (Safety Code 6 [95]), Mexico (IEEE), Japan, UK or Australia (Australian Radioprotection and Nuclear safety Agency ARPANSA [96]). It must be pointed out that while in most countries, these EMF exposure limits are mandatory, there are several, where no binding regulations coexists, following only recommended limits from international standards and guidelines [58]. On the other hand, EE countries [97] safety standards aim to protect against as-yet unproven non-thermal hazards that could be caused from a continuous long-term EMF exposure (dose concept for cumulative EMF limitation [69], [91], [97], [98]), even though at low exposure levels. Therefore, more restrictive (variation by factors of 10 or even 100, based on the frequency and the type of public exposure) than the previous presented safety standards [19]. In some countries (Switzerland, India, Italy, just to give an example) the application of the precautionary principle or the confirmation of its application which took place years earlier (as happens in Italy) is partially motivated by RF social concerns against new arising 5G technologies giving rise to potential regulatory compliance challenges for the deployment of 5G BS [80], [99], [100]. All these EMF criterium issues can be attributed to differences in the conceptualization, the development or the methodology followed in the safety legislation, regulation and standardization procedures, but mainly to the risk perception involved.

D. AIM OF THIS WORK

The aim of this work is to provide a comprehensive and intensive in-depth study from an empirical and simulation approach of the environmental RF-EMF radiation exposure in public shopping malls, as an example of indoor context aware environments, where multiple wireless communication systems coexist. For that purpose, current personal mobile communications (2G-5G FR1) and Wi-Fi services (IEEE 802.11n/ac) considering their different frequency ranges have been precisely analyzed in order to provide clear insight in terms of RF-EMF assessment. In this sense, a complete environmental public shopping mall campaign of measurements in different countries is included, performed with frequency-selective exposimeters (PEMs) focused on RF-EMF exposure evaluation, allowing discrimination contributions from multiple sources. Empirical methodologies based on PEM measurements adoption are widely used/tested for EMF exposure assessment and evaluation in epidemical work studies for complex heterogeneous environments, as the presented shopping mall case study [6], [8]–[11], [56], [57]. At the same time, the selected countries in the research case study contribute to evaluate RF-EMF exposure assessment under the different EMF exposure safety standards, previously presented: Spain (ICNIRP 2020 - mandatory), Poland (more restrictive than ICNIRP/IEEE - mandatory) and Mexico (IEEE 2019 – not mandatory). Thus, providing empirical E-field dataset results present in dense complex heterogeneous environments, characterized by different regulatory frameworks, as this allows to verify and evaluate the impact of the regulatory frameworks on the environmental RF-EMF radiation exposure in real case conditions. These effects are currently under investigation in order to achieve a good tradeoff between technology development (lack or late 5G development motivated by too stringent RF-EMF exposure limits) and health and safety concerns. In addition, discussion regarding current health effects and safety issues is provided from the obtained empirical datasets.

Finally, a deterministic in-house RF-EMF safety simulation methodology for complex heterogeneous environments is presented, in order to provide a precise RF-EMF exposure assessment, allowing 3D scenarios definition and spatial characterization with different variation of node distributions, user density and case conditions (real-case or worst-case conditions among others). Simulation have been performed in order to alter measurements datasets into challenging incremental high-node user dense scenarios to provide results in worst case conditions and the RF-EMF assessment for current wireless communication technologies to which occupational and general public are exposed.

Although only current available wireless communication technologies have been measured, simulated and fully analyzed in this work, the obtained results and the presented methodology is extendable to the RF-EMF assessment basis of future 5G FR2 developments on the mmWave frequency range, where massive high-node user density networks are expected.

In Fig. 1, the rendered view of the considered public shopping mall scenario is depicted superposed with its corresponding bidimensional RF-EMF radiation exposure result plane (see simulation results - Case III for reference), as an

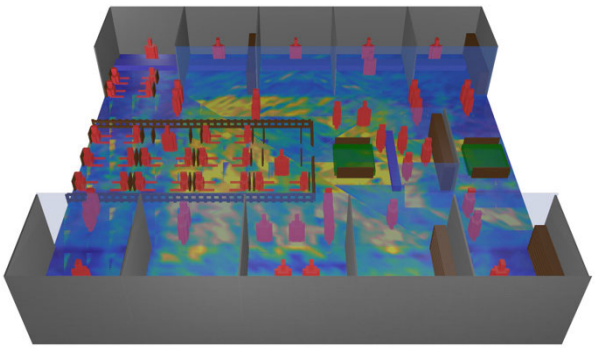


FIGURE 1. Schematic view of the rendered scenario with the simulation results for Case III.

example of the potential of the presented RF-EMF safety simulation technique.

The remaining parts of this work are outlined as follows: In Section 2, a complete description of the campaign of measurements procedure followed in the commercial centers is explained including the different measurement equipment and setups. In addition, the proposed in-house deterministic EMF safety simulation technique is introduced as well as the scenario description of the considered incremental high node user density study cases. An in-depth statistical analysis of the measurement campaign results is presented in Section 3, providing real experimental datasets allowing discussion in terms of EMF radiation exposure characterization. Section 4 presents the simulation results for the different Wi-Fi and cellular technologies (from 2G to 5G FR1) in the high node density considered scenario with incremental Cumulative Distribution Function (CDF) study cases and spatial E-field distribution characterization studies showing good agreement with the experimental measurements. Furthermore, discussion regarding different international exposure level thresholds is included highlighting the effects of the coexistence of multiple heterogenous networks and services for RF-EMF radiation exposure assessment considering current and future wireless technologies deployments. Finally, conclusions and future work are summarized in Section 5.

II. MATERIALS AND METHODS

A. MEASUREMENT CAMPAIGN

In order to provide clear insight of the personal EMF exposure in public shopping malls to which general public is exposed, a measurement campaign was performed in different countries with different EMF regulatory frameworks. Comparable modern shopping malls were selected for the field study in various locations: Warszawa (Poland), Madrid (Spain), Pamplona (Spain), Santa Cruz de Tenerife (Spain) and Monterrey (Mexico). Real photos of the chosen shopping malls and their main features can be found in Fig. 2 and Table 1, respectively. In addition, measurements were performed with different user distributions and densities in order to provide an accurate RF-EMF exposure assessment in normal business days, respecting the usual routine of the shopping malls. Therefore,

FIGURE 2. Real photos of the selected shopping malls.

TABLE 1. Main features of the selected public shopping malls.

	MAD	WAW	TEN	PNA	MTY
Country	Spain	Poland	Spain	Spain	Mexico
Location	Dt*	Peri**	Peri	Peri	Dt
Surface (m^2)	85.000	110.000	30.000	30.000	90.000
Local Cellular	yes	yes	yes	yes	yes
Local Public Wi-Fi	yes	yes	yes	yes	yes

*Dt = Downtown; **Peri = Periphery.
Specific and dedicated Local Cellular BS deployment in the main shopping mall building
Free Local Public Wi-Fi available at the full shopping mall area.

this work presents E-field distributions levels obtained for different scenario setups enabling personal EMF exposure comparison and EMF safety compliance evaluation (with legal international exposure thresholds).

There are different strategies or methodologies to precisely characterize the RF-EMF exposure in complex urban indoor environments such as shopping malls. Static or dynamic methods can be applied based on the study required measurement targets [101]. On the one hand, by means of spectrum analyzers, static procedures are the general measurement approach to precisely determine the EMF exposure contribution of a specific frequency band over the total exposure in a particular location and time. However, this static measurement campaigns carried out with spectrum analyzers present some important disadvantages such as the following:

- Very expensive in terms of equipment, training and staff costs.
- Considerable time-consuming measurements design and implementation methods.
- Low accuracy on time dynamic conditions.

On the other hand, dynamic procedures allow EMF exposure monitoring over complex wide urban scenarios, such as shopping malls, by means of RF-EMF frequency-selective exposure meters (known as exposimeters, or more precisely E-field exposimeters PEMs). The main advantage of this measurement strategy, using PEM devices, is the cost and effort reduction (due to their small size, weight and easy use)

enhancing, at the same time, the EMF exposure assessment accuracy with multiple measurements at diverse and selected locations in dynamic conditions. Despite their portability, PEMs may also be used to perform RF-EMF static measurement campaigns in specific locations, monitoring the EMF exposure over time. Nevertheless, their widespread use is focused on dynamic wide measurement campaigns based on multiple measurements performed by a set of trained volunteers. In that sense, several epidemical work studies associated with EMF exposure assessment and evaluation in complex heterogeneous environments employing PEMs can be found in the literature [6], [8]–[11], [56], [57], [102], [103].

FIGURE 3. EME SPY Evolution and EME SPY200 personal dosimeters used for the measurement campaign within the shopping malls.

Two different PEM devices have been selected for the EMF exposure measurements study presented in this work: EME SPY Evolution and EME SPY200 frequency selective exposimeters (from Microwave Vision Group MVG, https://www.mvg-world.com/es) which are presented in Fig. 3. Both devices are portable, pocket-sized (weighting less than 500 g), battery-powered RF-EMF exposure data monitors and loggers of the environmental power flux density and E-field RMS strength levels over time. The main difference between them is that the EME SPY Evolution has the possibility to measure more frequency bands than the EME SPY200 and is customizable in terms of the scenario region setup. Based on the measurement campaign region: the European Union (EU) or the United States of America (USA), two pre-defined frequency ranges setups (including the bands of 4th generation mobile networks, WiMAX or Wi-Fi 5G, which correspond to the most common RF-EMF applications used in usual/typical public environment such as a shopping malls) have been considered in terms of frequency selective RF-EMF exposure evaluation. The EME SPY200 has been used with the EU frequency range setup and the EME SPY Evolution has been customized according to the measured location scenario (EU and USA regions). The detailed information for the frequency bands of each region for cellular and Wi-Fi setups are summarized in Table 2.

The sensitivity of the SPY 200 and the SPY EVO is 0,005 V/m in each individual frequency band and the E-field measurement range is 0,05-5 V/m and 0.02-6 V/m, respectively. Moreover, both devices are equipped with an internal

TABLE 2. EU and USA cellular and Wi-Fi frequency bands configurations for the measurement campaigns based on the PEM devices setup.

	Frequency Ranges (MHz)					
	Spy 200 EU - Setup		Spy Evo EU - Setup		Spy Evo USA - Setup	
	Min.	Max.	Min.	Max.	Min.	Max.
LTE 800 DL	791	821	791	821	746	756
LTE 800 UL	832	862	832	862	777	787
GSM&UMTS 900 UL	880	915	880	915	814	849
GSM&UMTS 900 DL	925	960	925	960	859	894
GSM 1800 UL	1710	1785	1710	1785	1850	1915
GSM 1800 DL	1805	1880	1805	1880	1930	1995
UMTS 2100 UL	1920	1980	1920	1980	1710	1755
UMTS 2100 DL	2110	2170	2110	2170	2110	2155
LTE 2600 UL	2500	2570	2500	2570	2500	2570
LTE 2600 DL	2620	2690	2620	2690	2620	2690
Wi-Fi 2G	2400	2483	2400	2483	2400	2483
Wi-Fi 5G	5150	5850	5150	5850	5150	5850

*Reference for all PEMS and scenarios setups corresponding Cellular and Wi-Fi bands:
SPY 200: LTE 800 (DL) – SPY EVO EU: B20DL – SPY EVO USA: B13DL
SPY 200: LTE 800 (UL) – SPY EVO EU: B20UL – SPY EVO USA: B13UL
SPY 200: GSM&UMTS 900(UL) – SPY EVO EU: B8UL – SPY EVO USA: B26UL
SPY 200: GSM&UMTS 900(DL) – SPY EVO EU: B8DL – SPY EVO USA: B26DL
SPY 200: GSM 1800 (UL) – SPY EVO EU: B3UL – SPY EVO USA: B25UL
SPY 200: GSM 1800 (DL) – SPY EVO EU: B3DL – SPY EVO USA: B25DL
SPY 200: UMTS 2100 (UL) – SPY EVO EU: B1UL – SPY EVO USA: B4UL
SPY 200: UMTS 2100 (DL) – SPY EVO EU: B1B10DL – SPY EVO USA: B4DL
SPY 200: LTE 2600 (UL)– SPY EVO EU: B7UL – SPY EVO USA: B7UL
SPY 200: LTE 2600 (DL)– SPY EVO EU: B7DL – SPY EVO USA: B7DL
SPY 200: WIFI 2G – SPY EVO EU: W2G – SPY EVO USA: W2G
SPY 200: WIFI 5G – SPY EVO EU: W5G – SPY EVO USA: W5G

memory which allows more than 12K or 16K samples per device with the maximum recording sampling rate. It must be remarked that the recording sampling rate is restricted according to the pre-configured region scenario setup. Specifically, on the one hand, measurements campaigns in Monterrey, Mexico were carried out with the Spy Evolution's USA multi-band scenario configuration, with the minimum measurement recording sampling rate allowed, obtaining an E-field sample every five seconds. On the other hand, the EU multi-band scenario setup was selected for the other measurements campaigns performed in EU with an E-field sampling rate of four seconds in the SPY 200 and 5 seconds in the SPY Evolution. Hence, the recording programmable sampling rate parameter is one of the most relevant configuration setups of a measurement campaign using PEM devices. In general, higher recording sampling rate equals to more accuracy in the measurements results due to a more continuous evaluation of the spectrum, with less signal gaps over the time. A further description of the measurement campaign design is presented in Table 3.

TABLE 3. Design, devices and configuration setups for the measurement campaigns performed in the different shopping malls.

	MAD	WAW	TEN	PNA	MTY
PEM device	SPY 200	SPY 200	SPY 200	SPY EVO	SPY EVO
Scenario Setup	EU	EU	EU	EU	USA
PEM Precision (V/m)	Max. 0.005	Max. 0.005	Max. 0.005	Max. 0.005	Max. 0.005
PEM Precision Range (V/m)	0.05 -5	0.05 - 5	0.05 - 5	0.02 - 6	0.02 - 6
Sampling rate (sec)	Min. 4	Min. 4	Min. 4	Min. 5	Min. 5
Measurement Campaigns	HD/LD*	HD/LD*	HD/LD*	HD/LD*	HD/LD*
Total Recording Range (hr)	2	2	2	2	2
Recording Range per Area (min)	20	20	20	20	20

*HD/LD: High- and Low-User-Density measurements campaigns

The same measurement campaign procedures have been followed for all the shopping malls, regardless the device/s used or the region. The main characteristics of the measurement campaign design were the following:

- Measurements have been performed continuously for a period of two hours inside the shopping malls.
- Measurements included three different areas: indoor shops, general corridors and indoor/outdoor coffee-shops with a minimum of twenty minutes in each one of them.
- Measurements campaigns were performed with two different user densities and distributions: defined in this work as high- and low-density scenarios (HD/LD). In this sense, measurements in HD scenarios were performed during Christmas holidays or the first sales periods days. On the contrary, LD scenarios were considered when the shopping malls were almost empty, in normal business days at first open hours or during usual working hours. It must be pointed out that measurements in all the shopping malls were performed during the year 2019, with normal conditions before any kind of restriction was applied to shopping malls due to the worldwide SARS-CoV-2 pandemic.
- Measurements respected the normal business routine of the shopping malls with no interaction and without conditioning, over customers, general public or workers/staff.
- Measurements were carried out in general public exposure areas instead of in occupational areas, restricted for workers or staff. They were performed in public, open, accessible and authorized locations for customers or general public.

Nevertheless, there are remarkable factors and effects that must be carefully considered for a correct EMF exposure assessment. In that sense, it must be pointed out that EMF measurements can be conditioned by overall wireless systems interference signals. Therefore, electronic equipment such as handsets, laptops or tablets were not allowed during all the data collection campaign in order to avoid erroneous measurements or mitigate unreliable ones. Moreover, EMF measurements obtained by means of PEM devices, are also sensitive to the selected measurement technique, the type of scenario or location and in particular, to the shielding effect of the human body in the proximity of the antenna [58], [104]. Accordingly, it is worth noting that body shielding affectation over E-field exposure levels, can underestimate or even reduce drastically the measured values, generating inaccurate or incorrect EMF results [105]–[107]. Hence, a validated measurement approach has been followed in the present work, with the PEM hardware devices located in the vicinity of the staff body, but not directly on the body, with the aim of avoiding or at least decreasing underestimation (only 1 V/m of body shielding effect when another user/scatterer is located between the radiating antenna and the receiver) [58]. Thus, by means of this technical measurement procedure, the presented E-field exposure levels and the corresponding EMF safety assessment evaluation, are consistent in terms of reliability and accuracy.

B. MODELING TECHNIQUE

Several types of simulation methodologies can be found in the literature to adequately characterize the propagation channel. Ranging from empirical simulation methods [108], [109], which are based on multiple measurements over a specific scenario, to full wave methods [110], based on the strict development of the Maxwell equations, each approach presents advantages and disadvantages. For example, on the one hand, when employing empirical simulation techniques over complex heterogeneous environments, a reduction in simulation time/cost is achieved, but with high deviation in the obtained results [111], [112]. On the other hand, full wave methods, such as Finite-Difference-Time-Domain (FDTD) or the Method-of-Moments (MoM), provide very precise estimations, but are not suitable for large scenarios due to their currently unattainable computational cost [110]. Between these two approaches, 3D Ray Launching (3D-RL) deterministic techniques emerge enabling complex indoor scenarios evaluation, considering all the elements and environment characteristics with an optimal tradeoff between precision and processing time [111], [112]. In this work, an in-house developed 3D-RL methodology is proposed in order to assess and predict in advance EMF exposure safety in complex high-node density heterogeneous environments. Following this modelling approach, the impact of different user densities and distributions can be precisely characterized and analyzed in terms of non-ionizing radiation exposure for the most common wireless PLMN which provide services in public dense environments. Thus, E-field volumetric distributions can be obtained as a function of user distribution within the shopping malls.

The presented 3D-RL algorithm has been developed under MATLAB programming ecosystem. The principle of the Ray

Launching (RL) methodology is to approximate the wave front of the radiated wave by using multiple rays replicating the same wave behavior. For that purpose, a combination of electromagnetic theories and equations based on Geometrical Optics (GO) and Geometrical Theory of Diffraction (GTD) [113], have been considered. Moreover, the in-house developed 3D-RL code has been optimized in order to decrease processing time by means of hybrid simulation methodologies, as neural networks, or using collaborative filtering and the diffusion equation, enabling the evaluation of large complex heterogeneous environments [114]–[116]. In this sense, the simulation tool has been widely tested and validated for wireless propagation channel characterization and EMF exposure assessment in indoor and outdoor urban scenarios [117]–[119].

The algorithm is based on three main phases:

- 3D scenario creation
- RL Simulation process
- Results Analysis

In the first phase, the three-dimensional scenario is created considering all the details of the environment and respecting real dimensions, morphology, topology and the material features of all the obstacles, walls and transceivers within it.

In the second phase, during the simulation, multiple rays are launched following the transmitter antenna radiation diagram pattern, interacting with all the obstacles within the scenario. Therefore, depending on the geometry and the material electric characteristics, these interactions are affected by electromagnetic propagation phenomena such as reflection, refraction, diffraction or scattering. Moreover, the volume of the scenario is spatially divided using a grid of cuboids with a fixed resolution size where each ray's propagation data is stored in its corresponding matrix. Hence, the definition of a set of simulation parameters is required in order to achieve accurate characterization results with an optimal computational load. Thus, input parameters such as frequency of operation, radiated power, radiation patterns, antennas directivity, transceiver locations, maximum number of multipath reflections, wave polarization and ray angular and spatial resolution must be defined. In this work, simulations have been performed following an optimal already-validated tradeoff between spatial resolution for large complex scenarios [120] and the number of multipath reflections [113].

Finally, in the third phase, results analyses are performed. The 3D-RL algorithm rely on a modular programming structure, where different type of results can be obtained [121]. In this work, EMF safety analysis has been implemented as a new module providing full support for non-ionizing radiation exposure results in complex heterogeneous environments with high-node user density. In this library, precise E-field exposure evaluation for the complete volume of the scenario under analysis can be achieved applying conversion EMF equations to the matrix of power level results, obtained in the previous simulation phase [58], [59]. It must be clearly remarked that RL simulation techniques provide uncertain near field results in the vicinity of the transmitter antenna. Therefore, exclusion areas of 5λ distance have been considered around the transmitter location based on the frequency under analysis, avoiding unreliable near field results [122].

C. SCENARIO DESCRIPTION

In order to analyze EMF exposure safety conditions considering wireless communications systems densification within a shopping mall, one of the real measured shopping malls scenarios has been modeled for simulation purposes. The selected scenario is a generic section of Valle Oriente Shopping Mall in Monterrey, Mexico where multiple shops coexist with public corridors and open coffee shops areas. In Fig. 4, a real photo of the considered scenario is presented with its corresponding schematic model for simulation.

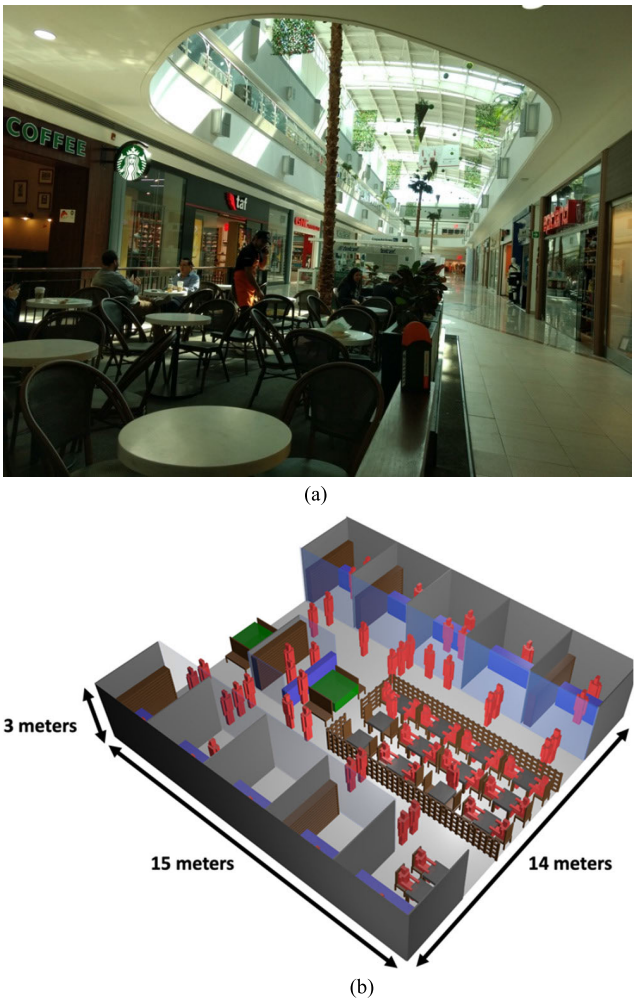


FIGURE 4. The considered scenario where (a) is a real photo of the selected section of the shopping mall and (b) is the 3D rendered view of the model for simulation.

Three incremental case studies have been selected for simulation considering different Wi-Fi and cellular technologies (from 2G to 5G) and their corresponding system operation in terms of DL or UL connection links and frequency of operation, in order to provide environmental RF-EMF exposure

TABLE 4. Description of the considered incremental cases for simulation.

Cases	System & Operation	Frequency (MHz)	Users/ Total Users per case	Antenna	Users Density
Case I	2G/3G DL	900	3/8	Omni	HND*
		1800			
		2100			
	4G DL	800	3/8		
		1800			
		2600			
	Wi-Fi DL	2400	2/8		
		5000			
Case II	2G/3G DL/UL	900	6/16	Omni	HND*
		1800			
		2100			
	4G DL/UL	800	6/16		
		1800			
		2600			
	Wi-Fi DL/UL	2400	4/16		
		5000			
Case III	2G/3G DL/UL	900	6/20	Omni	HND*
		1800			
		2100			
	4G DL/UL	800	6/20		
		1800			
		2600			
	Wi-Fi DL/UL	2400	4/20		
		5000			
	5G FR1 DL/UL	700	4/20		
		3700			

*HND = High-Node Density simulation scenario

assessment for high-node density conditions, as a function of transceiver location within the complete volume of the scenario under analysis. Starting from a first scenario where only the DL connection links of current cellular technologies (2G to 4G) are considered; a more realistic second scenario where UL and DL cellular connection links and Wi-Fi services are evaluated; to a third final scenario, where all cellular technologies (2G to 5G) in UL and DL are considered as well as Wi-Fi services, emulating total environmental E-field exposure from the providing services, considering worst case conditions, with high node user density for all technologies coexisting at the same time. In Table 4, a detailed summary of all the considered cases for simulation is presented.

The considered densification criteria have been stablished based on the active user proportion and distribution per area, technology and communication link operation. In this sense, an incremental number of active connection links (DL/UL) have been considered per case, increasing from a basic dense scenario (Case I – 8 active DL users simultaneously) to a worst dense scenario (Case III – 20 active DL/UL users simultaneously). It must be remarked that worst-case conditions in terms of E-field exposure levels consider the worst time instant when all interconnecting active devices are operating at the same time, providing the inter-system cumulative RF-EMF exposure per incremental case. These criteria lead to a total of 8 users in Case I, 16 users in Case II and 20 users in Case III considering the different technology systems (2G-5G/Wi-Fi) and operation (UL/DL). A detailed summary of all the active users' combination per incremental case can be seen in Table 4. In Fig. 5, a schematic view of the complete incremented scenario is depicted in order to provide clear insight of the wireless system characterization and the considered distribution.

TABLE 5. Summary of the simulation parameters for all the considered incremental case setups.

Simulation Parameters		Ref.
Frequency of operation	See Table 4.	
Transmitted power level DL	15 dBm	[123-124]
Transmitted power level UL	10 dBm	
Tx / Rx Gain	0 dBi	
Antenna Type	Omnidirectional	
Horizontal angular resolution ($\Delta\varphi$)	π/180 rad	[113]
Vertical angular resolution ($\Delta\theta$)	π/180 rad	[113]
Permitted maximum reflections	7	[113]
Cuboids size	20 cm	

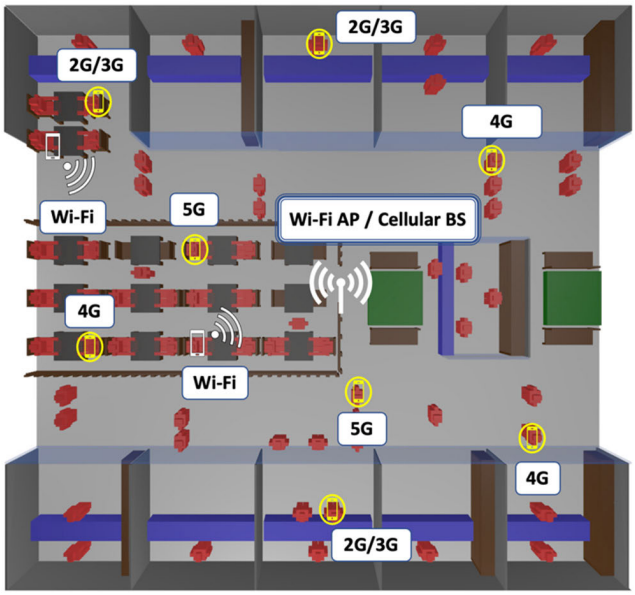


FIGURE 5. Schematic view of the full final model of the considered scenario, where all the transmitter locations and analyzed services are presented for simulation.

Simulations have been performed considering different transmitter heights and realistic conditions in terms of frequencies of service as well as power and bit rate transmission. Simulation cut planes results have been obtained corresponding with the same heights as the transmitter is placed for all the analysed cases: 1.2 m height emulating both the chest and the head height of a seated or standing person respectively, 1.6 m height emulating the head height of a standing person and 0.9 m for the chest height of a seated person. A full description of the main important parameters for all the simulation case setups is presented in Table 5.

III. MEASUREMENT RESULTS AND DISCUSSION

Measurement results have been analysed by means of the time-averaged root-mean-square (RMS) value of the E-field

strength, expressed in volt per meter, V/m. This relevant statistical parameter has been selected in order to analyse the influence of the exposure effect for each measured frequency band. The RMS E-field value has been calculated according the following formula:

$$E_{RMS} = \sqrt{\sum E_i^2} \tag{1}$$

where E_i is the E-field strength measured for each frequency band presented in Table 2, i.e.: E_{FM}, E_{TV3}, E_{Tetra}, $E_{GSM900Tx}$, $E_{GSM900Rx}$, etc.

First, rough measurement data have been converted to Excel (MS Office) numerical data sheets for further analysis. Preliminary visual control of results of measurements shows that some frequency bands did not contribute in the evaluated exposure, while at first sight the most significant bands were cellular phones and Wi-Fi frequency bands. To verify this hypothesis, the comparison between the total measured E-field value reported by the exposimeters with the RMS E-Field value calculated with (1) considering only cellular and Wi-Fi frequency bands have been performed.

The analysis has been performed with the use of median, 95-th centile and maximum values from recordings in particular datasets. These values have been chosen as they are the most representative of human exposure parameters. The minimum and 5-th centile values are significantly more unstable in recordings from the low-exposure environment, because significant number of measurement results are in the same range as the sensitivity of used measurement devices. The averaged value and standard deviation (very frequently used as statistical metrics of recorded values from various measurements) have not been used because the distributions of measurement results in particular datasets do not fit a Normal distribution.

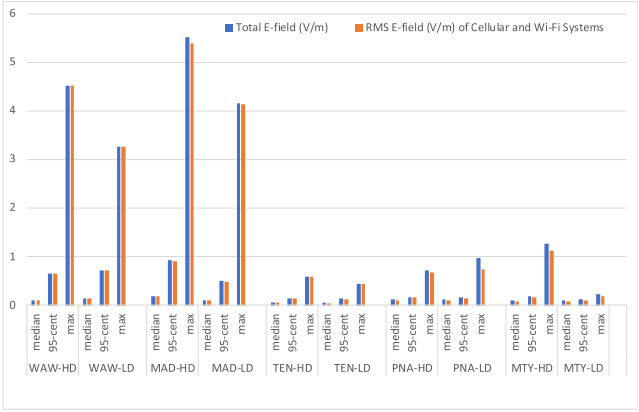


FIGURE 6. RMS E-field of Cellular Systems and Wi-Fi vs Total E-field measurements for the different cities for high and low-density cases.

The comparison between the total measured E-field value reported by the exposimeters versus the RMS E-Field value calculated with (1) considering only cellular and Wi-Fi frequency bands is presented in Fig. 6. As it can be seen, for all analysed shopping centres in the different cities, the most significant radiation exposure is for cellular and Wi-fi bands from all the analysed measured frequency bands, as it is observed that the obtained values for each case are very similar. To have insight into the specific values, Table 6 presents the test results in percentage for the five different considered shopping centres in the different cities, for high and low-density cases.

TABLE 6. RMS E-field* (%) of Cellular Systems and Wi-Fi vs Total E-field** measurements.

MAD		WAW		TEN		PNA		MTY	
HD	LD	HD	LD	HD	LD	HD	LD	HD	LD
98	99	99	99	89	79	86	85	83	82

*Cellular and Wi-Fi bands: LTE 800 (DL), LTE 800 (UL), GSM&UMTS 900(UL), GSM&UMTS 900(DL), GSM 1800 (UL), GSM 1800 (DL), UMTS 2100 (UL), UMTS 2100 (DL), WIFI 2G, LTE 2600 (UL), LTE 2600 (DL), WIFI 5G.
**Total measured bands in the exposimeters.

TABLE 7. RMS E-field* (%) of Cellular Systems (only DL) and Wi-Fi vs Total E-field** measurements of Cellular Systems and Wi-Fi.

MAD		WAW		TEN		PNA		MTY	
HD	LD	HD	LD	HD	LD	HD	LD	HD	LD
99	97	94	98	84	93	74	73	74	73

*Cellular (only DL) and Wi-Fi bands: LTE 800 (DL), GSM&UMTS 900(DL), GSM 1800 (DL), UMTS 2100 (DL), WIFI 2G, LTE 2600 (DL), WIFI 5G.
**Cellular and Wi-Fi bands: LTE 800 (DL), LTE 800 (UL), GSM&UMTS 900(UL), GSM&UMTS 900(DL), GSM 1800 (UL), GSM 1800 (DL), UMTS 2100 (UL), UMTS 2100 (DL), WIFI 2G, LTE 2600 (UL), LTE 2600 (DL), WIFI 5G.

From Table 6, it can be observed that in all cities, both in high and low-density cases, the percentage of RMS E-field values of cellular and Wi-Fi systems is greater than 80% (greater than 95% in the case of Madrid and Warszawa). These results confirm our previous hypothesis that the significant values of radiation exposure in all the considered shopping centres correspond to the cellular phones and Wi-Fi systems. Therefore, we will concentrate on these systems in the subsequent analyses.

As in the previous hypothesis, we have focus now in the most significant bands among the cellular and Wi-fi frequency bands to analyse exposure effects. For that purpose, after previous data analysis, our hypothesis is that the UL frequency bands can be skipped from the analysis in the recording datasets. To verify this hypothesis, the comparison between the total measured E-field value for cellular and Wi-Fi systems reported by the exposimeters with the RMS E-Field value calculated with (1) considering only cellular (only DL) and Wi-Fi systems have been performed. Table 7 presents the test results in percentage for the five different considered shopping centres in the different countries, for high and low-density cases.

From Table 7, it can be observed that in all cities, both in high and low-density cases, the percentage of RMS E-field values of downlinks (DL) cellular and Wi-Fi systems is greater than 70% of the total cellular (DL and UL) and Wi-Fi systems (greater than 95% in the case of Madrid and Warszawa).

Therefore, after this preliminary analysis, we will focus on cellular systems (DL) and Wi-Fi, as they are statistically significant in our recording datasets. Among these systems,

TABLE 8. RMS E-field* (%) of 2G/3G (DL), 4G (DL) and Wi-Fi vs Total E-field** measurements of Cellular Systems and Wi-Fi.

	MAD		WAW		TEN		PNA		MTY	
	HD	LD	HD	LD	HD	LD	HD	LD	HD	LD
2G/3G	96	90	80	93	55	62	48	49	50	51
4G	12	8	7	5	14	16	25	27	32	32
Wi-Fi	10	12	19	12	41	42	51	40	41	40

*2G/3G bands: GSM&UMTS 900(DL), GSM 1800 (DL), UMTS 2100 (DL).
4G bands: LTE 800 (DL), LTE 2600 (DL).
Wi-Fi bands: WIFI 2G, WIFI 5G.
**Cellular and Wi-Fi bands: LTE 800 (DL), LTE 800 (UL), GSM&UMTS 900(UL), GSM&UMTS 900(DL), GSM 1800 (UL), GSM 1800 (DL), UMTS 2100 (UL), UMTS 2100 (DL), WIFI 2G, LTE 2600 (UL), LTE 2600 (DL), WIFI 5G.

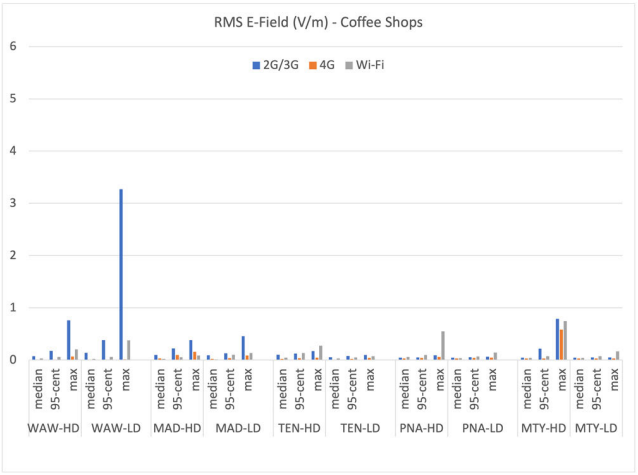
the analysis of the most representative in terms of radiation exposure within the considered shopping centers is presented: 2G/3G (DL), 4G (DL) or Wi-Fi systems. Following the same approach as the previous hypothesis, Table 8 presents the comparison in percentage of the RMS E-field of the frequency bands for 2G/3G (DL), 4G (DL) and Wi-Fi systems versus Total E-field measurements of cellular systems and Wi-Fi.

From Table 8, it can be seen that in Madrid and Warszawa, the most significant radiation exposure is from 2G/3G DL frequency bands, both in high and low-density cases. However, in the other three analyzed cities, radiation exposure from 2G/3G DL and Wi-Fi are in the same percentage approximately, being the least significant the frequency band of 4G (DL) for all shopping center cities.

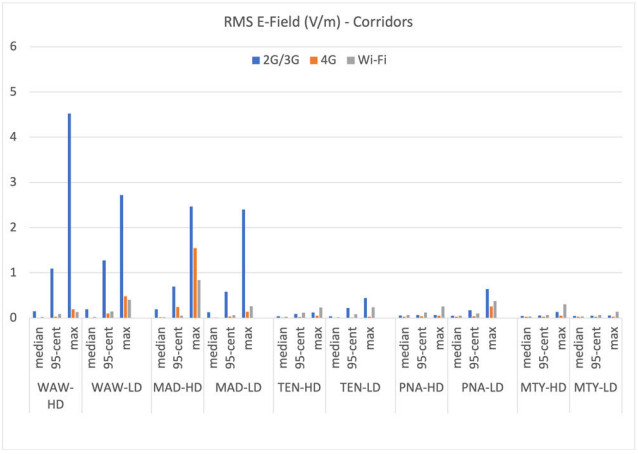
In order to have insight into the differences in general radiation exposure in the different areas of the shopping centers, three different scenarios within the shopping centers have been considered, as explained previously these areas are indoor shops, general corridors and indoor/outdoor coffee-shops. Recording datasets have been discriminated according to the specific area under consideration, and results for radiation exposure for the frequency bands under analysis are shown in Fig. 7 for the different cities for high and low-density cases. It can be observed that the EU bigger cities, i.e., Warszawa and Madrid, have more radiation exposure than the other cities, being the highest RMS E-Field level for 2G/3G frequency bands for the three areas. Regarding the areas, the highest peaks have been obtained for indoor shops in a high-density case in the city of Madrid, with a maximum of 5.4 V/m (13.09% of ICNIRP reference level), followed by general corridors in a high-density case in the city of Warszawa, with a maximum of 4.5 V/m (10.90% of ICNIRP reference level), and finally coffee shops in a low-density case in the city of Warszawa, with a maximum of 3.3 V/m (8% of ICNIRP reference level). It must be remarked that all the maximums peaks have been recorded for 2G/3G DL frequency bands.

In order to have insight into the impact of radiation exposure of the three areas considered within the shopping centers in the different cities, Tables 9, 10 and 11 presents the comparison in percentage of the RMS E-field of the frequency bands for 2G/3G (DL), 4G (DL) and Wi-Fi systems versus the total E-field measurements of cellular systems and Wi-Fi, for coffee shops, general corridors and indoor shops, respectively.

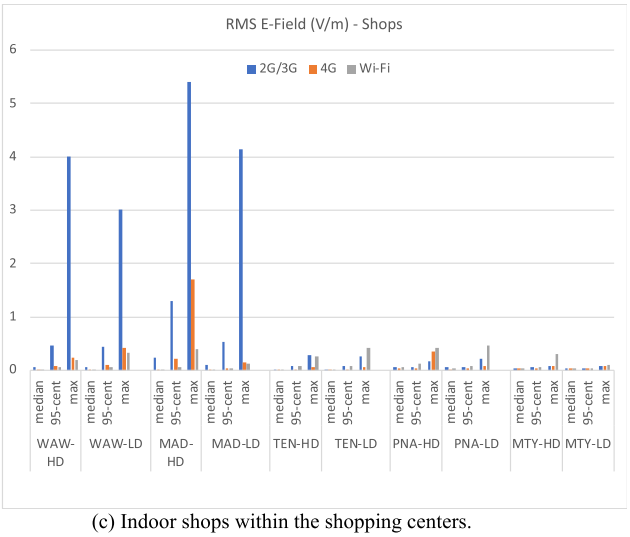
From these tables, it is observed that in coffee shops, in all the cities, the most significant values of radiation exposure



(a) Coffee shops within the shopping centers.



(b) General corridors within the shopping centers.



(c) Indoor shops within the shopping centers.

FIGURE 7. RMS E-field of 2G/3G (DL), 4G (DL) and Wi-Fi vs Total E-field measurements for the different cities for high and low-density cases per different areas, (a) coffee shops, (b) general corridors and (c) indoor shops.

TABLE 9. RMS E-field* (%) of 2G/3G, 4G and Wi-Fi in coffee shops vs Total E-field** measurements of Mobile Systems (only DL) and Wi-Fi.

	MAD		WAW		TEN		PNA		MTY	
	HD	LD	HD	LD	HD	LD	HD	LD	HD	LD
2G/3G	84	90	81	95	84	80	42	47	49	50
4G	24	21	8	4	19	13	28	29	33	31
Wi-Fi	17	12	34	15	36	43	59	36	43	43

*2G/3G bands: GSM&UMTS 900(DL), GSM 1800 (DL), UMTS 2100 (DL).
4G bands: LTE 800 (DL), LTE 2600 (DL).
Wi-Fi bands: WIFI 2G, WIFI 5G.
**Cellular and Wi-Fi bands: LTE 800 (DL), LTE 800 (UL), GSM&UMTS 900(UL), GSM&UMTS 900(DL), GSM 1800 (UL), GSM 1800 (DL), UMTS 2100 (UL), UMTS 2100 (DL), WIFI 2G, LTE 2600 (UL), LTE 2600 (DL), WIFI 5G.

TABLE 10. RMS E-field* (%) of 2G/3G, 4G and Wi-Fi in general corridors vs Total E-field** measurements of Mobile Systems (only DL) and Wi-Fi.

	MAD		WAW		TEN		PNA		MTY	
	HD	LD	HD	LD	HD	LD	HD	LD	HD	LD
2G/3G	95	95	90	93	53	71	47	48	50	51
4G	9	5	4	3	13	12	23	26	31	32
Wi-Fi	8	11	15	10	39	37	54	46	39	41

*2G/3G bands: GSM&UMTS 900(DL), GSM 1800 (DL), UMTS 2100 (DL).
4G bands: LTE 800 (DL), LTE 2600 (DL).
Wi-Fi bands: WIFI 2G, WIFI 5G.
**Cellular and Wi-Fi bands: LTE 800 (DL), LTE 800 (UL), GSM&UMTS 900(UL), GSM&UMTS 900(DL), GSM 1800 (UL), GSM 1800 (DL), UMTS 2100 (UL), UMTS 2100 (DL), WIFI 2G, LTE 2600 (UL), LTE 2600 (DL), WIFI 5G.

TABLE 11. RMS E-field* (%) of 2G/3G, 4G and Wi-Fi in indoor shops vs Total E-field** measurements of Mobile Systems (only DL) and Wi-Fi.

	MAD		WAW		TEN		PNA		MTY	
	HD	LD	HD	LD	HD	LD	HD	LD	HD	LD
2G/3G	97	92	71	62	54	61	49	50	49	51
4G	8	6	7	8	13	18	24	26	32	32
Wi-Fi	8	12	15	13	40	42	46	37	40	40

*2G/3G bands: GSM&UMTS 900(DL), GSM 1800 (DL), UMTS 2100 (DL).
4G bands: LTE 800 (DL), LTE 2600 (DL).
Wi-Fi bands: WIFI 2G, WIFI 5G.
**Cellular and Wi-Fi bands: LTE 800 (DL), LTE 800 (UL), GSM&UMTS 900(UL), GSM&UMTS 900(DL), GSM 1800 (UL), GSM 1800 (DL), UMTS 2100 (UL), UMTS 2100 (DL), WIFI 2G, LTE 2600 (UL), LTE 2600 (DL), WIFI 5G.

come from 2G/3G DL and Wi-Fi systems, and the less significant comes from 4G systems. In Madrid, Warszawa and Tenerife, 2G/3G DL RMS E-field values in coffee shops are bigger than 80%, whilst in Pamplona and Monterrey, 2G/3G DL and Wi-Fi systems are representative in the same percentage. In general corridors and indoor shops, in all shopping centers of all the analyzed cities, the most significant values of radiation exposure come from 2G/3G DL, followed by Wi-Fi systems and at the end 4G systems.

From these results, it can be concluded that radiation exposure from 2G/3G DL is the most significant in all measured cases, regardless of the specific area under consideration within the shopping center. In the cities of Tenerife, Pamplona and Monterrey, the 2G/3G DL and Wi-Fi systems are significant, regardless of the area under analysis.

The UL or DL wireless signals impact to radiation exposure in different complex environments such as shopping malls depends on many factors, such as the proximity of wireless facilities in the measured scenario or the employed measurement campaign technique, where exposure from own's cellular phone is considered or not. As stated in Section II.A, all measurements presented in this work have been performed without considering the impact of radiation exposure from the own cell handset, to give insight into population exposure from by-standers cell phones and wireless devices. Results are in accordance with other works in the literature which presents on the average higher DL exposures, such as a recent study performed in five different EU countries [61] or the work presented in [48], which presents five different urban areas in Belgium.

IV. SIMULATION RESULTS AND DISCUSSION

Nevertheless, as presented before, radiation exposure impact can vary depending on many factors. In this section, in order to analyze EMF exposure safety conditions within a shopping mall, the three incremental use cases presented in Section II.C have been simulated by means of the 3D-RL technique, providing E-field distribution estimations within the complete volume of the considered shopping mall, thus, assessing environmental RF-EMF exposure impact for different dense use cases.

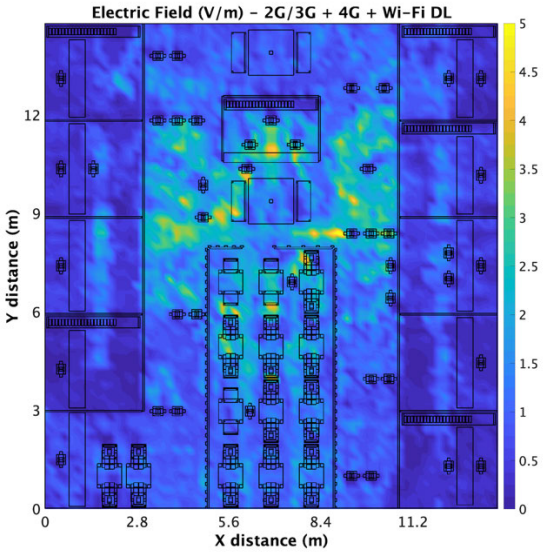


FIGURE 8. Bi-dimensional plane of E-field exposure levels for Case I (see Table 4 for reference) within the simulated shopping mall.

Fig. 8-10 represent the bi-dimensional mapping of E-field exposure levels at 1.2 m from the ground, corresponding to the head and the chest of respectively a seated or standing person located in the scenario shown in Fig. 5 and 11. It must be emphasized that worst-case conditions are considered, in terms of E-field exposure levels, provided at the worst time instant when all interconnecting devices operate at the same time, and the total inter-system cumulative RF-EMF exposure levels is presented for the different incremental cases.

The three use cases analyzed (Case I to III) are depicted, showing higher E-field levels concentration for the worst-case scenario (Case III), as expected. In addition, higher exposure is concentrated in the open area rather than in the lateral shops, as almost of the users are located in this area which is not affected by attenuation from the walls as is the case of the shops positioned laterally (see Fig. 5 and 11 for reference).

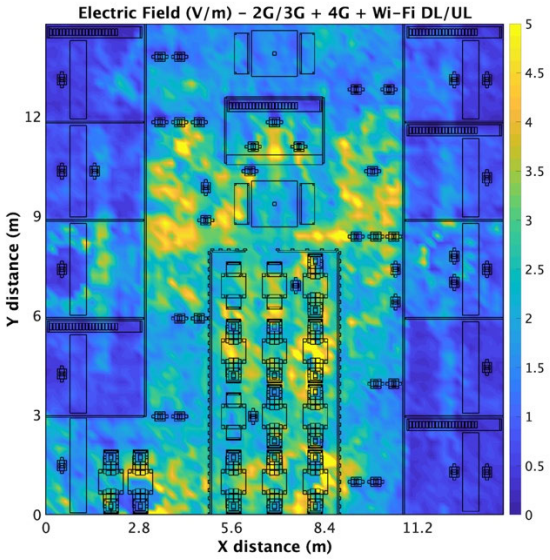


FIGURE 9. Bi-dimensional plane of E-field exposure levels for Case II (see Table 4 for reference) within the simulated shopping mall.

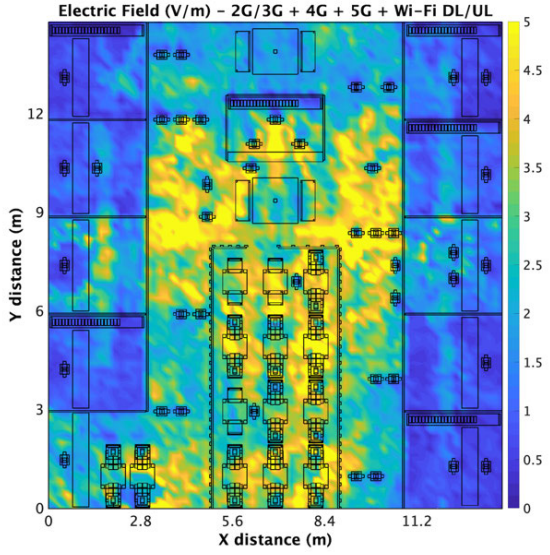


FIGURE 10. Bi-dimensional plane of E-field exposure levels for Case III (see Table 4 for reference) within the simulated shopping mall.

In order to have insight into the impact of 5G FR1 within the shopping mall, Fig. 12 and 13 presents the bi-dimensional planes of E-field exposure levels for only 5G, DL and UL respectively, considering two users transmitting at the same time at different frequencies for each case (see Table 4 for reference). As it can be seen from the figures, the impact of 5G is not high even considering worst-case condition (an increase of 0.87 V/m – 3% of ICNIRP reference values), showing a uniform E-field distribution within almost all the spatial points of the scenario. This leads to observe that RF-EMF exposure may increase with the densification of wireless devices operating at the same time, but it can be stated that 5G FR1 systems alone do not provide higher exposure than the current wireless systems present in public indoor environments, such as shopping malls.

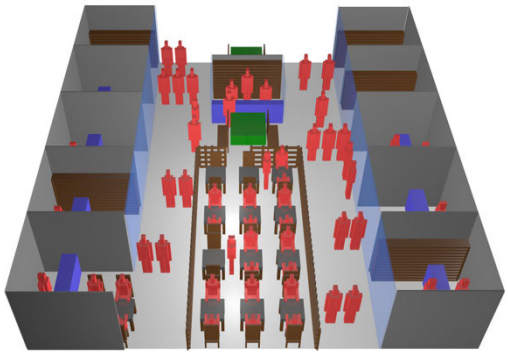


FIGURE 11. Shopping mall simulated scenario configuration for the simulation results presented in Fig. 8 to 10.

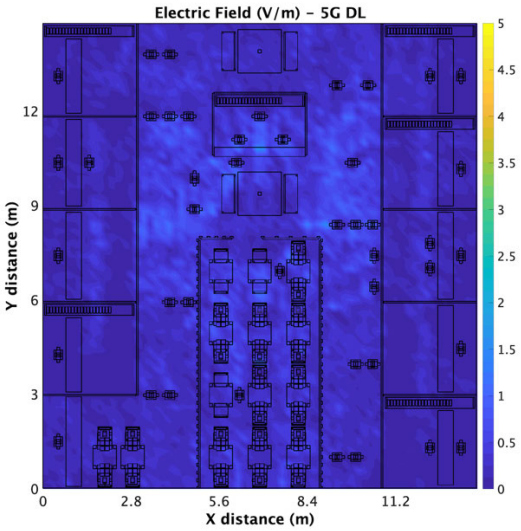


FIGURE 12. Bi-dimensional plane of E-field exposure levels for 5G DL within the simulated shopping mall.

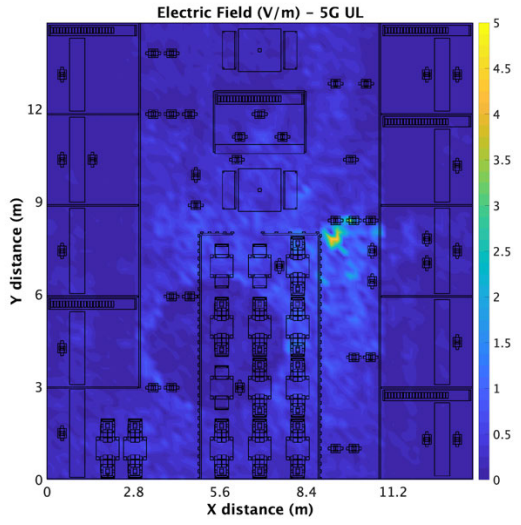


FIGURE 13. Bi-dimensional plane of E-field exposure levels for 5G UL within the simulated shopping mall.

To provide clear insight into the relevance of E-field exposure levels within the analyzed environment, Fig. 14 to

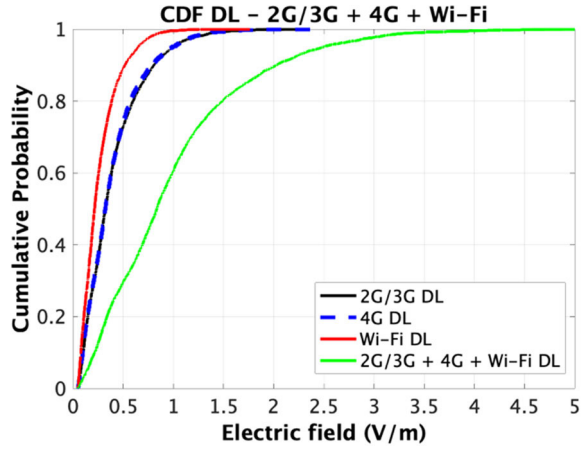


FIGURE 14. CDF of E-field average exposure values for Case I (see Table 4 for reference) within the simulated shopping mall.

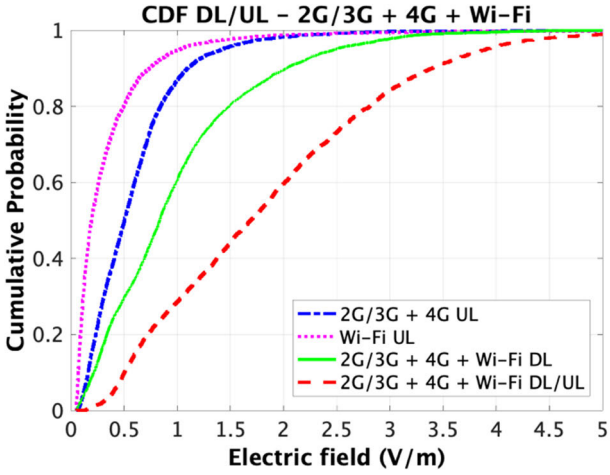


FIGURE 15. CDF of E-field average exposure values for Case II (see Table 4 for reference) within the simulated shopping mall.

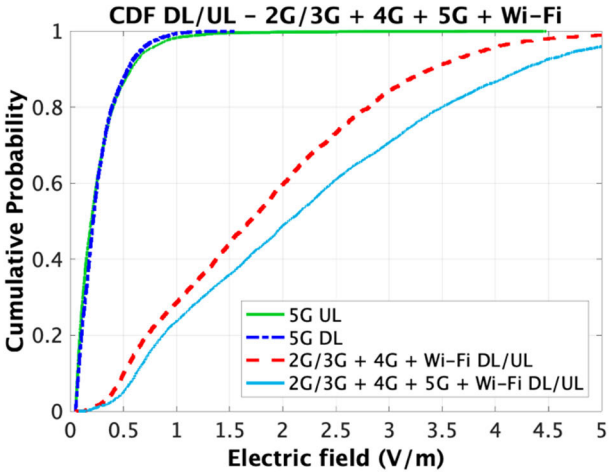


FIGURE 16. CDF of E-field average exposure values for Case III (see Table 4 for reference) within the simulated shopping mall.

16 present the CDF of E-field distribution levels within the considered scenario for the three different incremental use cases at 1.2 m height. Case I (see Fig. 8 for reference)

TABLE 12. RF-EMF exposure levels for worst case conditions of different use cases within 90% of locations of the shopping mall selected area with the percentage values of the lowest reference level provided by ICNIRP guidelines for the corresponding frequency band (ranging from 36.37 V/m to 61 V/m).

Use Case	Users	E (V/m)	% ICNIRP ref. level
Downlink			
2G/3G + 4G DL	6	1.52	3.9%
5G DL	2	0.54	1.48%
Wi-Fi DL	2	0.51	0.83%
2G/3G + 4G + Wi-Fi DL (Case I)	8	2.03	5.21%
Uplink			
2G/3G + 4G UL	6	1.09	2.8%
5G UL	2	0.97	2.66%
Wi-Fi UL	2	0.73	1.03%
Downlink / Uplink			
2G/3G + 4G + Wi-Fi DL/UL (Case II)	16	3.39	8.71%
2G/3G + 4G + 5G + Wi-Fi DL/UL (Case III)	20	4.26	11.71%

considers the DL of 8 users operating at the same time within the selected area of the shopping mall. From the obtained results, it can be observed that for a probability of 90%, the total spatial exposure within the shopping mall for Case I is lower than 2.03 V/m (which correspond with an 5.21% of ICNIRP reference values). Considering only the DL for cellular technologies (2G/3G/4G), with a 90% of probability, the spatial total exposure is lower than 1.52 V/m (3.9% of ICNIRP maximum values), and for DL Wi-Fi is lower than 0.51 V/m (0.83% of ICNIRP reference values).

Case II (see Fig. 9 for reference) considers the DL and UL of 16 users operating at the same time within the same scenario. In this case, the spatial total exposure for a 90% of probability within the shopping mall is lower than 3.39 V/m (8.71% of ICNIRP reference values). Considering only the UL for cellular technologies (2G/3G/4G), with a 90% of probability, the spatial total exposure is lower than 1.09 V/m (2.08% of ICNIRP reference values), and for UL Wi-Fi is lower than 0.73 V/m (1.03% of ICNIRP reference values).

Finally, in Case III (see Fig. 10 for reference), a total of 20 users operating at the same time with DL and UL are considered. It can be observed that for this case, for a 90% of probability the spatial total exposure is lower than 4.26 V/m (11.71% of ICNIRP reference values). Considering only the UL for 5G FR1, with a 90% of probability, the spatial total exposure is lower than 0.97 V/m (2.66% of ICNIRP maximum values), and for DL 5G FR1 is lower than 0.54 V/m (1.48% of ICNIRP reference values).

Table 12 presents a summary of the obtained RF-EMF exposure levels for all the analyzed cases within 90% of locations of the shopping mall selected area with the percentage values of the lowest reference level provided by ICNIRP guidelines for the corresponding frequency band (ranging from 36.37 V/m to 61 V/m). It can be seen that the densification of nodes can increase exposure levels, but the worst case considered in this work (which is highly unlikely) do not exceed the 12% of ICNIRP reference levels, which remains

significatively low when compared with the threshold values provided by the standards and guidelines.

The different use cases presented by the 3D-RL simulation technique are in accordance with the presented measurement campaign results performed in different shopping malls of different countries at HD user conditions. The highest measured exposure levels have ranged from 3.3 V/m to 5.4 V/m (8% to 13.09% of ICNIRP reference levels) and the highest simulated exposure levels provided by the Cases II and III (incremental worst cases) have ranged from 3.39 V/m to 4.26 V/m (8.71% to 11.71% of ICNIRP reference levels). In addition, from the obtained results, it can be observed/predicted that the use/implementation of 5G FR1 systems do not increase the overall/cumulative exposure levels significatively rather than the densification of wireless systems and the co-existence of different technologies within the environment.

V. CONCLUSIONS AND FUTURE WORK

A. CONCLUSION

This work presents a complete RF-EMF exposure assessment within five different shopping malls located in three different countries by means of measurement campaigns performed with two different type of PEMs and a simulation approach based on deterministic techniques.

The campaign of measurements presents the environmental RF-EMF exposure within the different shopping malls for the different frequency bands. In general, the measured exposure levels depend on the PEM distance from wireless facilities and the methodology of measurements. In this work, the followed methodology has not considered the exposure provided by the own wireless handsets, to have insight into the exposure produced by nearby cell phones and wireless devices. Measurements were performed in different days with different user densities within the shopping malls (high and low-user densities) and distinguishing three different areas (corridors, shops and coffee-shops), always considering locations where the general public have access. The obtained results present the most significant radiation exposure for both, high and low-density cases, in the 2G/3G DL frequency bands for the two EU larger cities of Madrid and Warszawa, and 2G/3G DL and Wi-Fi, for the other three cities analyzed, being the least significant the frequency band of 4G DL for all shopping mall. Regarding the three different analyzed areas, the highest peaks have been obtained for indoor shops in a high-density case in the city of Madrid, with a maximum of 5.4 V/m (13.09% of ICNIRP reference level), followed by general corridors in a high-density case in the city of Warszawa, with a maximum of 4.5 V/m (10.90% of ICNIRP reference level), and finally coffee shops in a low-density case in the city of Warszawa, with a maximum of 3.3 V/m (8% of ICNIRP reference level). It's worth noting that all the maximums peaks have been recorded for 2G/3G DL frequency bands regardless the specific area under consideration within the shopping malls.

In order to analyze environmental RF-EMF exposure in incremental controlled high-node density use case scenarios, the in-house deterministic 3D-RL methodology has been followed to obtain E-field exposure estimations for the complete volume of one of the shopping mall scenarios. This simulation approach allows the RF-EMF assessment of the indoor scenario distribution impact in terms of topology and morphology as well as considering its different materials properties. Three different incremental case studies have been selected for simulation considering different Wi-Fi and cellular technologies (from 2G to 5G) and their corresponding system operation in terms of DL or UL connection links and frequency of use, in order to provide environmental RF-EMF exposure assessment for high-node density conditions, as a function of transceiver location within the complete volume of the scenario under analysis. Worst-case conditions are considered, in terms that E-field exposure levels are provided at the worst time instant when all interconnecting devices operate at the same time, and the total inter-system RF-EMF exposure estimations are presented for the different cases. The presented worst-case simulation cases (Cases II and III) are in accordance with the highest peaks measured levels registered in the campaign of measurements. From the obtained results, it can be concluded that radiation exposure from 5G FR1 systems and cellular handsets is not higher than the measured from current technologies. However, the co-existence and densification of a large number of devices operating at the same time can lead to a slightly increase of total RF-EMF exposure in contrast with the one presented when systems are operating alone. Exposure levels shown in this work present the total inter-system exposure levels at the same instant of time (worst-case condition) yet remaining far below the reference levels provided by the ICNIRP (11.71% of ICNIRP reference level). Thus, it can be anticipated that the averaged E-field values in time will present lower environmental RF-EMF exposure in all cases, also remaining well below the regulation limits.

It must be clearly remarked that, in the current state of knowledge, the results of scientific and epidemiological research have shown that in case of exposures at E-field levels below of far below the ICNIRP limits, there is no evidence of a relationship between exposure to radiofrequency fields produced by wireless technologies and potential adverse health effects. However, since the trend of 5G technology in towards the use of higher frequency ranges, it would be of great importance to carry out studies aimed at characterizing the effects of mmWave exposures, for which the information from scientific literature is not so complete and exhaustive as for the sub 6 GHz frequencies. This is a sort of knowledge gap that must be filled up to permit a specific and targeted surveillance held by the authorized health agencies and possibly an update of the guidelines/standards currently in use.

The proposed simulation methodology can be a useful and suitable technique to satisfactorily assess and verify in advance environmental RF-EMF exposure recommendations and limits to implement safe, efficient and reliable current and

future wireless deployments for complex high-node density heterogeneous environments.

B. FUTURE WORK

The emergence deployment and rapid expansion of 5G FR2 cellular networks into widespread usage will produce a more ubiquitous presence of mmWaves in the environment, hence, attracting public attention into possible health effects and safety issues concerning RF-EMF exposure. The development of 5G FR2 will require densification of small cells in order to provide reliance and effective indoor/outdoor coverage, and beamforming MIMO antennas to provide directional link connections, enhancing quality of service and allowing high data transmission at higher speeds with less latency. Therefore, environmental RF-EMF exposure in the mmWave spectrum will increase at the same time as the health effects and safety concerns from the general public into the new exposure of 5G technology networks. It must be remarked that those effects have not been thoroughly researched as the ones associated with RF exposures at lower frequencies (below 6 GHz). Thus, more relevant, rigorous and high-quality research studies are required in order to analyze the bio affection of RF-EMF radiation exposure on the mmWave spectrum, stablishing appropriate protocols, standards and evaluation criteria.

Addressing health effects and safety issues regarding exposure of the general public to RF-EMF from 5G wireless communications networks must consider the following perspectives:

- There is a lack of consistent reliable and valid scientific research studies based on the relationship between RF-EMF exposure from mmWaves and human health effects. Further studies are needed in order to precisely characterize the body penetration beyond the outer skin layers and the thermal body response to mmWaves exposure considering long-term periods, especially for occupational exposure.

- Experimental measurements for the validation of theoretical and numerical models are required ensuring trustfulness results on mmWave frequency ranges by means of multiple samples datasets, particularly in worst-case conditions.

- Further studies must address RF-EMF assessment in complex heterogeneous environments with several wireless networks coexisting on the mmWave spectrum. From environmental exposure due to BSs and APs, to local exposure from transmitters own devices or nearby users. In this sense, directional beamforming link services must be precisely characterized considering Advanced Antenna Systems (AAS) in DL/UL operation as well as with different traffic volumes, in order to assess compliance with exposure limits, with especial emphasis in high-node user dense environments.

- The own-user exposure assumption (mostly and normally associated to UL signals from the own-user device) must be analyzed in deepness, specially over context aware environments with potentially massive networks of multiple transceivers operating simultaneously, due to the continuous growth of the interconnection of IoT and 5G services.

REFERENCES

[1] A. Zeghnoun, F. Dor, *Description du Budget Espace Temps et Estimation de Lexposition de la Population Francaise Dans Son Logement*. Lyon, France: Institut de Veille Sanitaire, 2010.

[2] P. Lopez-Iturri, S. de Miguel-Bilbao, E. Aguirre, L. Azpilicueta, F. Falcone, and V. Ramos, "Estimation of radiofrequency power leakage from microwave ovens for dosimetric assessment at nonionizing radiation exposure levels," *BioMed Res. Int.*, vol. 2015, pp. 1–14, Feb. 2015.

[3] K. Gryz, J. Karpowicz, W. Leszko, and P. Zradziński, "Evaluation of exposure to electromagnetic radiofrequency radiation in the indoor workplace accessible to the public by the use of frequency-selective exposimeters," *Int. J. Occupational Med. Environ. Health*, vol. 27, no. 6, pp. 1043–1054, Dec. 2014.

[4] S. de Miguel-Bilbao, M. A. Martín, A. Del Pozo, V. Febles, J. A. Hernández, J. C. F. de Aldecoa, and V. Ramos, "Analysis of exposure to electromagnetic fields in a healthcare environment: Simulation and experimental study," *Health Phys.*, vol. 105, no. 5, pp. S209–S222, Nov. 2013.

[5] S. de Miguel-Bilbao, E. Aguirre, P. Lopez Iturri, L. Azpilicueta, J. Roldán, F. Falcone, and V. Ramos, "Evaluation of electromagnetic interference and exposure assessment from S-health solutions based on Wi-Fi devices," *BioMed Res. Int.*, vol. 2015, pp. 1–9, Jan. 2015.

[6] S. de Miguel-Bilbao, J. García, V. Ramos, and J. Blas, "Assessment of human body influence on exposure measurements of electric field in indoor enclosures," *Bioelectromagnetics*, vol. 36, no. 2, pp. 118–132, Feb. 2015.

[7] E. Chiaramello, M. Bonato, S. Fiocchi, G. Tognola, M. Parazzini, P. Ravazzani, and J. Wiart, "Radio frequency electromagnetic fields exposure assessment in indoor environments: A review," *Int. J. Environ. Res. Public Health*, vol. 16, no. 6, p. 955, Mar. 2019.

[8] S. de Miguel-Bilbao, V. Ramos, and J. Blas, "Assessment of polarization dependence of body shadow effect on dosimetry measurements in 2.4 GHz band," *Bioelectromagnetics*, vol. 38, no. 4, pp. 315–321, May 2017.

[9] S. de Miguel-Bilbao, V. Ramos, and J. Blas, "Responses to comments on assessment of polarization dependence of body shadow effect on dosimetry measurements in the 2.4 GHz band," *Bioelectromagnetics*, vol. 38, no. 8, pp. 650–652, Dec. 2017.

[10] S. de Miguel-Bilbao, J. Blas, and V. Ramos, "Effective analysis of human exposure conditions with body-worn dosimeters in the 2.4 GHz band," *J. Visualized Exp.*, vol. 135, May 2018, Art. no. e56525, doi: 10.3791/56525.

[11] K. Gryz, P. Zradziński, and J. Karpowicz, "The role of the location of personal exposimeters on the human body in their use for assessing exposure to the electromagnetic field in the radiofrequency range 98-2450 MHz and compliance analysis: Evaluation by virtual measurements," *BioMed Res. Int.*, vol. 2015, Mar. 2015, Art. no. 272460.

[12] *Exposure to High Frequency Electromagnetic Fields, Biological Effects and Health Consequences (100 kHz-300 GHz). Review of the scientific Evidence on Dosimetry, Biological Effects, Epidemiological Observations, and Health Consequences Concerning Exposure to High Frequency Electromagnetic Fields (100 kHz to 300 GHz)*, International Commission on Non-Radiation Protection (ICNIRP), Munich, Germany, 2009, vol. 16.

[13] A. Ahlbom, M. Feychting, A. Green, L. Kheifets, D. A. Savitz, and A. J. Swerdlow, "Epidemiologic evidence on mobile phones and tumor risk: A review," *Epidemiology*, vol. 20, no. 5, pp. 639–652, 2009.

[14] E. Cardis *et al.*, "Brain tumour risk in relation to mobile telephone use: Results of the INTERPHONE international case–control study," *Int. J. Epidemiology*, vol. 39, no. 3, pp. 675–694, Jun. 2010.

[15] *Opinion on Potential Health Effects of Exposure to Electromagnetic Fields 15 (EMF)*, SCENIHR approved this opinion at the 9th plenary meeting on 27, SCENIHR (Scientific Committee on Emerging and Newly Identified Health Risks), Brussels, Belgium, Jan. 2015.

[16] L. Hardell, M. Carlberg, F. Söderqvist, and K. Hansson Mild, "Meta-analysis of long-term mobile phone use and the association with brain tumours," *Int. J. Oncol.*, pp. 1097–1103, May 2008.

[17] *Non-Ionizing Radiation—Part 2: Radiofrequency Electromagnetic Fields*, The WHO/IARC, IARC Monographs, International Agency for Research on Cancer (IARC), Lyon, France, 2013, vol. 102.

[18] J. Karpowicz, S. de Miguel-Bilbao, P. Zradzinski, K. Gryz, F. Falcone, and V. Ramos, "Comparative study of radiofrequency electromagnetic exposure in the public shopping centers," in *Proc. Int. Symp. Electromagn. Compat. (EMC EUROPE)*, Aug. 2018, pp. 972–975.

[19] J. T. Bushberg, C. K. Chou, K. R. Foster, R. Kavet, D. P. Maxson, R. A. Tell, and M. C. Ziskin, "IEEE committee on man and radiation—COMAR technical information statement: Health and safety issues concerning exposure of the general public to electromagnetic energy from 5G wireless communications networks," *Health Phys.*, vol. 119, no. 2, pp. 236–246, Aug. 2020.

[20] *European Parliament Resolution of 2 April 2009 on Health Concerns Associated With Electromagnetic Fields (2008/2211(INI))*. Accessed: Dec. 10, 2020. [Online]. Available: https://www.europarl.europa.eu/sides/getDoc.do?pubRef=-//EP//NONSGML+TA+P6-TA-2009-0216+0+DOC+PDF+V0//EN

[21] S. Mattisson, "An overview of 5G requirements and future wireless networks: Accommodating scaling technology," *IEEE Solid StateCircuits Mag.*, vol. 10, no. 3, pp. 54–60, Aug. 2018.

[22] A. N. Uwaechia and N. M. Mahyuddin, "A comprehensive survey on millimeter wave communications for fifth-generation wireless networks: Feasibility and challenges," *IEEE Access*, vol. 8, pp. 62367–62414, 2020.

[23] J. Kim and I. Lee, "802.11 WLAN: History and new enabling MIMO techniques for next generation standards," *IEEE Commun. Mag.*, vol. 53, no. 3, pp. 134–140, Mar. 2015.

[24] F. Rebecchi, M. D. de Amorim, V. Conan, A. Passarella, R. Bruno, and M. Conti, "Data offloading techniques in cellular networks: A survey," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 2, pp. 580–603, 2nd Quart., 2015.

[25] R. Du, P. Santi, M. Xiao, A. V. Vasilakos, and C. Fischione, "The sensable city: A survey on the deployment and management for smart city monitoring," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 2, pp. 1533–1560, 2nd Quart., 2019.

[26] W. Ayoub, A. E. Samhat, F. Nouvel, M. Mroue, and J.-C. Prevotet, "Internet of mobile things: Overview of LoRaWAN, DASH7, and NB-IoT in LPWANs standards and supported mobility," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 2, pp. 1561–1581, 2nd Quart., 2019.

[27] R. Ramirez-Vazquez, I. Escobar, A. Thielens, and E. Arribas, "Measurements and analysis of personal exposure to radiofrequency electromagnetic fields at outdoor and indoor school buildings: A case study at a Spanish school," *IEEE Access*, vol. 8, pp. 195692–195702, 2020.

[28] N. Moraitis, I. Popescu, and K. S. Nikita, "Frequency selective EMF measurements and exposure assessment in indoor office environments," in *Proc. 14th Eur. Conf. Antennas Propag. (EuCAP)*, Mar. 2020, pp. 1–5.

[29] G. Dürrenberger, J. Fröhlich, M. Röösli, and M.-O. Mattsson, "EMF monitoring—Concepts, activities, gaps and options," *Int. J. Environ. Res. Public Health*, vol. 11, no. 9, pp. 9460–9479, Sep. 2014.

[30] M. Bonato, L. Dossi, E. Chiaramello, S. Fiocchi, S. Gallucci, G. Tognola, P. Ravazzani, and M. Parazzini, "Single user EMF exposure assessment in a case of incoming 5G indoor scenario," in *Proc. Int. Symp. Electromagn. Compat. - EMC Eur.*, Sep. 2020, pp. 1–4.

[31] T. H. Loh, F. Heliot, D. Cheadle, and T. Fielder, "An assessment of the radio frequency electromagnetic field exposure from a massive MIMO 5G testbed," in *Proc. 14th Eur. Conf. Antennas Propag. (EuCAP)*, Mar. 2020, pp. 1–5.

[32] S. E. Widergren and R. G. Pratt, "Definitions, scope, visions, and benefits," in *Smart Grid Handbook*, C.-C. Liu, S. McArthur, and S.-J. Lees, Eds. West Sussex, U.K.: Wiley, 2016, pp. 1–18.

[33] S. Sagar, S. Dongus, A. Schoeni, K. Roser, M. Eeftens, B. Struchen, M. Foerster, N. Meier, S. Adem, and M. Röösli, "Radiofrequency electromagnetic field exposure in everyday microenvironments in Europe: A systematic literature review," *J. Exposure Sci. Environ. Epidemiology*, vol. 28, no. 2, pp. 147–160, Mar. 2018.

[34] L. Chettri and R. Bera, "A comprehensive survey on Internet of Things (IoT) toward 5G wireless systems," *IEEE Internet Things J.*, vol. 7, no. 1, pp. 16–32, Jan. 2020.

[35] P. I. Tebe, K. Ntiamoah-Sarpong, W. Tian, J. Li, Y. Huang, and G. Wen, "Using 5G network slicing and non-orthogonal multiple access to transmit medical data in a mobile hospital system," *IEEE Access*, vol. 8, pp. 189163–189178, 2020.

[36] S. Lonn, U. Forssen, P. Vecchia, A. Ahlbom, and . Feychting, "Output power levels from mobile phones in different geographical areas; implications for exposure assessment," *Occupational Environ. Med.*, vol. 61, no. 9, pp. 769–772, Sep. 2004.

[37] A. Boursianis, P. Vanias, and T. Samaras, "Measurements for assessing the exposure from 3G femtocells," *Radiat. Protection Dosimetry*, vol. 150, no. 2, pp. 158–167, Jun. 2012.

[38] D. Plets, W. Joseph, K. Vanhecke, G. Vermeeren, J. Wiart, S. Aerts, N. Varsier, and L. Martens, "Joint minimization of uplink and downlink whole-body exposure dose in indoor wireless networks," *BioMed Res. Int.*, vol. 2015, pp. 1–9, Feb. 2015.

[39] A. Krayni, A. Hadjem, G. Vermeeren, A. Sibille, C. Roblin, W. Joseph, L. Martens, and J. Wiart, "Modeling and characterization of the uplink and downlink exposure in wireless networks," *Int. J. Antennas Propag.*, vol. 2017, pp. 1–15, Jan. 2017.

[40] Y. Huang. (2017). *Thesis: Study of the Exposure of a Population to a Wireless Communication Network Via Dosimetric Tools and Statistic. Networking and Internet Architecture [cs.NI]. Ecole Nationale Supérieure Mines-Télécom Atlantique*. English. Accessed: Nov. 10, 2020. [Online]. Available: https://tel.archives-ouvertes.fr/tel-01810089/document

[41] B. Zeleke, C. Brzozek, C. Bhatt, M. Abramson, R. Croft, F. Freudenstein, P. Wiedemann, and G. Benke, "Personal exposure to radio frequency electromagnetic fields among Australian adults," *Int. J. Environ. Res. Public Health*, vol. 15, no. 10, p. 2234, Oct. 2018.

[42] S. I. Henderson and M. J. Bangay, "Survey of RF exposure levels from mobile telephone base stations in Australia," *Bioelectromagnetics*, vol. 27, no. 1, pp. 73–76, Jan. 2006.

[43] J. F. Bolte and T. Eikelboom, "Personal radiofrequency electromagnetic field measurements in The Netherlands: Exposure level and variability for everyday activities, times of day and types of area," *Environ. Int.*, vol. 48, pp. 133–142, Nov. 2012.

[44] J. T. Rowley and K. H. Joyner, "Comparative international analysis of radiofrequency exposure surveys of mobile communication radio base stations," *J. Exposure Sci. Environ. Epidemiology*, vol. 22, no. 3, pp. 304–315, May 2012.

[45] J. Estenberg and T. Augustsson, "Extensive frequency selective measurements of radiofrequency fields in outdoor environments performed with a novel mobile monitoring system," *Bioelectromagnetics*, vol. 35, no. 3, pp. 227–230, Apr. 2014.

[46] P. Gajsek, P. Ravazzani, J. Wiart, J. Grellier, T. Samaras, and G. Thuroczy, "Electromagnetic field exposure assessment in Europe ra- diofrequency fields (10 MHz-6 GHz)," *J. Exposure Sci. Environ. Epidemiology*, vol. 25, pp. 37–44, Jan. 2015.

[47] H. Jalilian, M. Eeftens, M. Ziaei, and M. Röösli, "Public exposure to radiofrequency electromagnetic fields in everyday microenvironments: An updated systematic review for Europe," *Environ. Res.*, vol. 176, Sep. 2019, Art. no. 108517.

[48] M. Velghe, W. Joseph, S. Debouvere, R. Aminzadeh, L. Martens, and A. Thielens, "Characterisation of spatial and temporal variability of RF-EMF exposure levels in urban environments in flanders, Belgium," *Environ. Res.*, vol. 175, pp. 351–366, Aug. 2019.

[49] J. Stephan, M. Brau, Y. Corre, and Y. Lostanlen, "Joint analysis of small-cell network performance and urban electromagnetic field exposure," in *Proc. 8th Eur. Conf. Antennas Propag. (EuCAP)*, Apr. 2014, pp. 2623–2627.

[50] T. Mazloum, B. Fetouri, N. Elia, E. Conil, C. Grangeat, and J. Wiart, "Assessment of RF human exposure to LTE small-and macro-cells: UL case," in *Proc. 11th Eur. Conf. Antennas Propag. (EUCAP)*, Mar. 2017, pp. 1592–1593.

[51] L. Chiaraviglio, M. Fiore, and E. Rossi, "5G technology: Which risks from the health perspective," in *The 5G Italy Book 2019: A multiperspective view of 5G, Parma*. Rome, Italy: Consorzio Nazionale Interuniversitario per le Telecomunicazioni, 2019.

[52] E. Degirmenci, B. Thors, and C. Tornevik, "Assessment of compliance with RF EMF exposure limits: Approximate methods for radio base station products utilizing array antennas with beam-forming capabilities," *IEEE Trans. Electromagn. Compat.*, vol. 58, no. 4, pp. 1110–1117, Aug. 2016.

[53] *International Electrotechnical Commission. Technical Report. Case Studies Supporting IEC 62232—Determination of RF Field Strength, Power Density and SAR in the Vicinity of Radiocommunication Base Stations for the Purpose of Evaluating Human Exposure*, Standard IEC TR 62669:2019, Edition 2.0, 2019.

[54] P. Baracca, A. Weber, T. Wild, and C. Grangeat, "A statistical approach for RF exposure compliance boundary assessment in massive MIMO systems," in *Proc. 22nd Int. ITG Workshop Smart Antennas WSA*, Bochum, Germany, Mar. 2018, pp. 1–6.

[55] T. Kopacz and D. Heberling, "Impact of the elevation scanning angle on the vertical compliance distance of 5G massive MIMO antennas," in *Proc. IEEE 13th Eur. Conf. Antennas Propag. (EuCAP)*, Krakow, Poland, Mar. 2019, pp. 1–5.

[56] G. Neubauer, S. Cecil, W. Giczi, B. Petric, P. Preiner, J. Fröhlich, and M. Röösli, "The association between exposure determined by radiofrequency personal exposimeters and human exposure: A simulation study," *Bioelectromagnetics*, vol. 31, no. 7, pp. 535–545, Oct. 2010.

[57] M. Röösli, P. Frei, J. Bolte, G. Neubauer, E. Cardis, M. Feychting, P. Gajsek, S. Heinrich, W. Joseph, S. Mann, L. Martens, E. Mohler, R. C. Parslow, A. H. Poulsen, K. Radon, J. Schüz, G. Thuroczy, J.-F. Viel, and M. Vrijheid, "Conduct of a personal radiofrequency electromagnetic field measurement study: Proposed study protocol," *Environ. Health*, vol. 9, no. 1, pp. 9–23, Dec. 2010.

[58] M. Celaya-Echarri, L. Azpilicueta, P. Lopez-Iturri, E. Aguirre, S. De Miguel-Bilbao, V. Ramos, and F. Falcone, "Spatial characterization of personal RF-EMF exposure in public transportation buses," *IEEE Access*, vol. 7, pp. 33038–33054, 2019.

[59] M. Celaya-Echarri, L. Azpilicueta, J. Karpowicz, V. Ramos, P. Lopez-Iturri, and F. Falcone, "From 2G to 5G spatial modeling of personal RF-EMF exposure within urban public trams," *IEEE Access*, vol. 8, pp. 100930–100947, 2020.

[60] P. Joshi, F. Ghasemifard, D. Colombi, and C. Tornevik, "Actual output power levels of user equipment in 5G commercial networks and implications on realistic RF EMF exposure assessment," *IEEE Access*, vol. 8, pp. 204068–204075, 2020.

[61] L. E. Birks *et al.*, "Spatial and temporal variability of personal environmental exposure to radio frequency electromagnetic fields in children in Europe," *Environ. Int.*, vol. 117, pp. 204–214, Aug. 2018.

[62] R. Werner, P. Knipe, and S. Iskra, "A comparison between measured and computed assessments of the RF exposure compliance boundary of an *in-situ* radio base station massive MIMO antenna," *IEEE Access*, vol. 7, pp. 170682–170689, 2019.

[63] S. Aerts, L. Verloock, M. Van Den Bossche, D. Colombi, L. Martens, C. Tornevik, and W. Joseph, "*In-situ* measurement methodology for the assessment of 5G NR massive MIMO base station exposure at Sub-6 GHz frequencies," *IEEE Access*, vol. 7, pp. 184658–184667, 2019.

[64] L. Azpilicueta, P. L. Iturri, E. Aguirre, J. J. Astrain, J. Villadangos, C. Zubiri, and F. Falcone, "Characterization of wireless channel impact on wireless sensor network performance in public transportation buses," *IEEE Trans. Intell. Transp. Syst.*, vol. 16, no. 6, pp. 3280–3293, Dec. 2015.

[65] E. Aguirre, P. Lopez-Iturri, L. Azpilicueta, A. Redondo, J. J. Astrain, J. Villadangos, A. Bahillo, A. Perallos, and F. Falcone, "Design and implementation of context aware applications with wireless sensor network support in urban train transportation environments," *IEEE Sensors J.*, vol. 17, no. 1, pp. 169–178, Jan. 2017.

[66] K. Gryz and J. Karpowicz, "Radiofrequency electromagnetic exposures during the use of wireless links of portable computers inside trains without internal WiFi services," in *Proc. Int. Symp. Electromagn. Compat. - EMC Eur.*, Sep. 2019, pp. 1030–1033.

[67] E. Aguirre, P. L. Iturri, L. Azpilicueta, S. de Miguel-Bilbao, V. Ramos, U. Gárate, and F. Falcone, "Analysis of estimation of electromagnetic dosimetric values from non-ionizing radiofrequency fields in conventional road vehicle environments," *Electromagn. Biol. Med.*, vol. 34, no. 1, pp. 19–28, Jan. 2014.

[68] E. Aguirre, J. Arpón, L. Azpilicueta, P. López, S. de Miguel, V. Ramos, and F. Falcone, "Estimation of electromagnetic dosimetric values from non-ionizing radiofrequency fields in an indoor commercial airplane environment," *Electromagn. Biol. Med.*, vol. 33, no. 4, pp. 252–263, Dec. 2014.

[69] International Commission on Non-Ionizing Radiation Protection (ICNIRP), "Guidelines for limiting exposure to electromagnetic fields (100 kHz to 300 GHz)," *Health Phys.*, vol. 118, no. 5, pp. 483–524, May 2020.

[70] *IEEE Approved Draft Standard for Safety Levels With Respect to Human Exposure to Electric, Magnetic and Electromagnetic Fields*, Standard C95.1-1991 0 Hz to 300 GHz, 2019.

[71] World Health Organization (WHO). Fact Sheet 304. (May 2006). *Base Stations and Wireless Technology*. [Online]. Available: http://www.who.int/peh-emf/publications/factsheets/en/

[72] M. Karaboytcheva, "Effects of 5G wireless communication on human health," European Parliamentary Research Service, Brussels, Belgium, Tech. Rep. PE 646.172, Mar. 2020.

[73] A. Di Ciaula, "Towards 5G communication systems: Are there health implications?" *Int. J. Hygiene Environ. Health*, vol. 221, no. 3, pp. 367–375, Apr. 2018.

[74] (Mar. 2020). *Review of Published Literature Between 2008 and 2018 of Relevance to Radiofrequency Radiation and Cancer, U.S. Food & Drug Administration*. [Online]. Available: https://www.fda.gov/media/135043/download

[75] *World Cancer Report 2020—Cancer Research for Cancer Prevention*, IARC/OMS, Lyon, France, 2020.

[76] B. Xu, K. Zhao, Z. Ying, D. Sjoberg, W. He, and S. He, "Analysis of impacts of expected RF EMF exposure restrictions on peak EIRP of 5G user equipment at 28 GHz and 39 GHz bands," *IEEE Access*, vol. 7, pp. 20996–21005, 2019.

[77] M. Bonato, L. Dossi, E. Chiaramello, S. Fiocchi, S. Gallucci, G. Tognola, P. Ravazzani, and M. Parazzini, "Human RF-EMF exposure assessment due to access point in incoming 5G indoor scenario," *IEEE J. Electromagn., RF Microw. Med. Biol.*, early access, Dec. 4, 2020, doi: 10.1109/JERM.2020.3042696.

[78] C. Tornevik, T. Wigren, S. Guo, and K. Huisman, "Time averaged power control of a 4G or a 5G radio base station for RF EMF compliance," *IEEE Access*, vol. 8, pp. 211937–211950, 2020.

[79] A. W. Wood and K. Karapidis, Eds. *Non-Ionizing Radiation Protection: Summary of Research and Policy Options*. New York, NY, USA: Wiley, 2017, pp. 186–204.

[80] K. R. Foster, C.-K. Chou, and R. C. Petersen, "Radio frequency exposure standards," in *Bioengineering and Biophysical Aspects of Electromagnetic Fields*, B. Greenebaum and F. Barness, Eds. Boca Raton, FL, USA: CRC Press, 2018, pp. 463–511.

[81] *Evaluating Compliance With FCC Guidelines for Human Exposure to Radiofrequency Electromagnetic Fields*, Federal Communications Commission Office of Engineering & Technology; OET Bulletin 65, Edition 97-01, FCC, Washington, DC, USA, 1997.

[82] S. Valbonesi, C. Carciofi, and B. Bisceglia, "Precautionary principle application and 5G development," in *Proc. IEEE 29th Annu. Int. Symp. Pers., Indoor, Mobile Radio Commun. (PIMRC)*, Sep. 2018, pp. 1192–1196.

[83] *Guidelines on the Application of the Precautionary Principle*, HB/hb d, European Commission DG XXIV, Brussels, Belgium, 1988.

[84] *Communication From the Commission on the Precautionary Principle*, COM1, European Commission, Brussels, Belgium, 2000

[85] *On the Limitation of Exposure of the General Public to Electromagnetic Fields (0 Hz to 300 GHz)*, document 1999/519/EC, European Council Recommendation, 1999.

[86] International Commission on Non-Ionizing Radiation Protection (ICNIRP), "Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz)," *Health Phys.*, vol. 75, no. 5, pp. 494–522, 1998.

[87] *Amending Directive 2004/40/EC on Minimum Health and Safety Requirements Regarding the Exposure of Workers to the Risks Arising From Physical Agents (Electromagnetic Fields) (18th Individual Directive Within the Meaning of Article 16(1) of Directive 89/391/EEC)*, document 2013/35/UE, European Parliament and of the Council Directive, 2013

[88] *Spain. BOE-A-2001-18256*. Accessed: Dec. 10, 2020. [Online]. Available: https://www.boe.es/eli/es/rd/2001/09/28/1066/con

[89] R. Stam. (May 2011). *Comparison of International Policies on Electromagnetic Fields (Power Frequency and Radiofrequency Fields) Bilthoven, The Netherlands: National Institute for Public Health and the Environment*. [Online]. Available: http://ec.europa.eu/health/electromagnetic_fields/docs/emf_comparision_policies_en.pdf

[90] *Federal Communications Commission. Specific Absorption Rate (SAR) for Cellular Telephones*, FCC, Washington, DC, USA, 2011. [Online]. Available: http://www.fcc.gov/encyclopedia/specific-absorption-rate-sar-cellular-telephones

[91] M. Repacholi, Y. Grigoriev, J. Buschmann, and C. Pioli, "Scientific basis for the soviet and russian radiofrequency standards for the general public," *Bioelectromagnetics*, vol. 33, no. 8, pp. 623–633, Dec. 2012.

[92] I. Laakso, R. Morimoto, J. Heinonen, K. Jokela, and A. Hirata, "Human exposure to pulsed fields in the frequency range from 6 to 100 GHz," *Phys. Med. Biol.*, vol. 62, no. 17, pp. 6980–6992, Aug. 2017.

[93] K. R. Foster, M. C. Ziskin, Q. Balzano, and G. Bit-Babik, "Modeling tissue heating from exposure to radiofrequency energy and relevance of tissue heating to exposure limits: Heating factor," *Health Phys.*, vol. 115, no. 2, pp. 295–307, 2018.

[94] A. Hirata, D. Funahashi, and S. Kodera, "Setting exposure guidelines and product safety standards for radio-frequency exposure at frequencies above 6 GHz: Brief review," *Ann. Telecommun.*, vol. 74, nos. 1–2, pp. 17–24, Feb. 2019.

[95] Health Canada. (2009). *Limits of Human Exposure to Radiofrequency Electromagnetic Energy in the Frequency Range From 3 KHz to 300 GHz. Safety Code 6 (2009)*. Health Canada, Healthy Environments and Consumer Safety Branch, Ottawa, ON, USA, 2009. [Online]. Available: http://www.rfsafetysolutions.com/RF%20Radiation%20Pages/Safety_Code_6.html
[96] ARPANSA, Australian Radiation Protection and Nuclear Safety Agency. (2013). *Radiofrequency Radiation*. [Online]. Available: http://www.arpansa.gov.au/radiationprotection/basics/rf.cfm
[97] P. Gajšek, A. G. Pakhomov, and B. J. Klauenberg, "Electromagnetic field standards in central and eastern European countries: Current state and stipulations for international harmonization," *Health Phys.*, vol. 82, no. 4, pp. 473–483, Apr. 2002.
[98] J. M. Osepchuk and R. C. Petersen, "Historical review of RF exposure standards and the international committee on electromagnetic safety (ICES)," *Bioelectromagnetics*, vol. 24, no. S6, pp. 7–16, 2003.
[99] L. Chiaraviglio, A. S. Cacciapuoti, G. Di Martino, M. Fiore, D. Trucchi, and N. B. Melazzi, "Planning 5G networks under EMF constraints: State of the art and vision," *IEEE Access*, vol. 6, p. 51021, 2018.
[100] *SERIES K: Protection Against Interference, Supplement 14: The Impact of RF-EMF Exposure Limits Stricter Than the ICNIRP or IEEE Guidelines on 4G and 5G Mobile Network Deployment*, document ITU-T Rec., The International Telecommunication Union, Geneva, Switzerland2018.
[101] D. Urbinello, A. Huss, J. Beekhuizen, R. Vermeulen, and M. Röösli, "Use of portable exposure meters for comparing mobile phone base station radiation in different types of areas in the cities of basel and Amsterdam," *Sci. Total Environ.*, vols. 468–469, pp. 1028–1033, Jan. 2014.
[102] J. F. B. Bolte, M. Maslanyj, D. Addison, T. Mee, J. Kamer, and L. Colussi, "Do car-mounted mobile measurements used for radio-frequency spectrum regulation have an application for exposure assessments in epidemiological studies?" *Environ. Int.*, vol. 86, pp. 75–83, Jan. 2016.
[103] J. González-Rubio, A. Nájera, and E. Arribas, "Comprehensive personal RF-EMF exposure map and its potential use in epidemiological studies," *Environ. Res.*, vol. 149, pp. 105–112, Aug. 2016.
[104] U. Knafl, H. Lehmann, and M. Riederer, "Electromagnetic field measurements using personal exposimeters," *Bioelectromagnetics*, vol. 29, no. 2, pp. 160–162, 2008.
[105] G. Neubauer, S. Cecil, W. Giczi, B. Petric, P. Preiner, and J. Fröhlich, "Final report on the project C2006-07, evaluation of the correlation between RF dosimeter reading and real human exposure," Austrian Res. Centers GmbH, Seibersdorf, Austria, Tech. Rep. ARC-Report ARC-IT-0218, Apr. 2008.
[106] J. Blas, F. A. Lago, P. Fernández, R. M. Lorenzo, and E. J. Abril, "Potential exposure assessment errors associated with body-worn RF dosimeters," *Bioelectromagnetics*, vol. 28, no. 7, pp. 573–576, 2007.
[107] S. Iskra, R. McKenzie, and I. Cosic, "Factors influencing uncertainty in measurement of electric fields close to the body in personal RF dosimetry," *Radiat. Protection Dosimetry*, vol. 140, no. 1, pp. 25–33, Jun. 2010.
[108] Z. E. Khaled, W. Ajib, and H. Mcheick, "An accurate empirical path loss model for heterogeneous fixed wireless networks below 5.8 GHz frequencies," *IEEE Access*, vol. 8, pp. 182755–182775, 2020.
[109] N. Faruk, S. I. Popoola, N. T. Surajudeen-Bakinde, A. A. Oloyede, A. Abdulkarim, L. A. Olawoyin, M. Ali, C. T. Calafate, and A. A. Atayero, "Path loss predictions in the VHF and UHF bands within urban environments: Experimental investigation of empirical, heuristics and geospatial models," *IEEE Access*, vol. 7, pp. 77293–77307, 2019.
[110] Z. El Ahdab and F. Akleman, "An efficient 3-D FDTD-PE hybrid model for radio wave propagation with near-source obstacles," *IEEE Trans. Antennas Propag.*, vol. 67, no. 1, pp. 346–355, Jan. 2019.
[111] M. M. Taygur and T. F. Eibert, "A ray-tracing algorithm based on the computation of (exact) ray paths with bidirectional ray-tracing," *IEEE Trans. Antennas Propag.*, vol. 68, no. 8, pp. 6277–6286, Aug. 2020.
[112] S. Hussain and C. Brennan, "Efficient preprocessed ray tracing for 5G mobile transmitter scenarios in urban microcellular environments," *IEEE Trans. Antennas Propag.*, vol. 67, no. 5, pp. 3323–3333, May 2019.
[113] L. Azpilicueta, M. Rawat, K. Rawat, F. Ghannouchi, and F. Falcone, "Convergence analysis in deterministic 3D ray launching radio channel estimation in complex environments," *Appl. Comput. Electromagn. Soc. J.*, vol. 29, no. 4, pp. 256–271, 2014.
[114] L. Azpilicueta, F. Falcone, and R. Janaswamy, "A hybrid ray launching-diffusion equation approach for propagation prediction in complex indoor environments," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 214–217, 2017.
[115] L. Azpilicueta, M. Rawat, K. Rawat, F. M. Ghannouchi, and F. Falcone, "A ray launching-neural network approach for radio wave propagation analysis in complex indoor environments," *IEEE Trans. Antennas Propag.*, vol. 62, no. 5, pp. 2777–2786, May 2014.
[116] F. Casino, P. Lopez-Iturri, E. Aguirre, L. Azpilicueta, F. Falcone, and A. Solanas, "Enhanced wireless channel estimation through parametric optimization of hybrid ray launching-collaborative filtering technique," *IEEE Access*, vol. 8, pp. 83070–83080, 2020.
[117] F. Granda, L. Azpilicueta, M. Celaya-Echarri, P. Lopez-Iturri, C. Vargas-Rosales, and F. Falcone, "Spatial V2X traffic density channel characterization for urban environments," *IEEE Trans. Intell. Transp. Syst.*, early access, Feb. 26, 2020, doi: 10.1109/TITS.2020.2974692.
[118] L. Azpilicueta, C. Vargas-Rosales, and F. Falcone, "Intelligent vehicle communication: Deterministic propagation prediction in transportation systems," *IEEE Veh. Technol. Mag.*, vol. 11, no. 3, pp. 29–37, Sep. 2016.
[119] H. Klaina, I. P. Guembe, P. Lopez-Iturri, J. J. Astrain, L. Azpilicueta, O. Aghzout, A. V. Alejos, and F. Falcone, "Implementation of an interactive environment with multilevel wireless links for distributed botanical garden in University campus," *IEEE Access*, vol. 8, pp. 132382–132396, 2020.
[120] L. Azpilicueta, E. Aguirre, P. López-Iturri, and F. Falcone, "An accurate UTD extension to a ray-launching algorithm for the analysis of complex indoor radio environments," *J. Electromagn. Waves Appl.*, vol. 30, no. 1, pp. 43–60, Jan. 2016.
[121] L. Azpilicueta, P. Lopez-Iturri, J. Zuñiga-Mejia, M. Celaya-Echarri, F. A. Rodríguez-Corbo, C. Vargas-Rosales, E. Aguirre, D. G. Michelson, and F. Falcone, "Fifth-generation (5G) mmWave spatial channel characterization for urban Environments' system analysis," *Sensors*, vol. 20, no. 18, p. 5360, Sep. 2020.
[122] S. Salous, *Radio Propagation Measurement and Channel Modelling*. Hoboken, NJ, USA: Wiley, 2013.
[123] *Characteristics of Terrestrial IMT-Advanced Systems for Frequency Sharing/Interference Analyses*, document Rep. ITU-R M.2292-0, The International Telecommunication Union, Geneva, Switzerland, 2014. [Online]. Available: http://www.itu.int/publ/R-REP/en
[124] *LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) Radio Transmission and Reception*, Standard ETSI TS 136 101 V11.2.0 (2012-11), (3GPP TS 36.101 version 11.2.0 Release 11). European Telecommunications Standards Institute, 2012.

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