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Planning 5G Networks Under EMF Constraints: State of the Art and Vision

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ABSTRACT The deployment of 5G networks will necessarily involve the installation of new base station (BS) equipment to support the requirements of next-generation mobile services. In a scenario where there exist already many sources of electromagnetic fields (EMFs), including overlapping 2G/3G/4G technologies of competing network operators, there is a growing concern that the planning of a 5G network will be severely constrained by the limits on maximum EMF levels established in a wide set of regulations. The goal of this paper is to shed light on EMF-aware 5G network planning and, in particular, on the problem of site selection for 5G BS equipment that abides by downlink EMF limits. To this end, we present the current state of the art in EMF-aware mobile networking and overview the current exposure limits and how the EMF constraints may impact 5G planning. We then substantiate our analysis by reporting on two realistic case studies, which demonstrate the saturation of EMF levels already occurring under current 2G/3G/4G networks, as well as the negative impact of strict regulations on network planning and user quality of service. Finally, we discuss the expected impact of 5G technologies in terms of EMFs and draw the guidelines for an EMF-aware planning of 5G. Our analysis suggests that the EMF-aware 5G planning risks to be a real challenge for network operators, which stimulates further actions at governmental, societal, technological, and research levels.

INDEX TERMS 5G networks, 5G cellular network planning, EMF saturation, EMF limits, 5G guidelines, EMFs, QoS.

I. INTRODUCTION

5G is expected to become a dominant General Purpose Technology (GPT) in the coming decade, enabling a variety of services that will generate trillions of global economic output [1]. To achieve this, 5G technologies will have to meet strong performance requirements such as a dramatic increase of user throughput up to 10 Gbps, or extremely low order-of-millisecond communication latency. To meet these goals, 5G will combine new radio access technologies [2] that will increase the offered capacity with the softwarization of network functions [3], which will improve network operation efficiency and reduce management costs. Field tests of 5G technologies are being currently run by different vendors and operators (see [4]), and the first extensive trials of complete architectures are expected to be operative during 2018 in many countries (see [5]). Following the trial phase, the deployment of the 5G network will start by 2020, with the installation of substantial amounts of new 5G radio access equipment, which will be co-located with legacy equipment in existing sites or placed in new dedicated sites.

Similarly to what happens with the currently deployed 2G/3G/4G technologies (henceforth denoted as ''pre-5G''), the new 5G deployments will have to abide by applicable regulations on Electromagnetic Field (EMF) exposure, which impose strict limits on the EMF levels resulting from the composition of the different sources of radiated power over the territory [6]. Many countries worldwide adopt the conservative EMF limits set by the International Commission on

Non-Ionizing Radiation Protection (ICNIRP) [7], but different countries (e.g., China, India, Russia, Switzerland, Italy, Canada and Poland) enforce national laws with even more stringent limits [6], [8].

Planning a pervasive deployment of 5G networks under strict EMF exposure limits is not a simple task, especially in densely populated urban areas where multiple 5G radio access infrastructures of different operators have to coexist, jointly adding EMFs to the exposure already caused by pre-5G technologies. Network planning is a complex problem per se [9], [10], which targets the minimization of CAPital EXpenditures (CAPEX) by the network operator, by jointly (*i*) selecting proper locations for the sites hosting the Base Stations (BSs), (*ii*) dimensioning the radio equipment installed at each BS, and (*iii*) fulfilling performance constraints on coverage, offered capacity and Quality of Service (QoS) perceived by end users. Factoring in both EMF exposure limits and the specificities of 5G radio technologies in terms of EMF emissions further complicates the problem.

Addressing the 5G planning problem is however critical for the roll-out of 5G, as its solution directly impacts the operator CAPEX, as well as the capacity of 5G to pervasively support its many novel envisioned services. A planning of 5G sites that is oblivious of strict EMF constraints risks to create a need for hastened a-posteriori amending, with a negative impact on both the CAPEX costs incurred by the operator and the Quality of Service (QoS) perceived by users. Such a situation would results in poor 5G coverage or limited support for 5G services in the worst cases. In fact, these are actually major concerns for operators [8], as also emerged during recent International Telecommunication Union (ITU) events [11], [12].

Despite its importance for the success of 5G as a GPT, the problem of 5G network planning under EMF exposure limits is still completely open. It gives rise to several key questions, such as: How do current EMF limits affect the 5G deployment? What is the EMF impact of already installed pre-5G sites on the deployment of future 5G sites? How do different regulations on EMF emissions influence 5G planning? The goal of this paper is to answer these questions, by also outlining the research challenges and opportunities that they trigger. Our contributions are summarized as follows:

- we thoroughly review the current state of the art on EMF-aware mobile networks;
- we present the main issues that EMF emission limits could entail during the planning phase of 5G networks, in particular during the installation of new 5G BS sites;
- we provide evidence of EMF saturation in a representative real-world case study already in presence of sole pre-5G technologies;
- we show through a second real-world case study how strict regulations on EMF emission can severely impact the planning of a 5G deployment, hence the QoS experienced by users of 5G services;
- we discuss the main characterizing technologies of 5G radio access networks in terms of their expected impact on EMF emissions;
- we draft a very first set of guidelines for the planning of 5G networks under EMF constraints;
- we report on the research challenges and opportunities that emerge from our analysis, and, if properly addressed, will lead to effective EMF-aware 5G planning.

To the best of our knowledge, no previous work presented a similar analysis. Although the planning problem with EMF constraints has been already faced in the context of legacy pre-5G networks (see [13], [14]), the unique features of 5G radio technologies, and their combination with pre-5G deployments already pervasive over the territory, make the problem new and even more challenging.

The remainder of the paper is organized as follows. Sec. II summarizes the state of the art. Sec. III presents an overview of current EMF regulations. The influence of EMF limits on the planning of cellular networks is discussed in Sec. IV. Sec. V presents the results of investigations on EMF emissions by mobile networks in two representative case studies. Sec. VI discusses the expected impact of 5G technology features in terms of EMFs. Our guidelines for an EMF-aware 5G planning are described in Sec. VII. Sec. VIII highlights the main challenges and opportunities that emerge in the target context. Finally, Sec. IX draws the conclusions of our study.

II. STATE OF THE ART

We divide the related work into the following four categories: (*i*) projects investigating EMF emissions by pre-5G networks, (*ii*) measurements of EMF levels in cellular networks, (*iii*) planning and management of cellular networks under EMF constrains, (*iv*) impact of 5G technologies in terms of EMFs. Each category is discussed separately below.

A. PROJECTS ON EMF EMISSIONS BY PRE-5G NETWORKS

Tesanovic *et al.* [13] describe the LEXNET project, whose main goal is to study EMF-aware networks based on 3G, 4G, and WiFi radio access technologies. More precisely, the authors detail a new EMF exposure index, which condenses in a single parameter multiple factors, such as the temporal and the spatial variation of traffic, as well as the transmission power in the uplink and the downlink directions. The main goal of LEXNET is to provide guidelines on EMF-aware antenna configurations, assuming that BS sites are given. Thus, LEXNET focuses on pre-5G network management, rather than the planning of 5G systems that is our target.

MONICEM [14] is another relevant project. Here, the main goal is to monitor and control the EMFs generated by BS sites, by: (*i*) overviewing and comparing the methodologies and techniques currently adopted by the operators to minimize the EMF pollution; (*ii*) defining a set of guidelines that limit the EMF pollution, including planning practices; (*iii*) discussing the harmonization of technical issues with the EMF constraints imposed by applicable laws. The scope of the MONICEM project is limited to one specific country (i.e., Italy), and 2G/3G technologies, which makes its outcome not applicable to the current technological context.

B. MEASUREMENT OF EMF LEVELS IN CELLULAR NETWORKS

A much larger literature is devoted to the measurement of EMF levels in operational cellular networks. Koprivica *et al.* [15] perform a measurement campaign of the Global System for Mobile Communications (GSM) 900 [Mhz] downlink band in the Belgrade urban area, showing that the EMF levels vary in space and time. Koprivica *et al.* [16] describe measurements of the EMFs generated by GSM and Universal Mobile Telecommunications System (UMTS) BSs in Serbia, showing that the EMF levels exceed the limits in 15.6% of the locations. Similar measurements are carried out by Urbinello *et al.* [17], in a different region, finding EMF levels to be below the limits. Eventually, the comparison by Huang *et al.* [18], carried out in different geographical areas located in France and in Serbia and covered by 3G networks, shows that there exists a substantial heterogeneity in EMF emissions recorded across different regions. In particular, the EMF levels tend to vary in time and in space, as well as with the considered country. The study also highlights that the EMFs generated by the User Equipments (UEs) are not negligible.

In a broader investigation, Fernández-García and Gil [19] report the EMF levels measured by all sources up to the 18 Ghz in a mid-size European city, showing that the EMF levels are in general lower than the maximum allowed ones. Conversely, Orłowski *et al.* [20] measure the EMFs generated by different pre-5G BSs located in Poland, showing that the total EMF generated by multiple operators exceeds the maximum limit in one case. Finally, Sagar *et al.* [21] survey the research works about EMF exposure in Europe during the period 2000-2015, and conclude that the measured EMF levels are in general lower than the limits imposed by law, yet there is a significant number of cases where such limits are not met.

Although all these works are of interest to our analysis, they are not focused on the planning phase of the network. Therefore, (*i*) they do not link EMF measurements to the possibility to install new sites, and (*ii*) they do not consider the actual policies used to verify the compliance of newly deployed BSs with the applicable EMF regulations, which often operate on the maximum radiated power by the BSs, and not on the actual emissions during network operation.

C. NETWORK PLANNING & MANAGEMENT UNDER EMF CONSTRAINTS

In fact, several works have considered the EMF levels in the network planning phase and/or during network management. Deruyck *et al.* [22] propose an algorithm for the power- and EMF-aware dynamic management of 4G networks. Their solution relies on the idea of powering on/off BSs, as well as tuning their radiated power, given a set of installed BSs. This is done by: (*i*) guaranteeing enough capacity to accommodate user traffic, and (*ii*) controlling the EMF generated over space. Plets *et al.* [23] design a planning tool for exposure calculation and optimization in indoor wireless networks where coverage is provided by Wi-Fi Access Points (APs) and Wi-Fi/Long Term Evolution (LTE) femtocells. A proposed heuristic allows to reduce the EMF levels from 3 to 6 times compared to traditional network deployments, also achieving a homogeneous EMF levels in the target building. With respect to these efforts, we focus on the network planning of outdoor 5G radio access infrastructure, which is better aligned with the upcoming roll-out of future-generation mobile networks.

Finally, different commercial tools (see [24]–[27]) are used by the operators to simulate the impact of newly installed BSs on the EMF levels. We recognize the effectiveness of such tools during the network planning process. However, in this work we also highlight the importance of solving a global optimization problem, which takes into account multiple constraints, in order to derive an optimal planning. Since 5G is not fully commercialized, we also introduce a set of selected guidelines that can be used during the planning phase.

D. IMPACT OF 5G ON EMFS

The influence of 5G technologies on EMF levels is still unclear, despite a number of dedicated studies. The International Telecommunication Union (ITU) has organized two recent workshops on the topic of 5G and EMFs [11], [12]. During these meetings, different presenters raised the issue that stringent EMF limits may decrease the QoS experienced by users, and increase the installation costs for the operators, owing to the impossibility of reusing the existing sites. In particular, in [12] the participants recognized that the EMF limits may be a barrier towards the deployment of 5G networks, especially in countries where the EMF limits are very restrictive. In this work, we provide evidence of such a situation in two real-world case studies of urban zones already hosting pre-5G BSs.

When assessing the compliance of a 5G BS in terms of EMF limits, a key problem is the definition of suitable models to estimate the radiated power – and consequently the EMFs. This is still an open problem under evaluation/standardization by international bodies such as ITU. To this aim, Baracca *et al.* [28] derive a statistical approach for the computation of the EMF generated by massive Multiple Input Multiple Output (MIMO) systems exploiting narrow beams. By exploiting a three dimensional spatial traffic model, they show that the compliance boundary, i.e., the zone that cannot be accessed by the general public around the BS, is almost halved compared to a traditional case, based on the maximum radiated power in all directions. Thors *et al.* [29] propose a model to compute realistic maximum power levels of 5G BSs exploiting massive MIMO. The proposed solution considers multiple factors, including BS utilization, time-division duplex, scheduling time, and spatial distribution of users.

Results demonstrate that the time-averaged radiated power is between 7%-22% lower than the maximum theoretical one. This is translated into a reduction of the distance from the antenna to the compliance boundary up to 60% compared to traditional evaluations. The importance of adopting new models for the EMF limits compliance, tailored to the specific 5G features, is also highlighted in our work.

More recently, Xu *et al.* [30] address the problem of exposure compliance of UEs in presence of MIMO systems, and Thors *et al.* [31] conduct an evaluation of the EMF exposure in the frequency range 10-60 GHz for an array of antennas. Their results are representative for devices used in close proximity (up to dozens of centimeters) to users. Similarly, different power measurement schemes for the EMF compliance assessment of 5G UEs are studied by Xu *et al.* [32]. Eventually, Zhao *et al.* [33] exploit a ray-tracing technique to evaluate the body effects on the channel characteristics in the downlink direction at 15 GHz and 28 GHz. The focus of all of the aforementioned works is on the UE antennas; while we recognize the importance of assessing the EMF generated by UE, our study targets planning, hence considers EMFs generated in the downlink by the BSs.

Finally, Wu *et al.* [34] review our current understanding of the potential biological effects of non-ionizing millimeter-wave (mmWave) radiation on the human body. They discuss the requirements ensuring that emerging mmWave technologies for 5G mobile communications networks are actually safe. In our work, we regard EMF limits as an input to the network planning problem.

III. OVERVIEW OF EMF EXPOSURE LIMITS

The World Health Organization (WHO) and ITU have endorsed ICNIRP to develop the international EMF exposure guidelines [7], which have been mainly derived from the observation of thermal effects induced by EMFs on the body. The observed effects include induced current and heating (for frequencies up to 300 MHz), body heating (for the frequencies between 300 MHz and tens of GHz) and skin heating (for the frequencies above tens of GHz). In fact, 5G is expected to operate on all the aforementioned bands: (*i*) below 1 GHz to provide coverage in rural, suburban and urban scenarios (including for Internet of Things devices), (*ii*) between 1 and 6 GHz to offer a mixture of coverage and capacity, and (*iii*) above 6 GHz to grant very high data rates [35].

From a health perspective, there is a growing concern from the society that an indiscriminate increase of the number of antennas results in an increase of cancer cases - especially to the brain. Different independent studies have tried to shed light on this issue (see [36]). However, a clear causal effect between the EMFs generated by cellular equipment (and in particular by mobile phones) and the risk of brain cancer is still under investigation (see, e.g., the recent work of Falcioni *et al.* [37]). In this scenario, WHO has classified radio-frequency EMF fields as possibly carcinogenic to humans, based on a possible increased risk for glioma, a malignant type of brain cancer, associated with the wireless phone use [38]. WHO pointed out that there could be a potential risk, and that further research, especially on long-term effects, is needed. In any case, if the EMF fields are kept below the ICNIRP limits, there should be no adverse effect for the public health. Therefore, in this work we will consider the ICNIRP limits as a reference.

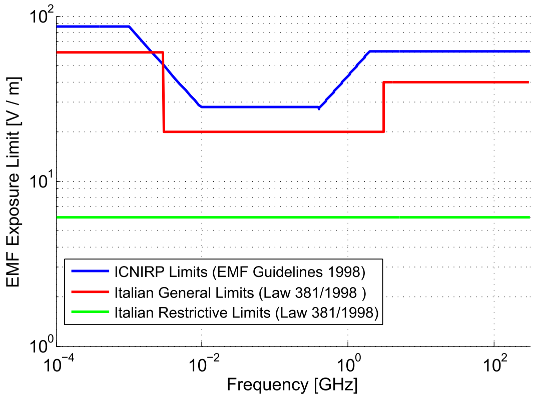


FIGURE 1. Comparison of the ICNIRP and the Italian EMF limits, on a logarithmic scale and versus frequency.

From a regulation perspective, many countries in the world adopt the conservative EMF limits set by ICNIRP [6], [8]. For example, the European council recommendation 1999/519/EC has set the EMF limits based on the values promoted by ICNIRP [39]. However, different countries (e.g., Canada, Italy, Poland, Switzerland, China, Russia) enforce national laws that set even more stringent limits [6]. As an example, in Italy two distinct classes of limits exist: (*i*) general limits (which are in most of cases already lower than the ICNIRP ones), and (*ii*) restrictive limits (named *attention levels*) applied to houses (including terraces and balconies), schools, and in general to buildings where people spend long, continued periods of time. Based on a precautionary principle, attention levels can be more than 10 times lower than the ICNIRP ones, as shown in Fig. 1, which illustrates the ICNIRP limits and the Italian ones, for different frequency bands. Eventually, further regulations may also introduce constraints even in the minimum distance that has to be enforced between a BS and a sensitive place (which may be, e.g., a school or a hospital) [40]. As a result, the actual network planning is subject to a wide set of regulations.

In the light of these considerations, ensuring that 5G deployments maintain EMF levels below the prescribed limits is a non-trivial task, which is made more complex by the geographical variability of heterogeneous laws on EMF emissions. In the next section, we discuss the influence of EMF regulations on 5G planning with a nuts-and-bolts approach.

IV. INFLUENCE OF EMF EXPOSURE LIMITS ON THE PLANNING OF CELLULAR NETWORKS

Stringent EMF exposure limits imply a reduced flexibility in the 5G network deployment that in turn sets heavy limitations for the operators in the installation of new sites. Fig. 2 shows

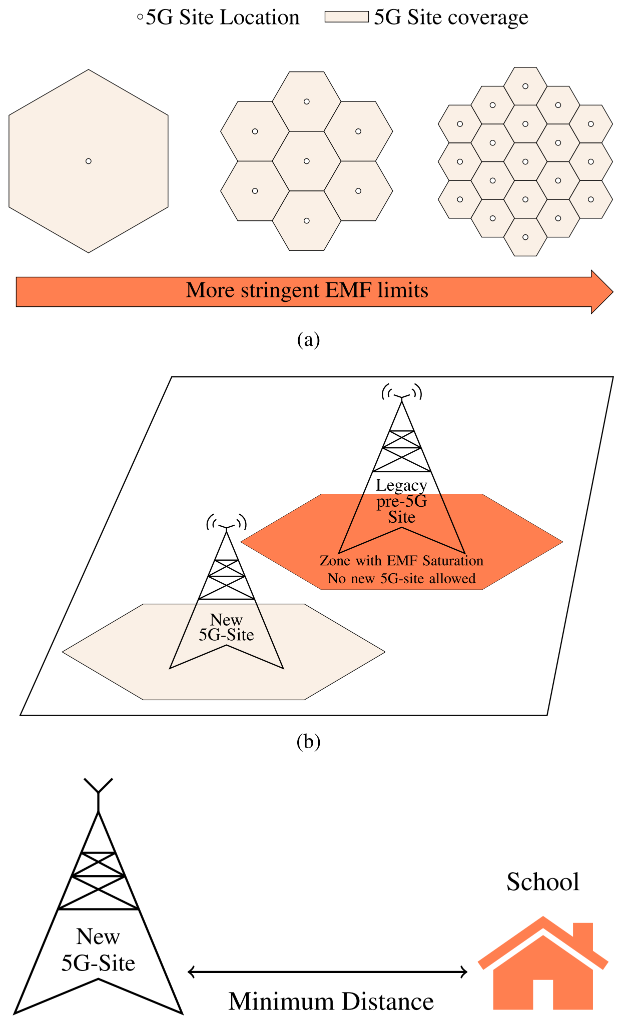


FIGURE 2. Three examples relative to the impact of EMF limits and EMF regulations on the 5G network planning. (a) Extensive 5G cell densification. (b) Presence of an EMF saturation zone. (c) EMF regulation based on a minimum distance.

three representative examples. Fig. 2.a highlights the 5G cell densification effect. To this aim, the more stringent the EMF limits are, the lower is the power that each BS is allowed to radiate over the territory. This results then in a higher number of sites needed to serve a given area. As a result, the operator will experience a general increase in the CAPEX costs. In the worst case, the operator may also decide to not serve a given area with 5G services, due to prohibitive CAPEX costs.

A second effect triggered by stringent EMF limits is the presence of EMF saturation zones. Fig. 2.b sketches a representative scenario, where a legacy pre-5G site is already serving part of the territory. Since the EMF limits are already saturated in the surroundings of the site, it is not possible to install a 5G site in the same location. Clearly, this condition is experienced independently of the technology features adopted by the 5G BS. As a consequence, the operator will have to install the 5G BS in a new site, thus increasing the CAPEX costs, and possibly reducing the QoS perceived by the users. Eventually, the EMF saturation effect may be also exploited by an operator already serving an area to deny the installation of a new 5G BS site belonging to a competitor. To this end, a large amount of radiated power is declared by the operator during the authorization phase, while the actual value set during operation is much lower.

Finally, Fig. 2.c recalls that regulations may also impose a minimum distance between a 5G site and a sensitive place (e.g., a school or a hospital). This condition prevents again the installation of a new 5G BS at the best location. The operator has then to choose another location, which likely results in a sub-optimal planning.

In this context, an EMF-constrained placement of 5G sites that is not carefully designed has a number of critical implications, namely: (*i*) CAPEX costs incurred by operators are increased, as a non-optimal planning entails the installation of additional infrastructure; (*ii*) the QoS perceived by users is reduced, due to a hindered deployment flexibility that cannot match the actual spatial distribution of the user demand; (*iii*) verticals and service providers are penalised, since 5G cannot support all of the many services it is expected to enable. All aspects above are exacerbated by the presence of multiple competing operators over the same territory, which further reduces elasticity in building 5G infrastructures while meeting EMF exposure limit requirements.

V. REAL-WORLD CASE STUDIES

We substantiate our discussion of the impact of EMF limits on 5G network planning by means of two complementary real-world case studies. Specifically, we first provide evidence of the EMF saturation effect in an operational scenario. We then consider the impact of regulations on the planning and on the user QoS in a second scenario.

A. EVIDENCE OF EMF SATURATION IN CURRENT CELLULAR NETWORKS

We focus on a portion of the Fuorigrotta district, in Naples, Italy. The considered area, portrayed in Fig. 3, covers 1100×1100 m^2. This portion of territory includes the San Paolo stadium and several buildings of the Engineering School of the University of Naples Federico II. The figure reports also the real positions of five BS sites installed in the area by two Italian mobile operators, i.e., TIM and Wind Tre.

Tab. 1 reports the main features of each antenna installed in the considered scenario, which include: the coordinates in UTM format (zone 33), the antenna height above the ground level, the azimuth pointing (measured clockwise with respect to North), the downtilt, the gain and the frequency band. The total number of antennas producing EMFs is equal to 39, due to the fact that each site can host multiple antennas. Moreover, the radiation pattern of each antenna has been also provided. However, it is here sufficient to report that the 3 dB azimuth

TABLE 1. Antenna settings for the Fuorigrotta case-study.

Antenna ID	Position UTM (N, S) [m]	Height [m]	Az. Pointing [°]	Downtilt [°]	Gain [dBd]	Frequency [MHz]	Max Input Power [W]
1	(432331.17, 4519798.21)	33.5	330	2	15.32	1855	7.20
2	(432331.17, 4519798.21)	33.5	330	4	14.17	947	10.94
3	(432331.17, 4519798.21)	33.5	330	2	16.25	2140	1.90
4	(432331.17, 4519798.21)	33.5	230	2	15.32	1855	7.20
5	(432331.17, 4519798.21)	33.5	230	6	14.13	947	9.10
6	(432331.17, 4519798.21)	33.5	230	2	16.25	2140	1.90
7	(432150.50, 4519705.20)	32.2	78	6	14.07	902	41.22
8	(432150.50, 4519705.20)	32.2	78	6	15.25	1750	38.56
9	(432150.50, 4519705.20)	32.2	78	7	15.66	1950	46.26
10	(432150.50, 4519705.20)	32.2	252	7	14.07	902	68.70
11	(432150.50, 4519705.20)	32.2	252	4	15.25	1750	23.13
12	(432150.50, 4519705.20)	32.2	252	7	15.66	1950	46.26
13	(432150.50, 4519705.20)	32.2	308	3	14.07	902	27.45
14	(432150.50, 4519705.20)	32.2	308	3	15.25	1750	15.42
15	(432150.50, 4519705.20)	32.2	308	3	15.66	1950	46.26
16	(432331.17, 4519798.21)	33.5	70	2	15.32	1855	7.20
17	(432331.17, 4519798.21)	33.5	70	4	14.17	947	10.94
18	(432331.17, 4519798.21)	33.5	70	2	16.25	2140	1.90
19	(432098.70, 4520178.40)	30.5	60	5	14.07	902	60.14
20	(432098.70, 4520178.40)	30.4	130	7	14.07	902	60.14
21	(432098.70, 4520178.40)	30.5	60	4	15.66	1950	47.11
22	(432098.70, 4520178.40)	30.4	130	5	15.66	1950	47.11
23	(432098.70, 4520178.40)	30.4	60	5	15.66	1950	41.91
24	(432098.70, 4520178.40)	30.4	130	7	15.66	1950	41.91
25	(432098.70, 4520178.40)	30.5	60	4	15.66	1950	37.68
26	(432098.70, 4520178.40)	30.4	130	5	15.66	1950	37.68
27	(431712.30, 4520081.80)	42.0	116	6	14.07	902	89.55
28	(431712.30, 4520081.80)	42.0	116	5	15.25	1750	68.12
29	(431712.30, 4520081.80)	42.0	116	9	15.66	1950	53.60
30	(432069.30, 4520517.20)	32.2	110	2	15.35	1855	15.80
31	(432069.30, 4520517.20)	32.2	250	0	15.35	1855	15.80
32	(432069.30, 4520517.20)	32.2	110	2	15.85	2110	2.50
33	(432069.30, 4520517.20)	32.2	250	0	15.85	2110	2.50
34	(431712.30, 4520081.80)	42.0	356	6	14.07	902	89.55
35	(431712.30, 4520081.80)	42.0	241	5	14.07	902	89.55
36	(431712.30, 4520081.80)	42.0	356	5	15.25	1750	50.00
37	(431712.30, 4520081.80)	42.0	241	4	15.25	1750	68.12
38	(431712.30, 4520081.80)	42.0	356	7	15.66	1950	53.60
39	(431712.30, 4520081.80)	42.0	241	8	15.66	1950	53.60

FIGURE 3. Terrain map and BS locations (Fuorigrotta case-study). Terrain map source: Google Earth.

aperture is about 60° (10 dB aperture about 120°), whereas the 3 dB vertical apertures is about 10° for frequencies lower than 1 GHz and about 5° for higher frequencies.

In the following, we analyze the EMF exposure on the considered scenario. To this aim, we utilize the ray tracing simulator developed in [41], which requires as input: (*i*) the description of the scene in terms of a Digital Elevation Model (DEM); (*ii*) a vector file containing vertex position and height of the buildings; (*iii*) the characterization of the antennas in terms of location, input power, radiation diagram, and pointing angles (see Tab. 1). The simulator outputs a map of the EMF level for each antenna, by leveraging electromagnetic models, including reflection and diffraction. Clearly, the accuracy of the obtained results significantly depends on the accuracy of the considered scene models. This also includes the characterization of the electromagnetic properties of building walls in terms of complex dielectric constants [42]. However, we point out that we are here concerned with the verification of the compliance with EMF limits, rather than with coverage evaluation, where areas with low field levels are investigated. Therefore, we focus on high EMF levels, which are less affected by scene model inaccuracies, since the main involved rays experience a limited amount of reflection and diffraction events. Eventually, the 39 EMF maps are combined to obtain the total EMF level in each point on the scene. Since all the involved frequencies (ranging from 902 MHz to 2140 MHz, i.e., lower than 3 GHz)

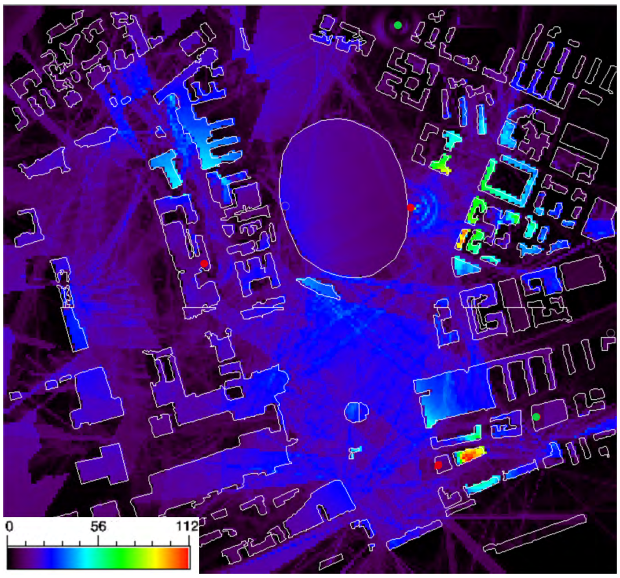
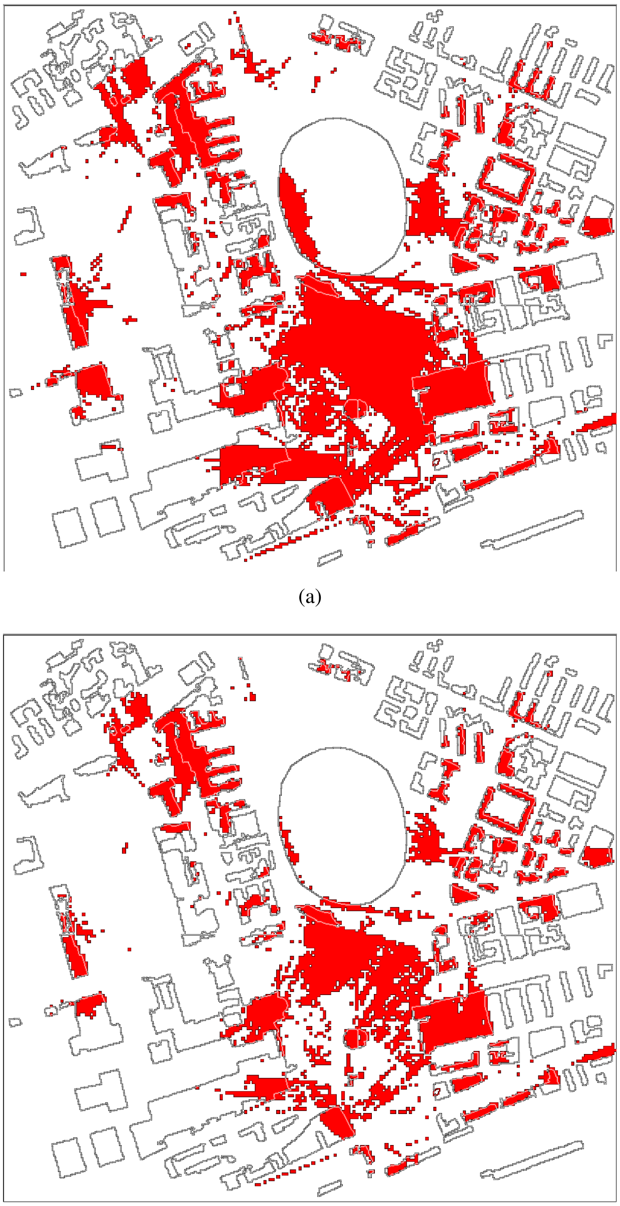


FIGURE 4. **EMF-level map (Fuorigrotta case-study). Figure best viewed in colors.**


(a)

(b)

FIGURE 5. **Impact of the variation of the maximum input power (Fuorigrotta case-study). Red colors mark the areas where EMF levels are above the Italian general limit of 20 V/m. (a) 100% maximum input power. (b) 75% maximum input power.**

are subject to the same Italian general EMF exposure limit (i.e., the red line of Fig. 1), a simple incoherent summation of the square modulus of the results obtained by each simulation can be performed. The final EMF levels are computed by applying the root square operator on this summation.

Fig. 4 reports the obtained EMF levels, where red dots and green dots mark the position of TIM and Wind Tre sites, respectively. The output map grid has a pixel size of 5×5 m^2 and the EMF levels are evaluated at 1.5 m above terrain or roof (where buildings are present). Interestingly, many zones experience EMF levels consistently higher than the limits. In particular, even discarding the areas associated to the roofs (which may be inaccessible to the inhabitants), large areas at street level experience EMF levels higher than the allowed ones. In order to better support this conclusion, Fig. 5.a highlights in red the zones where the limits are exceeded. In this situation, most of the large square located in the South of the stadium and several other areas of the scene experience EMF levels exceeding the 20 V/m limit.

It is important to note that the Italian regulations establish to evaluate the average EMF levels on a time interval of 24 hours, differently from the ICNIRP guidelines, which indicate a time interval of 6 minutes. Therefore, our results are obtained by assuming that each antenna constantly radiates the maximum declared power and, in particular, we evaluate the root mean square value of the electric field, which would be measured averaging out the fast variations of such an electric field, in agreement with the temporal average prescribed by the ICNIRP guidelines. The rationale for this kind of approach is quadruple: (*i*) it allows us to quantify the negative gap resulting from adopting limits more restrictive than the ICNIRP ones; (*ii*) the simple case-study can be exploited to gain some insights regardless of the particular national law; (*iii*) no limit is prescribed by law on the time interval for the maximum power emission; hence, at least in principle, a mobile operator is authorized to constantly use the maximum declared power; (*iv*) the procedure to verify the EMF compliance may be subject to revision; hence, laws (as the Italian ones) that contemplate the possibility to compute the EMF values as an average over a long time may be revised in the light of the actual values radiated by the 5G equipment.

Clearly, assuming that an antenna always radiates at its maximum power constitutes a worst-case scenario, even if it represents a common practice for conservative EMF level

FIGURE 6. Planimetry of Torrino-Mezzocammino (TMC) district in Rome (Italy) reporting current and planned buildings [45].

evaluation (see [29], [43], [44]). Hence, in Fig. 5.b we relax the aforementioned assumption, by evaluating the EMF levels when a radiated power equal to 75% of the maximum declared power is set for each antenna. Even in this case, the 20 V/m limit is exceeded in many parts of the scene.

Remark 1: The results confirm previous concerns about the potential impact of EMF limits on future deployment of 5G networks. Indeed, it is apparent that a non-negligible degree of EMF saturation has been reached in some scenarios already in legacy pre-5G networks, which will significantly limit the deployment of future 5G sites.

Remark 2: According to Andrews *et al.* [2] 5G will be characterized by a set of radically new technologies, including, e.g., beamforming techniques to concentrate the radiated power into small portions of territory or large exploitation of new frequency bands (including mmWave) with directional transmissions. These technologies can be beneficial for the EMF levels. Nevertheless, such gain needs to be assessed against: (*i*) the aggregate radiation generated by multiple cells operating with different access technologies, especially if legacy pre-5G networks already showed a certain level of EMF saturation as revealed by our case-study; (*ii*) the dependence of the EMF exposure on several factors, including e.g., the type of BS/UE, the BS/UE location with respect to the user, and the location of the user [13].

B. IMPACT OF REGULATIONS ON NETWORK PLANNING AND USER QOS

Our second case study proves that the current regulations have a large impact on the cellular network planning, as well as on the QoS provided to users. We focus on the ''Torrino-Mezzocammino'' (TMC) area in Rome, Italy, which spans over almost two millions of square meters. TMC is a relatively recent neighborhood, currently inhabited by more than 10,000 persons. The district includes residential houses, commercial buildings, schools, sports centers, and public parks. Fig. 6 portrays the planimetry of the TMC area, where most of the planned buildings have been already completed.

During the past years, in parallel with the growth of the neighborhood in terms of buildings and inhabitants, the three major Italian operators (TIM, Vodafone and Wind Tre) have requested to the local municipality authorizations to deploy different BS sites within the TMC area, by providing evidence that both the ICNIRP limits and the Italian one would have still been ensured after the installation of the new sites. However, all the requests have been denied due to the application of a municipal regulation, which imposes a minimum distance of 100 m between a BS site and a sensitive place, regardless of the amount of power radiated by the BS. Moreover, the definition of ''sensitive place'' is left open to interpretation. In general, schools and places where the children spend their time are considered as sensitive places. However, the selection of sensitive places depends on a case-by-case basis, with final decisions taken by the municipality, typically in accordance with the representatives of the population living in proximity to the candidate BS site. In this scenario, all requests to place new BSs inside the TMC district have been denied due to the proximity of the planned BSs to areas that have been recognized as sensitive. In one case, for example, a sports center has been considered as a sensitive place, due to the constant presence of children in the afternoon and evening. In another case, a commercial area, hosting shops and supermarkets, has been recognized as sensitive as well.

Stimulated by this background, we have decided to investigate how much the planning of currently deployed BSs impacts the offered service as well as the user QoS. To this end, we have employed CellMapper [46], a monitoring application that collects different cellular metrics of the BS(s) currently serving the user. One of the most interesting aspects of CellMapper is that each measurement also includes the GPS coordinates of the current position, as well as the current date and time. In addition, the application allows the users to upload their measurement on the CellMapper website, which reports constantly updated maps about the coverage of each BS. Unfortunately, at the time of the experiments, the TMC area was not covered by measurements of other users. This fact, coupled also with the need of analysing the measured data,[1] stimulated us to perform a measurement campaign over the TMC area and the three operators. More in depth, we have taken measurements by traveling (mainly by foot) inside TMC and also in the neighboring districts during the working days of May 2018. We have exploited as measurement devices three Long Term Evolution Advanced (LTE-A)-enabled smartphones, each of them equipped with a single SIM card of an operator and the CellMapper version 5.1.7 installed. We have then performed the following experiments: (*i*) localization of BSs covering TMC, (*ii*) investigation of the type of service offered by the operators, and (*iii*) evaluation of the QoS

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[1] The data measured by all users are used by CellMapper to build coverage maps. However, the raw data measured by users are not publicly available.

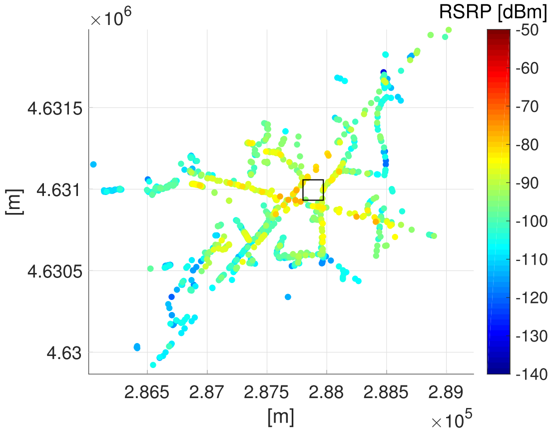

FIGURE 7. **Localization of a Vodafone BS through RSRP measurements (TMC case-study).**

provided to users. Details about each experiment are provided next.

1) BSS LOCALIZATION

During this task, we tried to answer the question: Where are located the BSs currently serving the TMC users? To answer this question, we have measured with CellMapper the Reference Signal Received Power (RSRP) metric of the current BS serving the user.[2] According to ETSI [47], the RSRP is defined as the linear average over the power contributions (expressed in Watts) of the resource elements that carry cell-specific reference signals within the considered measurement frequency bandwidth. Practically speaking, the RSRP provides indication about the quality of the incoming reference signal, and it can be used by the operator e.g., to trigger hand-over operations between one cell and another one. As suggested in [46], values close to -50 dBm are the best ones, values close to -90 dBm are good, and values lower than or equal to -110 dBm are the worst ones.

In our work, we have exploited the RSRP measurement together with the BS id assigned by CellMapper, in order to localize each BS.[3] Fig. 7 reports an example of localization for a Vodafone BS. More in depth, the values of RSRP (expressed in dBm) tend to increase when the measurement device is close to the serving BS. On the other hand, when the measurement device is located in proximity to the edges of the BS coverage area, the RSRP tends to be lower than -100 dBm. By analyzing the RSRP values, coupled with an on-site checking of the selected BSs, we are therefore able to localize each BS. However, we need to select only the BSs covering the TMC district. To do that, we have proceeded as follows: (*i*) we have initially performed measurements mainly inside the area of TMC; (*ii*) we have extracted the BS id from the measurements of i), by selecting only the ids appearing in at least 0.5% of the total number of measurements; (*iii*) for each BS id, we have taken measurements outside TMC to allow the BS localization; (*iv*) we have finally checked that the BSs are effectively installed in the selected BS locations.

Fig. 8 reports the results showing the localization of the BSs for the three operators. The number of BSs serving TMC is 12 and 11 for TIM/Vodafone and Wind Tre, respectively. Although these values may appear pretty high at a first glance, the actual BS positioning reveals that different BSs are located very far from TMC users, with a BS-to-user distance even in the order of different kilometers. Moreover, the figure highlights that most of BSs covering TMC are located in the neighboring districts. In the following, we better quantify the impact of this planning from the user side.

2) TYPE OF SERVICE OFFERED BY OPERATORS

During this step, we measure the type of service that each operator offers to its users. This information is in general made available in each smartphone, and in our case is collected by the CellMapper application. Fig. 9 reports the obtained results, which are retrieved from the TMC area and the neighborhoods in its proximity. Interestingly, we can note that the best service, namely the LTE-Advanced (LTE-A), is not widespread, with most of the territory served by the traditional LTE. Eventually, for the TIM case, in Fig.9(a), there is a zone apparently served by HSPA+, which is a legacy 3G service. Therefore, we can state that TMC is mostly served by a 4G service, even though the LTE-A is not common.

3) EVALUATION OF THE QUALITY OF SERVICE

In the following, we measure the QoS through the RSRP metric. We proceed as follows: (*i*) we collect the RSRP of the serving BS of the current operator, together with the coordinates of the measurement device, across the TMC area and the neighboring districts; (*ii*) we apply a uniform grid over the considered area, with a pixel resolution of 30 m; (*iii*) we consider the measurement points falling inside each pixel, and we compute the RSRP of the pixel as the average of its points; (*iv*) we repeat (*i*)-(*iii*) for each operator. Fig. 10 reports the obtained results. We recall that the RSRP is a measure of the quality of the reference received signal. According to [48], the Signal To Noise (SNR) ratio may be proportional to the values of RSRP. In our cases, different zones of TMC are exhibiting very low values of RSRP (e.g., lower than or equal to -110 dBm), thus suggesting that the QoS offered to users is pretty low in these zones. We have also manually verified this aspect, by experiencing frequent dropped calls, and difficulty in accessing to the Internet applications. Nevertheless, there are also some zones experiencing good RSRP values (i.e., higher than -90 dBm). By comparing Fig. 10 with Fig. 8 we can note that these zones are in general close to the BSs installed in the neighboring districts. Finally, we point out that the obtained measurements are taken outdoor at street level. We expect that the RSRP values measured inside buildings

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[2] No publicly available and/or updated data of BS positioning where available for the TMC area from other sources at the time of performing the measurements.

[3] Our measurements allowed also to verify that the association between each cell id and each BS id provided by CellMapper was correct.

(and in particular at lower floors) are even worse that those reported here.

Remark 3: The lack of BS sites inside the considered TMC area results in a sub-optimal planning, with a clear impact on both the type of service offered by the operator and the QoS perceived by users.

Remark 4: The decision to install a BS site is subject to wide set of regulations. Our case-study reveals that a regulation which integrates a minimum distance constraint between a BS and a sensitive place has impacted the planning of the network for the three main operators. In general, we expect that the geographical jeopardization of laws regulating the installation of BS sites will inevitably affect the planning of 5G networks. This will be translated into a non-uniform impact of 5G in terms of CAPEX from the operator side, as well as in terms of varied QoS experienced at the user side.

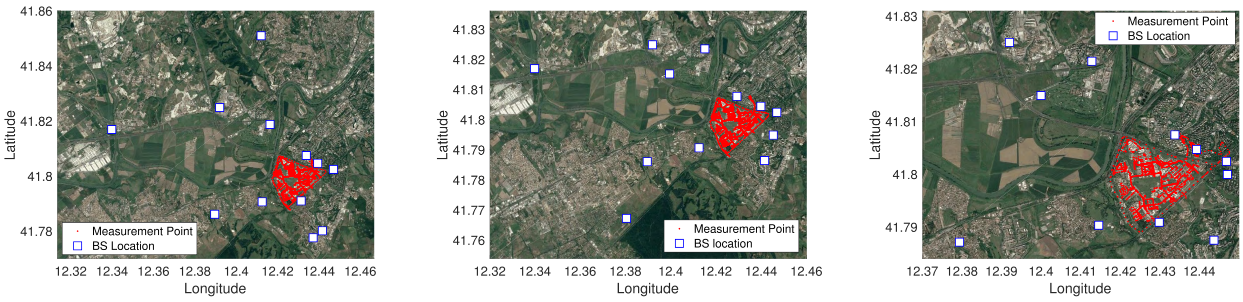
VI. 5G TECHNOLOGIES AND EMFS: FRIENDS OR FOES?

In this section, we concentrate our attention on the expected impact in terms of EMF levels of the main technologies that are envisioned to be adopted in a 5G network. To this aim, Tab. 2 summarizes the distinguishing features of 5G technologies, and briefly indicates their relevance to EMF emissions. The last column concludes on how each feature is ultimately expected to increase or decrease EMFs compared to currently deployed cellular networks. Clearly, we stress the importance of supporting these hypotheses through an extensive set of EMF measurements on a wide range of 5G BSs, a complex task that we believe is mandatory to be performed in the near future. Next, we discuss each feature.

In the 5G context, it is widely recognized that 5G sites will intensively exploit *massive MIMO* antenna arrays. Compared to current BSs, this feature will require the installation of a large number of antennas in each site. As highlighted in Sec. II-D, recent works suggest that MIMO may be beneficial for the EMF levels. However, these evidences cannot be generalized since the MIMO impact on the EMF levels highly depends on the specific configurations and on the adopted approach for measuring the EMF levels [29], [44]. As a consequence, further research is needed to assess the eventually MIMO gain in terms of EMF levels.

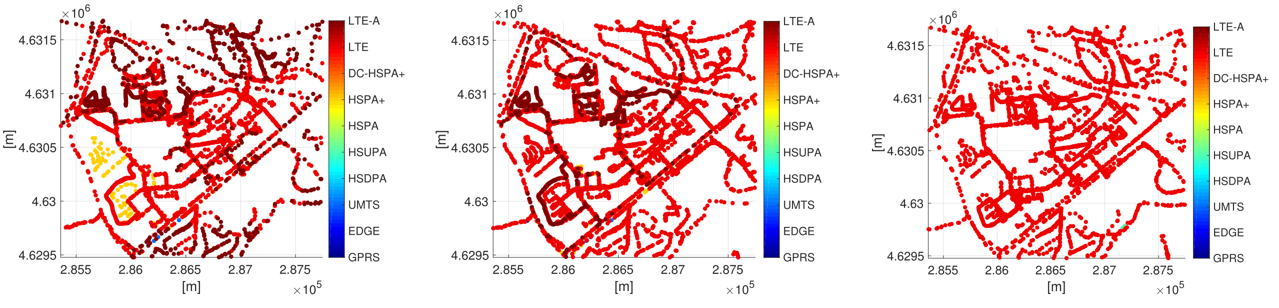
Focusing then on *beamforming*, this feature allows controlling the directionality of the radiated power in space. Hence, by adopting this solution, it will be possible to concentrate the power into the locations where the 5G services are requested. Compared to currently installed BSs, in which a single antenna (or very few) emanate power over a wide area, this feature may result in generally lower EMFs levels. However, since the radiation is concentrated into selected portions of territory, there may be an increase of EMFs in these points. Moreover, BSs capable of operating over the *mmWave bands* will be likely exploited in a 5G network. In general, the mmWave are subject to higher path-losses compared to the current micro-waves. As a result, the received EMF may be lower compared to the one generated by currently deployed BSs. Eventually, 5G will likely include the large exploitation of different layers of BSs. In particular, *small cells* will be densely deployed in proximity to users. Compared to the current cellular network, this will result in a general lower amount of received EMFs, thanks to the exploitation of the shorter BS-to-user distance. However, an increase of EMFs in proximity to the small cell may be also experienced when comparing to the current deployment, which is mainly composed of macro cells in many countries.

In addition, since the coverage regions of the BS sites will be largely overlapped (especially in urban zones, where different tiers of cells will coexist), *offloading mechanisms* will be largely exploited. This will result in a possible decrease of the power radiated from the most loaded cells, since users will be offloaded to other cells, which may be located e.g., in proximity to them. As a result, the EMFs may be (possibly) decreased. Eventually, one of the key enablers of 5G will be the exploitation of the *softwarization* paradigm, according to which different network functionalities, which were previously hardcoded in hardware, will be realized at software level. This include e.g., most of BS functionalities. The definition of virtual building-blocks for a cellular architecture will pave the way to the (possible) exploitation of the same BS hardware shared by multiple operators. This feature will be extremely interesting in urban zones where it would be otherwise not possible to install multiple BSs in the same site. This would result in a large EMF decrease, thanks to the fact



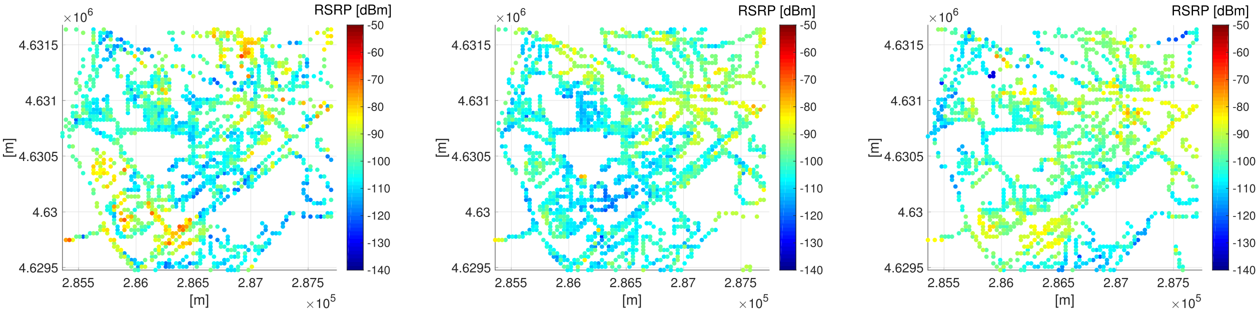
(a) (b) (c)

FIGURE 8. **Location of the BSs covering the considered area (TMC case-study). Terrain map source: Google Earth. (a) TIM. (b) Vodafone. (c) Wind Tre.**



(a) (b) (c)

FIGURE 9. Service offered by each operator (TMC case-study). (a) TIM. (b) Vodafone. (c) Wind Tre.



(a) (b) (c)

FIGURE 10. RSRP metric (TMC case-study). (a) TIM. (b) Vodafone. (c) Wind Tre.

TABLE 2. Expected impact of the 5G technology features on the EMF levels.

Feature	Relevance to EMFs	Expected EMF Increase/Decrease
MIMO	Increased number of antennas radiating power. Impact of computing the radiated power when assessing the compliance with EMF limits.	-/+ The impact on the EMFs levels depends on the specific MIMO configuration and on the adopted approach for measuring the EMF levels.
Beamforming	Directionality control of the radiated power. Power concentrated into selected locations.	- General decrease w.r.t. currently deployed BSs. + Increase in selected locations.
mmWave	Path loss increase of radiated signals on mmWave bands.	- (Possible) decrease w.r.t. BSs exploiting micro-waves.
Small Cells	Installation of additional sources of power. Less power required to macro cells.	- (Possible) decrease w.r.t. the current cellular network. + (Possible) increase in proximity to the small cells.
Offloading	(Possible) reduction of radiated power from the most loaded cells.	- (Possible) decrease w.r.t. the current cellular network.
Softwarization	Sharing of the hardware infrastructure by multiple operators. Less antennas installed in the shared sites.	- Large decrease w.r.t. the case in which each operator installs its own physical equipment in the same site.
MEC	(Possible) decrease in the amount of transferred data in the air, thus decreasing the radiated power.	- (Possible) decrease w.r.t. to the current MEC-unaware network.
D2D	Reduction of tha amount of data transferred (and consequently of power) between the BS and the UE.	- Decrease w.r.t. current deployments exploiting classical communication schemes (e.g., UE to BS).
Sleep mode	BSs put in sleep mode radiate zero (or very low) power. The BSs that remain powered on may have to increase their coverage area.	- Decrease in proximity to the BSs put in sleep mode. + (Possible) increase in proximity to the BSs that remain powered on.
2G/3G Dismission	Reduction of the current EMF saturation levels in urban zones.	- Large decrease w.r.t the case in which all the legacy technologies are maintained.

that the number of antennas radiating power over the territory is decreased with respect to the current situation.

Another envisioned 5G key paradigm is that of *Mobile Edge Computing (MEC)*. The idea of MEC is to move the cloud resources closer to the end users, by exploiting computing capabilities that are installed at the BS site. By properly managing the content stored in the MEC platforms, the operator may, e.g., optimize the Quality of Experience (QoE) of the users that exploit this feature, thus allowing a (possible) decrease of data transferred in the air, and consequently of EMFs. However, we also point out that this condition depends on the type of service provided by MEC, which may include e.g., high data rate services, such as augmented reality and very high definition videos. A relevant, related feature is that of *Device-to-Device (D2D) communication*, which may be performed by the UEs. This will allow a decrease in the amount of information exchanged between the UE and the BS, thus (possibly) reducing the amount of EMFs generated by the BS. Eventually, advanced power saving techniques, including deep *Sleep Modes (SMs)*, may be intelligently exploited by the 5G BSs. SM-based techniques may reduce the amount of EMFs, since the BS that are not used are completely switched off, or put in a low-power state. However, there could be also an increase in the EMFs, especially close to the BSs that remain powered on and have to increase their coverage also to the zones previously served by the BSs currently in SM. Finally, 5G will allow the *dismission of legacy 2G and 3G networks*, where still present. This will be also beneficial in terms of EMFs, especially for the reduction of the saturation levels currently experienced in the urban areas.

Clearly, Tab. 2 is not exhaustive, but only provides an initial presentation of the potential impact of 5G technologies on the EMF levels. As an example, beamforming and mmWave can be beneficial for the EMF levels. Nevertheless, as already pointed out in Remark 2, such gain needs to be assessed against the presence of already deployed pre-5G networks as well as the setting of multiple factors (e.g., the type of BS site and UE device, the BS location, or the UE positioning).

VII. GUIDELINES FOR AN EMF-AWARE 5G PLANNING

What clearly emerges from the previous discussion is that it is mandatory that the planning of a 5G network accounts for the EMF exposure limits. However, this is only one aspect. In fact, the planning of cellular networks is a complex problem per se (see [9]). In the context of 5G networks, we believe that the EMF-aware planning should take into account a variety of aspects, which are summarized as main guidelines in Fig. 11. Although these guidelines may appear pretty general at a first glance, we provide evidence that each of them is denoted by specific features related to the 5G technology, as well as to the ongoing debate about EMF limits.

A. MODELING OF THE 5G RADIO ACCESS TECHNOLOGIES

5G will be characterized by a set of radically new technologies [2], including: large antennas MIMO arrays to increase the system capacity, beamforming techniques to concentrate the radiated power into small portions of territory, and substantial exploitation of new frequency bands (including mmWave). As a result, 5G will be radically different from legacy pre-5G standards. In this context, new radio access models integrating the 5G features need to be utilized for EMF-aware 5G network planning, so as to select the proper configuration of installed equipment for each considered site. Having effective 5G radio access models is then mandatory to estimate the radiated power of each 5G site, which in turn enables the computation of the generated EMF levels over the territory.

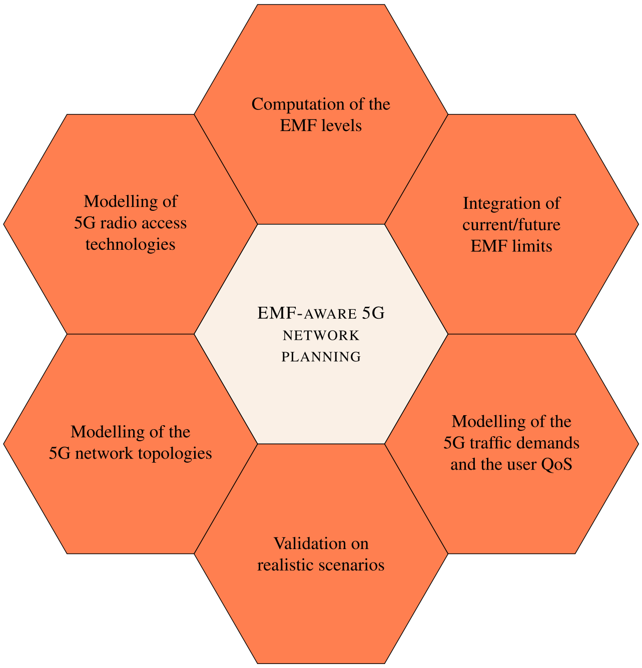


FIGURE 11. **Main guidelines that should be followed during the design of an effective EMF-aware 5G planning.**

B. COMPUTATION OF THE EMF LEVELS

One of the most disruptive innovation introduced by 5G at the physical layer is the utilization of the mmWave spectrum. The mmWave propagation has specific peculiarities, including an increased sensitivity to blockage and atmospheric effects [49]. As a result, the terrain morphology in terms of buildings and obstacles will likely introduce sharper spatial variations of the EMF levels. In these conditions, the adoption of deterministic techniques for the evaluation of the EMF level seems promising [41], [42], as also shown in Sec. V. More in detail, the EMFs may be computed based on ray-tracing techniques exploiting detailed information of the scenarios, including: DEM, building geometry, and electromagnetic characteristics. This step allows for a fine-grained antenna site characterization, based on the knowledge of the radiation pattern and of the emitted power of each antenna in the site, and, obviously, of the site position.

C. INTEGRATION OF CURRENT/FUTURE EMF LIMITS

Currently, the EMF limits vary across the different countries, and in many cases they depend also on the type of buildings in the considered area (e.g., residential or commercial buildings). As a result, the planning has to integrate suitable (and up-to-date) limits, by considering the most recent laws regulating the EMFs in the country and/or the revisions of EMF limits performed by the ICNIRP. In addition, it needs to include also the procedures to check the compliance with the EMF limits (see [50], [51]). These procedures are based, e.g., on the computation of the radiated power as an average over a daily time period, and are currently under revision for the 5G technology.

D. MODELLING OF THE SET OF CANDIDATES SITES

An effective EMF-aware 5G planning has to select a set of sites where to install BSs from a set of candidates ones. The set of initial candidates sites plays a crucial role in determining the effectiveness of the planning. In particular, this set may include the sites used to host legacy pre-5G services [52], as well as new locations selected ad hoc. In any case, a proper modeling, based on idealized distributions, or on operator-based constraints, needs to be integrated in the planning. Clearly, an uncontrolled positioning of the sites may lead to an unacceptable increase of both the installation costs and EMFs. On the other hand, a sparse set of sites may result in a lack of 5G coverage and/or 5G services.

E. MODELLING OF 5G TRAFFIC DEMANDS AND QoS

One of the most important aspect in the planning phase is a proper estimation of the traffic demands, which has an impact on the set of installed sites as well as their dimensioning. Two important features that emerge in 4G (and are expected to also dominate 5G loads) are the spatial (e.g., between different urban areas) and temporal fluctuations that characterize the service demand [53]. In this context, suitable models, able to characterize the nature of 5G traffic, need to be designed and incorporated in the planning. These models should provide indications about the demand in residential/business/entertainment/tourist areas and/or at weekdays/weekends/night hours/working hours. The modeling may be initially focused on 4G services that are clear forerunners of classes expected to dominate 5G traffic, such as extreme Mobile Broadband (eMBB) or Ultra-Reliable and Low-Latency Communications (URLLC). As a second step, suitable scaling factors can be introduced so as to account for the higher demand for such services in 5G networks. Eventually, more detailed models, taking into account the actual requirements of 5G services, will be then exploited as an outcome from the first 5G field trials.

In addition, another aspect that should be considered in this phase is the evaluation of the user QoS. We expect that each 5G service will be characterized by a set of QoS requirements, e.g., in terms of bandwidth and delay. Therefore, a proper modeling of the user QoS should be integrated in the planning: for instance, a planning minimizing solely the EMF levels may have a negative impact on QoS, and maximizing the user QoS may result in a violation of the EMF levels.

F. VALIDATION ON REALISTIC SCENARIOS

Demonstrating the designed network planning in real-world scenarios is a mandatory step. Apart from considering realistic settings for the set of candidates sites, their configurations, the 5G demands, the EMF limits, and the expected QoS, another fundamental aspect is the consideration of all the sources which radiate power over the area. This may include, e.g., the sites currently in use by other operators serving the area. In addition, the possibility of co-locating the sites of different operators needs to be taken into account.

VIII. CHALLENGES AND OPPORTUNITIES

Although the solution of the EMF-aware 5G network planning is a promising research topic, several challenges may affect the quality of results.

- **5G technologies not fully deployed and standardized**. Currently, 5G network equipment is under testing within the premises of different operators and vendors. In addition, the 5G network architecture is still not fully standardized. Both these issues may impact the modeling of the 5G technology features as well as the computation of the EMF levels. Clearly, it is expected that, as soon as more information from the field trials becomes available, new comprehensive 5G models will be proposed and validated by the research community;
- **Lack of 5G demand and 5G topology information**. Another big challenge of current research activities in 5G is the fact that, since the 5G network is not yet fully deployed, there is a general lack of patterns in terms of both 5G traffic and 5G site positioning. This issue could be faced by: (*i*) forecasting the predicted traffic of 5G services, (*ii*) characterizing the 5G demand from real measurement coming from the field trials, (*iii*) considering the set of sites currently hosting pre-5G services as candidate ones, and (*iv*) selecting new realistic candidate sites;
- **Revisions of regulations about EMF limits**. It is worth mentioning that a revision of the ICNIRP limits is currently in progress [54] . Moreover, there is also a growing concern about the jeopardization of EMF regulations across the different countries, which may trigger a harmonization of the limits in the near future. Clearly, the variation of the EMF limits may have a large impact on the obtained 5G planning.
- **Economic barriers for EMF compliance assessment**. The monitoring of EMFs in accordance to law regulations is done by using expensive EMF meters that cost dozens of thousands Euros each. This fact, coupled also with the ever increasing temporal and spatial variation of EMFs generated by cellular networks, makes EMF monitoring a very challenging (and expensive) operation, which is only performed by government authorities and/or operators.
- **Co-existence with current pre-5G networks**. The sites currently hosting pre-5G BSs may be not able to host additional 5G BSs. This imposes the operator to choose another site location, or not to serve the location with 5G service but keep the pre-5G ones, or to dismiss the legacy services. Deciding on the best option is not trivial, and will inevitably impact the roll-out of the 5G technology.
- **Lack of urban planning taking into account the cellular network**. Current cities are not planned with the

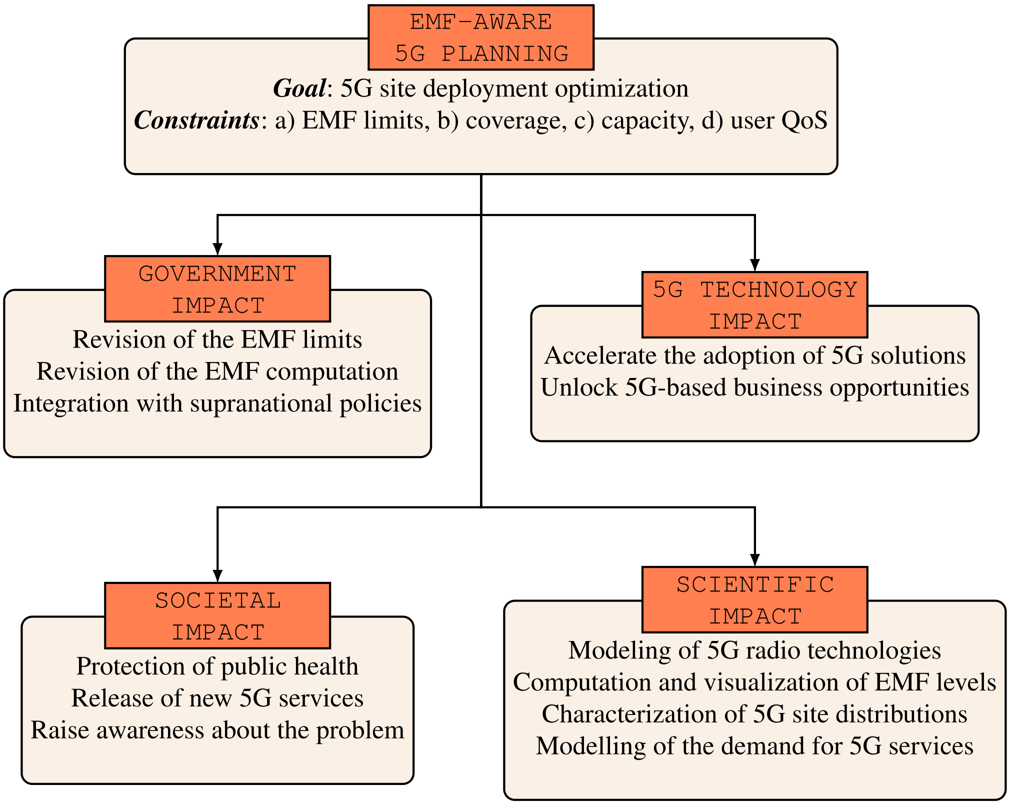


FIGURE 12. **Impact of the EMF-aware 5G network planning problem at the governmental, societal, technological, and scientific research levels.**

cellular network in mind. The construction of sensitive places, such as schools, hospitals, and more in general the residential buildings, should be done in accordance with the forecasted deployment of the cellular network in terms of new sites. An urban planning unaware of the expansion of the cellular network may result then in the inability to put new 5G sites over the territory, due to the lack of available candidate locations.

Apart from these challenges, we point out that the solution of the EMF-aware 5G planning problem will have a positive impact at different levels. To this aim, Fig. 12 summarizes the impact at the governmental, societal, technological, and scientific research levels. At the governmental level, a revision of the limits for the countries adopting more stringent limits than the ones of ICNIRP may be triggered. This process may be activated if the outcome of the planning will result into the inability of placing new 5G cells in zones already hosting sites from multiple operators and/or legacy pre-5G technologies. In this context, the procedure adopted to verify if the EMFs are lower than the maximum limits may be subject to revision. Actually, the assumption of constant maximum radiated power is very conservative. National laws contemplate the possibility to compute the radiated power as an average over time, but this option needs to be considered in the light of the actual values of radiated power that will be measured by the 5G equipment. In any case, it is expected that the countries will ensure the EMF constraints by adopting the best practices promoted by supranational bodies (e.g., ICNIRP, IEEE, and ITU).

In addition to the aforementioned aspects, we expect that assessing the feasibility of the EMF-aware 5G planning will be beneficial to the actual adoption of the 5G technology. Clearly, this step will also unlock new 5G-based business opportunities, which may be based on the commercialization of new 5G services and/or the deployment of new 5G radio equipment. Moreover, at the societal level, the solution of the problem ensuring the EMF exposure limits will guarantee the protection of the public health, while raising the awareness about the impact of EMFs on the planning. Eventually, the release of the 5G services will be another positive aspect experienced by the community. Finally, it is worth noting that the EMF-aware 5G planning stimulates the scientific research in the field, including: the modeling of the 5G radio technologies, the computation and visualization of EMF levels, the characterization of the set of candidate sites, and the modeling of the demand of 5G services.

IX. CONCLUSIONS

We have considered the problem of planning a 5G network (and in particular BS sites) under EMF exposure limits. After overviewing the current regulations in terms of EMF exposure levels, we have investigated the influence of EMFs on the 5G planning phase. We have corroborated our intuitions by considering two real-world case-studies of currently deployed cellular networks. Our results indicate that installing new 5G sites may be very challenging, especially in urban zones, due to presence of the EMF saturation effect. Moreover, we have shown that a sub-optimal planning, driven by strict regulations limiting the installation of new BS sites, has a not-negligible impact on the type of service that is provided by operators, as well as on the user QoS. Afterwards, we have discussed how the 5G technology features may impact the EMFs. In the following, we have analyzed the main guidelines that should be followed during the design of an EMF-aware 5G planning. In particular, we have shown that the EMF-aware planning in a 5G network is a complex problem, which include features that are specific of 5G. In addition, a wide set of parameters, belonging to different fields (e.g., research, technology development, regulations), has to be taken into account. Although solving the EMF-aware 5G problem is a very challenging task, this operation could trigger different opportunities at the governmental, societal, technological and scientific research levels. As future work, we plan to study the impact of positioning 5G sites in the considered scenarios. Moreover, we will take into account the other sources of EMFs, such as outdoor WiFi, high voltage transmission lines, etc.

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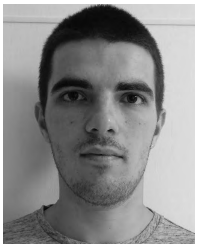

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