5G Planning under EMF Constraints

Angela Sara Cacciapuoti, Luca Chiaraviglio, Gerardo Di Martino and Marco Fiore

Abstract The planning of a 5G cellular network requires the installation of 5G Base Station (BS) sites and the configuration of each BS. This process takes into account several constraints, including the ElectroMagnetic Fields (EMF) levels radiated by the installed BSs. Different countries in the world (including Italy) adopt EMF constraints which are much stricter than the ones prescribed by international organization. The resulting planning is far away to be optimal, resulting in an increase of the CAPital EXpenditures (CAPEX) costs for the operator, and a decrease of the user Quality of Service (QoS). In this chapter, we shed light on this problem. After reporting the related work, we discuss the impact of strict EMF constraints on the 5G planning through a set of representative examples. We then report the outcomes from two case studies. Results clearly show that a saturation of EMF levels, preventing the installation of 5G BS sites, is already reached in currently deployed networks. In addition, we also quantify that the negative impact of the non-optimal planning on the user QoS. Finally, we discuss the expected impact of the main 5G technology features on the EMF levels.

Angela Sara Cacciapuoti
Department of Electrical Engineering and Information Technology (DIETI), University of Naples Federico II, and Consorzio Nazionale Interuniversitario per le Telecomunicazioni, e-mail: `angelasara.cacciapuoti@unina.it`

Luca Chiaraviglio
Department of Electronic Engineering, University of Rome Tor Vergata, Rome, Italy, and Consorzio Nazionale Interuniversitario per le Telecomunicazioni, Italy e-mail: `luca.chiaraviglio@uniroma2.it`

Gerardo Di Martino
Department of Electrical Engineering and Information Technology (DIETI), University of Naples Federico II, and Consorzio Nazionale Interuniversitario per le Telecomunicazioni, e-mail: `gerardo.dimartino@unina.it`

Marco Fiore
Institute of Electronics, Computer and Telecommunication Engineering, National Research Council of Italy, Turin, Italy, e-mail: `marco.fiore@ieiit.cnr.it`

1 Introduction

In the next decade, 5G is expected to enable a plethora of new services, with a potential economic impact of several trillions of dollars [1]. The success will depend on the capability of the 5G technologies 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.

The combined utilization of technologies, such as, e.g., *massive MIMO*, *adaptive beamforming*, *mmWave*, *softwarization* of the network functions, is expected to guarantee the required increase of the offered capacity, along with the flexibility and efficiency in the network management. In many countries, and among them in Italy, the first field trials will be operative by the end of 2018.

In this context, a very delicate and frequently underrated issue is related to the compliance of the new 5G deployments with regulations on Electromagnetic Field (EMF) exposure limits [2], which impose limits on the EMF levels resulting from the composition of the different radiating sources.

The EMF limits set by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) are widely adopted around the world. However, several other countries (e.g., China, India, Russia, Switzerland, Italy, Canada and Poland) impose even more stringent limits. Since 5G will operate on a very wide range of frequencies (ranging from hundreds of MHz, to provide coverage in rural areas, up to tens of GHz to support very high data rates) and it will coexist with some pre-5G technologies, stringent EMF limits are expected to have an especially strong impact on the planning of forthcoming 5G networks. Indeed, network planning is a complex problem per se. It aims at minimizing the 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 significantly complicates the problem.

Stemming from the above, a planning phase neglecting EMF constraints necessarily introduces an increased risk of sub-optimal planning, with an associated need of a posteriori refinements, impacting both the operator CAPEX and the user QoS [3]. However, despite its prominent role in the 5G roll-out, the 5G network planning under EMF constraints is still completely open.

In this chapter, we present a comprehensive analysis of this topic, starting from the work presented in [4]. Specifically, first, in Section 2 we review the current state of the art by analyzing different aspects related to EMF exposure levels: health risks, EMF measurements campaigns, and cellular network planning. In Section 3 we contextualize the EMF limits in Italy and we discuss their effects on the planning of 5G cellular networks. In support of the presented analysis, in Section 4, we present two Italian case studies. The first one provides evidences of EMF saturation already in presence of sole pre-5G technologies. The second case study provides evidences on the impact of restrictive EMF limits on the planning of a 5G deployment, and hence on the QoS perceived by the users. In Section 5 we outline the expected impact of the main 5G technology features on the EMF exposure levels. Finally, Section 6 draws relevant conclusions.

2 Related Work

We classify the related work in the following categories: i) health risks from EMFs due to cellular networks, ii) EMF measurements in mobile networks, iii) cellular planning with EMF constraints.

2.1 Health Risks of EMFs Exposure from Cellular Networks

The EMFs generated by the cellular network may trigger two types of risks associated with the health: i) heating of the radiated tissues, and ii) non-heating effects of the exposed body. Focusing on the first effect, there is a large literature clearly showing the negative effects on the health (we refer to reader to [5] and references therein). In this context, the ICNIRP has adopted a set of guidelines to adhere in order to avoid the heating effects [5]. These guidelines include the definition of EMF limits which differentiate between the workers that perform e.g., maintenance operations in proximity to a BS site and are aware of the risk, and the general public, which is not aware of the risk and need to be preserved through strict limits. In particular, the EMF limits defined by ICNIRP are several times below the critical values triggering heating effects.

Focusing instead on the non-heating effects, these phenomena may include cancer diseases appearing in mature life, which may be triggered even if the EMFs absorbed by the tissues are lower than the ICNIRP limits. In this context, the impact of non-heating EMF effects on the health is still a matter of research. The Interphone project [6, 7] started in 2000 as an international effort from different countries in the world in order to monitor the relantionship between the use of mobile phones and the appearance of tumors in the brain, the acoustic nerve and the parotid gland. The outcomes suggested that there is increased risk in the brain tumor. However, as noted by the World Health Organization (WHO) [8] bias and errors may have impacted the conclusions of [7]. Therefore, a causal interpretation between the use of mobile phone and the presence of tumors can not be found.

Recently, Falcioni *et al.* [9] performed several long-term experiments involving the exposure of rats to large EMFs generated by GSM equipment. Their results show a statistical increase in the incidence of heart tumor in rats exposed for a long period of time to an EMF of 50 [V/m]. In addition, an increase in both the heart Schwann cells hyperplasia and malignant glial tumors were observed (although not statistically significant). In this context, the United Station (US) National Toxicology Program (NTP) has recently concluded another study, which involved the exposure of rats to the EMF generated by 2G and 3G equipment [10, 11]. Their outcomes show a clear evidence of heart tumors in the rats (similarly to [9]), while some evidence of tumors in the brains and in the adrenal glands. It is important to remark that both the studies [9, 10, 11] have been conducted considering legacy technologies, while the impact of currently deployed one (i.e., 4G) and future ones (5G) is still an open issue.

In general, the International Agency for Research on Cancer - a branch of WHO - classifies the EMFs generated by radiofrequency devices (i.e., a wide set of equipment including mobile BSs and mobile phones) as possible carcinogenic to humans, based on an increase of brain cancer associated to the use of the wireless phones [12]. The International Agency for Research on Cancer (IARC) also suggests that further research needs to be performed [12], in order to thoroughly assess the long term of the EMFs on the public health.

2.2 EMF Measurements in Cellular Networks

The measurement of EMFs generated by cellular networks allows to derive indications about the impact of BSs and personal devices, such as mobile phones, on the total EMF absorbed by the body. Focusing on the EMFs generated by the BSs, Koprivica *et al.* [13] perform a measurement campaign of 2G BSs, highlighting the fact that the EMF tends to vary with the location, as well as the time of the measurements. In addition, they also found different locations experiencing EMF levels higher than the ones imposed by national limits. On the other hand, Urbinello *et al.* [14] perform EMF measurements in different European outdoor urban environments, concluding that the measured EMF are well above the national limits. Huang *et al.* [15] perform a wide set of measurements in different areas located in Serbia and in France, mainly focusing on 3G networks. Similarly to [13], they also observed a large variability in the measurements across space and time. Fernández-García and Gil [16] conduct a measurement campaign in an European city, observing EMF levels lower than the maximum ones enforced by national law. Orłowski *et al.* [17] measure the EMFs generated by different BSs located in Poland, concluding that the total EMF is lower than the maximum limit in all cases except one. Summarizing, the considered previous works study the EMFs generated by the BSs, showing that, in general, the BS EMFs are lower than the maximum values imposed by law. This outcome is also confirmed by the survey of Sagar *et al.* [18], which analyzes the research works about EMF exposure in Europe during the period 2000-2015.

A second taxonomy of works regards instead the measurements of EMFs generated by the mobile phones. Joseph *et al.* [19] perform a comparison of the EMF measured in proximity to users living in different European countries, finding that the largest contribution to the EMF exposure is due to mobile phones used in transport vehicles (e.g., trains, cars, buses). In particular, the EMF generated by mobile phones is larger than the one received from the BS in all the environments, except outdoor urban. Moreover, it is important to note that the study in [19] has been conducted different years ago, when state-of-the-art 4G and 5G technologies were not yet available. Frei *et al.* [20] examine the levels of exposure and the EMF sources for a sample of volunteers living in a Swiss city, showing that the exposure to EMFs notably varies across the different persons participating to the test. In addition, mobile phones, BSs, and cordless phones are the main sources of exposure in urban areas. More recently, Roser *et al.* [21] perform an assessment of the EMFs for a set of adolescents living in Swiss. Interestingly, the EMFs generated by the mobile phones dominates over all the other sources. Summarizing, mobile phones appear to be a non-negligible contributor to the EMFs absorbed by users, with different evidences suggesting that the EMFs generated by the mobile phones is larger than the one received by the BSs or other sources.

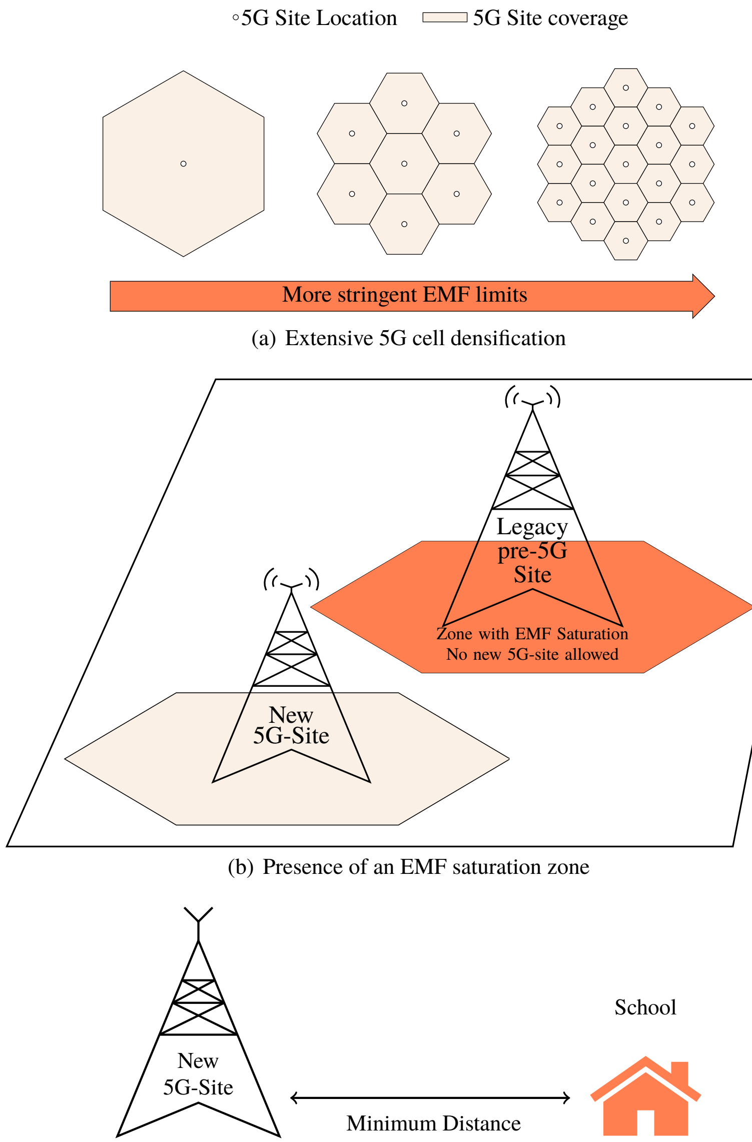
2.3 Planning with EMF constraints

The planning of cellular network is a challenging problem [22], which needs to select the locations of the sites which host BSs, as well as the configuration of each BS in terms, e.g., of radiated power. The planning of cellular networks under EMF constraints is even a more complex problem, as the presence of already deployed BSs, as well as the EMF limits, severely impacts the obtained planning, in terms of BS locations and their configuration [23]. In this context, several commercial tools (see e.g. [24, 25, 26, 27, 28]) are used by operators and regulators in order to simulate the impact of a given BS planning. These tools require a precise characterization of the scenario in terms e.g, of digital elevation model, 3D buildings/obstacles, already deployed networks, users/traffic distribution and EMF regulations. However, we stress the fact that both the selection of the initial set of BS sites and their configuration have a large impact on the obtained results [4].

3 EMF Limits in Italy and Their Effect on the Cellular Planning

EMF limits are thresholds on maximum EMF exposure, enforced by national regulations to ensure that technologies emitting electromagnetic fields do not represent a danger for the public wellbeing. In the specific case of 5G systems, radio access networks will operate across a wide spectrum of frequencies, from hundreds of MHz to tens of GHz, so as to support the variety of requirements entailed by the many emerging mobile applications [29]. At 5G frequencies, EMFs are known to induce mainly thermal effects (*i.e.*, induced current, or skin and body heating) on the human body; hence, the concerns above easily apply to next-generation cellular deployments.

Many countries worldwide, as well as the European Council, adopt EMF limits set by the ICNIRP [5]. Although ICNIRP limits are already fairly strict, Italy enforces different EMF limits on its national territory [30], which are even more constraining. Specifically, two distinct classes of limits are introduced by the italian law: (*i*) general limits that are in most cases around 30% lower than the ICNIRP ones, and



(a) Extensive 5G cell densification

(b) Presence of an EMF saturation zone

(c) EMF regulation based on a minimum distance

Fig. 1 Three situations where regulations on EMF limits impact the planning of 5G network infrastructure [4]

(*ii*) restrictive limits that are 10 times lower than the ICNIRP ones. The restrictive limits apply in fact to a vast portion of the national territory, including houses (including terraces and balconies), schools, and in general to buildings for human long-stay purposes. In addition, further regulations at local levels (see e.g., [31, 32]) establish minimum distances between BS sites and sensitive places (*e.g.*, schools or hospitals), as well as among base stations themselves. To cite an example, the city of Rome has a very stringent regulation, which adopts the national limits, plus a minimum distance of 100 [m] between a BS site and a sensitive place.

The current directives above jointly lead to a scenario where EMF limits risk to have a significant impact on the deployment of 5G radio access infrastructures. Indeed, EMF limits reduce the operators' flexibility in installing new base station sites in multiple ways. Three representative examples are outlined in Fig. 1. Fig. 1(a) illustrates the cell densification phenomenon: stringent EMF limits impose low radiation power at each antenna, which in turn forces a dense deployment of low-power sites, with a substantial increase in CAPEX for the operator. Fig. 1(b) shows a case where the 3G/4G sites serving the target region already saturate the EMF limits, hence the operator is forced to install 5G antennas in a new site, with increased CAPEX and reduced possibilities for network planning optimization. Fig. 1(c) recalls situations where a minimum distance must be respected between a new 5G site and a sensitive place, such as a school, again leading to sub-optimal network planning and possibly curbed Quality of Experience (QoE) by the mobile service end users.

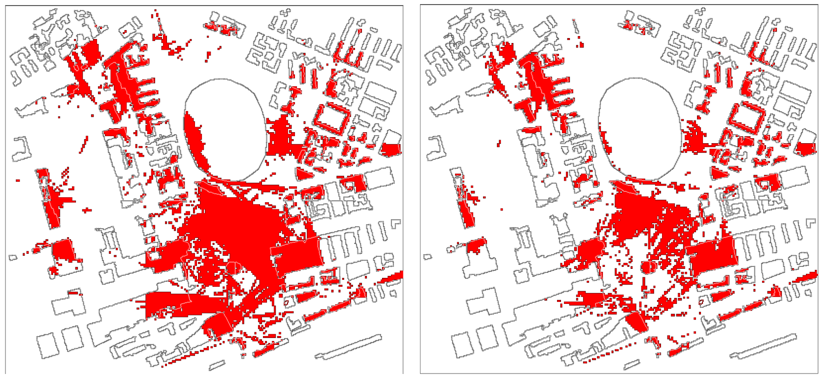
Those illustrated before are only a few, simple examples of the type of barriers that EMF limits may pose to the planning and deployment of next-generation cellular network radio access infrastructures. And, the presence of multiple competing operators will only exacerbate the problem, which thus exposes 5G systems, as well as the many and varied disruptive applications they are expected to enable, to serious risks of under-performance.

4 Case Studies

We present two case studies that provide insight on two complementary aspects of the impact of EMF limits on 5G network planning. In the first one we investigate the problem of EMF level saturation, an issue that can severely hamper the transition between pre-5G and 5G technologies. Then, we analyze the impact of restrictive EMF regulations on network planning and user QoS.

4.1 Evidence of EMF saturation

In the first considered case study we consider a 1100×1100 [m^2] zone in the Fuorigrotta district, Naples. The San Paolo stadium and several buildings of the Engineering School of the University of Naples Federico II are located in the area, which makes it a relevant test site, characterized by the presence of a huge number of users. Five known BS sites are present in this area, operated by two of the main Italian mobile operators, TIM and Wind Tre. Detailed information on the site configurations are reported in [4]. This information, along with a description of the scene in terms of

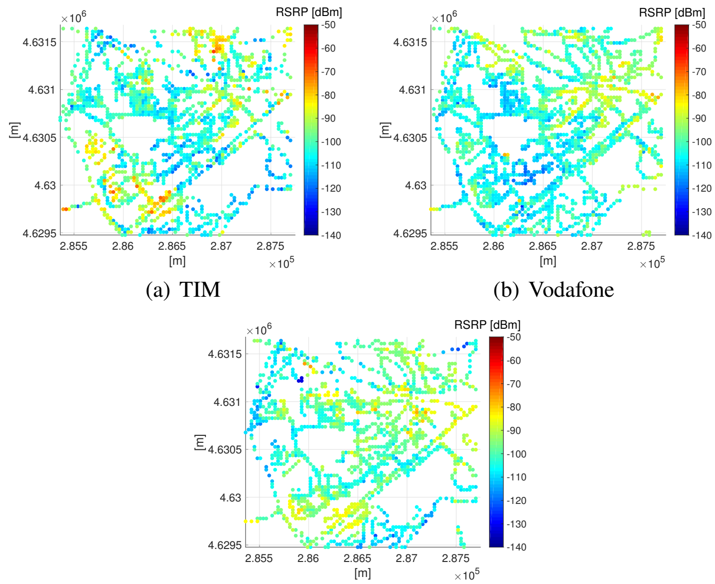


(a) 100% maximum input power (b) 75% maximum input power

Fig. 2 Impact of the maximum input power (Fuorigrotta case-study) [4].

a Digital Elevation Model and of a vector file providing description of the buildings, is used as input in a ray tracing simulator [33, 4]. Our purpose is to compare the overall EMF level produced by the antennas with Italian EMF limits: since the involved frequencies (lower than 3 GHz) share the same Italian general limit of 20 [V/m], the individual EMF intensities can be incoherently summed and a map of the overall EMF amplitude level can be obtained taking the square root of this summation. Once this map is available, it is possible to highlight those areas where EMF levels are higher than the allowed limits. In Fig. 2.a these areas are marked in red: actually, in most of the square located South of the stadium EMF levels are higher than 20 [V/m]. This result represents the worst-case scenario, obtained assuming that each antenna keeps radiating the maximum declared power during the whole measurement time, i.e. 6 minutes and 24 hours according to ICNIRP and Italian guidelines, respectively. This kind of approach is based on the fact that in principle no limit is imposed on mobile operators, which are authorized to constantly radiate the maximum declared power: note that this worst-case scenario approach is frequently assumed for EMF level evaluation [34, 35, 36]. Moreover, note that the measurement procedures used to verify the compliance of EMF levels not only change for different countries, but in a single country are likely to be revised, especially when 5G systems will begin to operate. In this situation, the proposed approach is useful to study EMF saturation regardless of the specific national laws. However, since the assumption that all the considered antennas constantly radiate the maximum power may be too strong, in Fig. 2.b we report the area where EMF limits are violated assuming that each antenna is radiating 75% of the maximum declared power: even in this case EMF limits are are exceeded in many parts of the scene.

The presented analysis confirms that EMF saturation may be a relevant issue for the deployment of future 5G sites, since in some scenario EMF values very close to the prescribed limits may have been reached by pre-5G networks. However, some of the new technologies associated to 5G networks, such as beamforming, may be used



(a) TIM (b) Vodafone

(c) Wind Tre

Fig. 3 RSRP metric (TMC case-study) [4].

to implement a smart planning of EMF levels over the area of interest, providing a potential way to limit the effects of EMF saturation. Some hints on this topic will be provided in Section 5.

4.2 Impact of EMF limits on planning and QoS

In this case study we focus on the area "Torrino-Mezzocammino" (TMC), Rome, Italy. It is a residential neighborhood, including commercial buildings, schools, public parks, with a population of more than 10000 people. In this area a local regulation dictates a minimum distance (100 [m]) between BS and "sensitive places", whose definition is referred to the municipality in accordance with the local population (e.g., highly frequented sport centers and commercial buildings have been marked as "sensitive"). In this situation, our aim is to investigate how local regulations impact on network planning and user QoS. In this analysis we used the CellMapper application [37] to measure relevant cellular network parameters, with associated geographic position data, while traveling along TMC area. Several interesting results were obtained from our analysis. First, thanks to CellMapper we identified the type of service offered by mobile operators in the TMC area: most of the area is served by a 4G LTE service, with some areas covered by LTE-Advanced and some other with a 3G HSPA+ service. As a further step, we provide an estimate of the

QoS based on the Reference Signal Received Power (RSRP) metric. In particular, thanks to CellMapper we are able to measure the RSRP of the current BS in the TMC area. Averaging the obtained values in 30x30 [m^2] cells allowed us to obtain a 30 [m] resolution RSRP map of the area of interest. This is done for each operator. Since there is a relantionship among the RSRP and the Signal to Noise Ratio (SNR) [38], this map can be considered as a good indicator of the quality of the radio link between the User Equipment (UE) and the BS. The RSRP maps obtained for the three operators are shown in Fig. 3, which testifies that some zones present values of RSRP lower than -110 [dBm], associated to a very low user QoS. This is confirmed by frequent drops of the radio link and difficulties in the access to internet services. Indeed, many of the areas experiencing good values of the RSRP are located in zones served by BSs installed outside the TMC area.

This case study demonstrates how an insufficient number of BS sites in the TMC area impacts both on the type of service provided by the operators and on the user QoS. Moreover, it shows how the coexistence of many heterogeneous regulations, not only at the international and national scales, but even at the local scale, severely hampers the deployment of 5G networks, limiting the possibility of developing general solutions to the planning problem.

5 Expected Impact of 5G Features on EMF

As indicated in [39], 5G will be characterized by a set of radically new technologies. In this Section, we analyze the main ones in term of relevance and expected impact on the EMF exposure levels compared to current deployed cellular networks. Clearly, the developed analysis is not exhaustive and it needs to be supported and verified via extensive EMF measurement campaigns.

Tab. 1 summarizes each 5G technology feature, as well as its relevance in terms of EMFs. To this aim, the utilization of massive MIMO antenna arrays is one of the recognized 5G features. In turn, this implies an increased number of antennas radiating power at each site. Although some recent works [40, 41] suggest that this 5G feature will impact positively on the EMF exposure levels, the reasonings in [40, 41] cannot be generalized. In fact, the MIMO impact highly depends on the selected configurations and on the adopted approach for measuring the EMF levels [34, 36]. As a consequence, the academic and industrial communities need to assess in the near future the potential MIMO gain in terms of EMF levels.

Beamforming constitutes another recognized 5G feature. It allows spatial selective communications, since the radiated power is concentrated into narrow and selected spatial directions. As a consequence, it is believed that, compared to current deployed BSs, beamforming will induce a general decrease of the EMF exposure levels. However, due to the power concentration into selected directions, there may be an increase of the EMF levels in the portions of the territory corresponding to these directions. Similarly, the exploitation in 5G networks of mmWave bands for directional communications may be beneficial for the EMF exposure levels. In fact, mmWave communications are characterized by higher path-losses compared to the current micro-waves communications. Hence, the received EMF may be lower compared to the one generated by currently deployed BSs. In this context, it is worthwhile to mention that 5G is envisioned to exploit different coexisting cell tiers with a dense deployment of small cells. Hence, it is expected a decrease of the EMF exposure levels compared to the current deployed BSs, due to the shorter BS-to-user distances. However, a possible increase of the EMF levels in proximity to the small cell may be also experienced when comparing to the current deployment. The EMF level decrease, promised by the small cell exploitation, is expected to be further enhanced by adopting offloading mechanisms, enabled by the unavoidable coverage overlapping among the different cell tiers. In fact, according to such mechanisms, the power radiated from the most loaded cells could be reduced by offloading the users to other cells in proximity to them.

Other key 5G technologies envisioned to decrease the EMF exposure levels are the softwarization and the Mobile Edge Computing (MEC). Specifically, on one hand with the softwarization, since different network functionalities, including most of the BS functionalities, will be realized at software level, it will be possible that multiple operators will share the same BS hardware. As a consequence, the number of antennas radiating power and installed in the same site will decrease with respect to the case in which each operator installs its own physical equipment in the shared site. On the other hand, with the MEC, cloud computing capabilities will be enabled at the edge of the network. By properly managing the content stored in the MEC platforms, it may be possible to decrease the amount of transferred data, thus decreasing the radiated power. However, this vision will be affected also on the type of service provided by MEC, which may include high data rate services as augmented reality. Similarly, the adoption of the Device-to-Device (D2D) paradigm in 5G networks is envisioned as a way to decrease the EMF exposure levels. In fact, with D2D a decrease in the amount of information exchanged between the UE and the BS will be expected. This in turn will reduce the amount of EMFs generated by the BS. In the same direction, advanced power saving techniques, including deep Sleep Modes (SMs), may be exploited in 5G networks. Specifically, SM-based techniques may reduce the amount of EMF exposure levels, since the BS that are not used are completely switched off (or in a low-power state). However, there could be an increase in the EMF levels in proximity 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, with the deployment of 5G networks, legacy 2G and 3G networks will be dismissed. Clearly, this will positively impact on the EMF exposure levels, especially in terms of reduction of the current EMF saturation levels in urban environments.

Clearly, the advantages and the disadvantages in terms of EMF exposure levels forecasted for the described 5G technologies need to be assessed against the aggregate radiation generated by the different BS layers operating with different access technologies, especially if legacy pre-5G networks already showed levels of EMF saturation, as revealed by our case-studies. Moreover, they need to be assessed against the dependence of the EMF exposure levels 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 [42].

Table 1 Expected Impact of the 5G Technology Features on the EMF levels [4].

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.

6 Conclusions and an outlook

In this work we focused on the planning of 5G networks under EMF exposure constraints. A detailed analysis of the state of the art regarding the EMF-related health risks, EMF measurement campaigns, and the impact of EMF limits on cellular network planning was presented. The effects of Italian EMF limits on cellular planning were considered and our observations were supported by two real-world Italian case studies. More in detail, these case studies provided evidences that: (i) the installation of 5G sites may be hampered by EMF saturation effects already observed in pre-5G sites; (ii) the sub-optimal planning due to the restrictive regulations on EMF exposure has a negative impact on the type of provided service as well as on the QoS perceived by the user. Finally, we analyzed the potential impact of the main 5G technologies on the EMF exposure levels. The presented analysis is not exhaustive and it needs to be verified and supported via extensive measurement campaigns. From the developed discussion, the complex nature of 5G planning under EMF constraints clearly emerges. However, this is a challenge that cannot be missed, if we want to avoid negative effects on the side of both the mobile operators (in terms of CAPEX increase) and the final users (in terms of perceived QoS).

References

1. *The 5G economy: How 5G technology will contribute to the global economy*. Available at https://cdn.ihs.com/www/pdf/IHS-Technology-5G-Economic-Impact-Study.pdf, last accessed on 7th Feb. 2018.
2. H. M. Madjar, "Human radio frequency exposure limits: An update of reference levels in Europe, USA, Canada, China, Japan and Korea," in *Proc. of EMC Europe, Wroclaw, Poland*, pp. 467–473, 2016.
3. *ITU-T K.Sup14 : The impact of RF-EMF exposure limits stricter than the ICNIRP or IEEE guidelines on 4G and 5G mobile network deployment*. Available at https://www.itu.int/rec/T-REC-K.Sup14-201805-I, last accessed on 25th July 2018.
4. L. Chiaraviglio, A. S. Cacciapuoti, G. di Martino, M. Fiore, M. Montesano, D. Trucchi, and N. Blefari-Melazzi, "Planning 5g networks under emf constraints: State of the art and vision," *IEEE Access*, 2018.
5. A. Ahlbom, U. Bergqvist, J. Bernhardt, J. Cesarini, M. Grandolfo, M. Hietanen, A. Mckinlay, M. Repacholi, D. Sliney, J. A. Stolwijk, M. L. Swicord, L. D. Szabo, M. Taki, T. S. Tenforde, H. P. Jammet, and R. Matthes, "Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz)," *Health physics*, vol. 74, no. 4, pp. 494–521, 1998.
6. A. Lahkola, A. Auvinen, J. Raitanen, M. J. Schoemaker, H. C. Christensen, M. Feychting, C. Johansen, L. Klæboe, S. Lönn, A. J. Swerdlow, *et al.*, "Mobile phone use and risk of glioma in 5 north european countries," *International journal of cancer*, vol. 120, no. 8, pp. 1769–1775, 2007.
7. I. S. Group, "Brain tumour risk in relation to mobile telephone use: results of the interphone international case–control study," *International journal of epidemiology*, vol. 39, no. 3, pp. 675–694, 2010.
8. *Interphone study reports on mobile phone use and brain cancer risk*. Available at https://www.iarc.fr/en/media-centre/pr/2010/pdfs/pr200_E.pdf, last accessed on 12th Nov. 2018.
9. L. Falcioni, L. Bua, E. Tibaldi, M. Lauriola, L. De Angelis, F. Gnudi, D. Mandrioli, M. Manservigi, F. Manservisi, I. Manzoli, I. Menghetti, S. Montella, R. Panzacchi, D. Sgargi, V. Strollo, V. A., and F. Belpoggi, "Report of final results regarding brain and heart tumors in Sprague-Dawley rats exposed from prenatal life until natural death to mobile phone radiofrequency field representative of a 1.8 GHz GSM base station environmental emission," *Environmental research*, vol. 165, pp. 496–503, 2018.
10. *National Toxicology Program releases final reports on rat and mouse studies of radio frequency radiation like that used in 2G and 3G cell phone technologies*. Available at https:

//www.niehs.nih.gov/news/newsroom/releases/2018/november1/index.cfm, last accessed on 2nd Nov. 2018.
11. M. E. Wyde, T. L. Horn, M. H. Capstick, J. M. Ladbury, G. Koepke, P. F. Wilson, G. E. Kissling, M. D. Stout, N. Kuster, R. L. Melnick, *et al.*, "Effect of cell phone radiofrequency radiation on body temperature in rodents: Pilot studies of the national toxicology program's reverberation chamber exposure system," *Bioelectromagnetics*, vol. 39, no. 3, pp. 190–199, 2018.
12. *IARC Classifies Radiofrequency Electromagnetic Fields as Possibly Carcinogenic to Humans*. Available at http://www.iarc.fr/en/media-centre/pr/2011/pdfs/pr208_E.pdf, last accessed on 29th Jan. 2018.
13. M. Koprivica, M. Petrić, M. Popović, J. Milinković, S. Nikšić, and A. Nešković, "Long-term variability of electromagnetic field strength for gsm 900mhz downlink band in belgrade urban area," in *Proc. of 22nd Telecommunications Forum Telfor (TELFOR), Belgrade, Serbia*, pp. 9–12, IEEE, 2014.
14. D. Urbinello, W. Joseph, A. Huss, L. Verloock, J. Beekhuizen, R. Vermeulen, L. Martens, and M. Röösli, "Radio-frequency electromagnetic field (rf-emf) exposure levels in different european outdoor urban environments in comparison with regulatory limits," *Environment international*, vol. 68, pp. 49–54, 2014.
15. Y. Huang, N. Varsier, S. Niksic, E. Kocan, M. Pejanovic-Djurisic, M. Popovic, M. Koprivica, A. Neskovic, J. Milinkovic, A. Gati, C. Person, and J. Wiart, "Comparison of average global exposure of population induced by a macro 3g network in different geographical areas in france and serbia," *Bioelectromagnetics*, vol. 37, no. 6, pp. 382–390, 2016.
16. R. Fernández-García and I. Gil, "Measurement of the environmental broadband electromagnetic waves in a mid-size european city," *Environmental research*, vol. 158, pp. 768–772, 2017.
17. A. Orłowski, R. Pawlak, A. Kalinowski, and A. Wójcik, "Assessment of human exposure to cellular networks electromagnetic fields," in *Proc. of 2018 Baltic URSI Symposium (URSI), Poznan, Poland*, pp. 1–4, IEEE, 2018.
18. 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," *Journal of Exposure Science and Environmental Epidemiology*, vol. 28, no. 2, p. 147, 2018.
19. W. Joseph, P. Frei, M. Roösli, G. Thuróczy, P. Gajsek, T. Trcek, J. Bolte, G. Vermeeren, E. Mohler, P. Juhasz, *et al.*, "Comparison of personal radio frequency electromagnetic field exposure in different urban areas across europe," *Environmental research*, vol. 110, no. 7, pp. 658–663, 2010.
20. P. Frei, E. Mohler, G. Neubauer, G. Theis, A. Bürgi, J. Fröhlich, C. Braun-Fahrländer, J. Bolte, M. Egger, and M. Röösli, "Temporal and spatial variability of personal exposure to radio frequency electromagnetic fields," *Environmental research*, vol. 109, no. 6, pp. 779–785, 2009.
21. K. Roser, A. Schoeni, B. Struchen, M. Zahner, M. Eeftens, J. Fröhlich, and M. Röösli, "Personal radiofrequency electromagnetic field exposure measurements in swiss adolescents," *Environment international*, vol. 99, pp. 303–314, 2017.
22. A. R. Mishra, *Fundamentals of cellular network planning and optimisation: 2G/2.5 G/3G... evolution to 4G*. John Wiley & Sons, 2004.
23. *MONICEM: monitoring and control activities relating to electromagnetic fields in the radio frequency (RF) range*. Available at http://www.isprambiente.gov.it/en/publications/reports/monicem-monitoring-and-control-activities-relating?set_language=en, last accessed on 23th July 2018.
24. *Forsk Atoll*. Available at http://www.forsk.com/atoll-overview, last accessed on 23th July 2018.
25. *Ranplan Wireless*. Available at https://ranplanwireless.com/, last accessed on 23th July 2018.
26. *InfoVista Planet 7*. Available at http://tiny.cc/bba0vy, last accessed on 23th July 2018.

27. *TEOCO Asset - Radio Planning*. Available at http://www.teoco.com/products/planning-optimization/asset-radio-planning/, last accessed on 23th July 2018.
28. *ATDI ICS TELECOM EV*. Available at http://www.atdi.com/ics-telecom/, last accessed on 12th November 2018.
29. *5GPPP Architecture Working Group – View on 5G Architecture Version 2.0*, Dec. 2017. Available at https://5g-ppp.eu/white-papers/, last accessed on 29th Jan. 2018.
30. *DECRETO 10 settembre 1998, n. 381 Regolamento recante norme per la determinazione dei tetti di radiofrequenza compatibili con la salute umana*. Available at http://www.gazzettaufficiale.it/eli/id/1998/11/03/098G0430/sg, last accessed on 29th Jan. 2018.
31. *Regolamento per la localizzazione, l'installazione e la modifica degli impianti di telefonia mobile, ai sensi dell'art. 8, comma 6, della legge n. 36 del 22 febbraio 2001 e per la redazione del Piano, ex art. 105, comma 4 delle NTA del PRG vigente, nonché per l'adozione di un sistema di monitoraggio delle sorgenti di campo elettrico, magnetico ed elettromagnetico.* Available at https://www.comune.roma.it/web-resources/cms/documents/DACDelib_N_26_14.05.2015.pdf, last accessed on 1st Nov. 2018.
32. *DELIBERAZIONE DELLA GIUNTA REGIONALE 5 settembre 2005, n.16-757*. Available at http://www.regione.piemonte.it/ambiente/elettromagnetismo/dwd/normativa/regionale/dgr_05_09_05.pdf, last accessed on 7th Nov. 2018.
33. G. Franceschetti, A. Iodice, D. Riccio, and G. Ruello, "A tool for planning electromagnetic field levels in urban areas," in *Proc. of IEEE Antennas and Propagation Society International Symposium, Monterey, California*, pp. 2211–2214, 2004.
34. B. Thors, A. Furuskär, D. Colombi, and C. Törnevik, "Time-Averaged Realistic Maximum Power Levels for the Assessment of Radio Frequency Exposure for 5G Radio Base Stations Using Massive MIMO," *IEEE Access*, vol. 5, pp. 19711–19719, 2017.
35. E. Degirmenci, B. Thors, and C. Törnevik, "Assessment of compliance with RF EMF exposure limits: Approximate methods for radio base station products utilizing array antennas with beam-forming capabilities," *IEEE Transactions on Electromagnetic Compatibility*, vol. 58, no. 4, pp. 1110–1117, 2016.
36. N. Perentos, S. Iskra, A. Faraone, R. J. McKenzie, G. Bit-Babik, and V. Anderson, "Exposure compliance methodologies for multiple input multiple output (MIMO) enabled networks and terminals," *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 2, pp. 644–653, 2012.
37. *CellMapper*. Available at https://www.cellmapper.net/, last accessed on 24th July 2018.
38. *3GPP TS 36.214 version 14.3.0 Release 14*. Available at https://www.etsi.org/deliver/etsi_ts/136200_136299/136214/14.03.00_60/ts_136214v140300p.pdf, last accessed on 24th July 2018.
39. J. G. Andrews, S. Buzzi, W. Choi, S. V. Hanly, A. Lozano, A. C. Soong, and J. C. Zhang, "What will 5G be?," *IEEE Journal on selected areas in communications*, vol. 32, no. 6, pp. 1065–1082, 2014.
40. B. Xu, M. Gustafsson, S. Shi, K. Zhao, Z. Ying, and S. He, "Radio frequency exposure compliance of multiple antennas for cellular equipment based on semidefinite relaxation," *IEEE Transactions on Electromagnetic Compatibility*, vol. on press, 2018.
41. B. Thors, D. Colombi, Z. Ying, T. Bolin, and C. Törnevik, "Exposure to RF EMF from array antennas in 5G mobile communication equipment," *IEEE Access*, vol. 4, pp. 7469–7478, 2016.
42. M. Tesanovic, E. Conil, A. D. Domenico, R. Aguero, F. Freudenstein, L. M. Correia, S. Bories, L. Martens, P. M. Wiedemann, and J. Wiart, "The lexnet project: Wireless networks and emf: Paving the way for low-emf networks of the future," *IEEE Vehicular Technology Magazine*, vol. 9, pp. 20–28, June 2014.