Do Dense 5G Networks Increase Exposure to Electromagnetic Fields?

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The debate over whether electromagnetic fields (EMFs) exposure poses a danger to human health is recurring and goes back centuries to when our society first began to rely on electricity [1]. The advent of wireless cellular networks, a few decades ago, further fueled such a controversy. Traditionally, citizens have complained against the installation of base station sites, especially when in close proximity to their homes, despite the fact that no clear causal correlation between legally compliant exposure levels from cellular towers and health diseases has been scientifically demonstrated to date [2].

Yet, that dispute has recently reached new heights with the ongoing deployment of 5G antennas in the era of social media. Online communities made up of avid opponents against 5G networks have appeared in several countries and, in some cases, have even been responsible for violent reactions, such as arson attacks on base station sites [3]. Why is it that the debate about the danger of 5G has so fiercely resumed? One important reason lies in the expected increase in the number of distributed (small) base station sites—almost a 10× factor in the next half a dozen years (see

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the predictions from wireless communications industry [4]).

On the one hand, *antenna densification* is a key step toward supporting new services that require huge throughput, very low latency, and effective coverage of high-density user areas, including residential districts, shopping malls, airports, train/bus stations, and so on. However, on the other hand, quoting one among the many *Stop-5G* sites [5], "5G requires significantly more cell towers, which will increase involuntary exposure to wireless radiation in our communities."

This allegation is supported by apparently straightforward and intuitive reasoning: each base station is a source of radiation; densification implies installing a huge number of base stations; therefore, dense 5G networks notably increase radiation over the territory. However, intuition eventually suggests that it should be quite the opposite! For an extreme analogy, when listening to music in a large park, would you really prefer to be in the vicinity of one large, extremely loud amplifier that is designed to cover the entire area, or rather walk through multiple small speakers scattered capillary throughout the park?

The goal of the article is to shed some light on this matter and show that the whole densification debate is ill-poised. We use very simple (but still quantitative) arguments—designed to be understandable also by the reader with basic knowledge of wireless networks. In the next sections, we will specifically address the following questions.

1) *Q1:* What is cellular densification and why is needed by 5G?
2) *Q2:* How does 5G densification change our understanding of exposure?
3) *Q3:* How does 5G densification affect exposure over the territory?
4) *Q4:* Which is the impact of 5G densification on exposure at selected locations (e.g., in close proximity to the base station and/or and at the cell edge)?
5) *Q5:* How does 5G densification affect exposure to the population?

The reader interested in more in-depth insights may refer to Section VI, which clarifies why antenna densification is also instrumental in reducing exposure from other 5G-specific features (such as mm-Wave frequencies, beamforming, and massive Internet-of-Things (IoT) device deployment) and how 5G densification is implemented in commercial networks. Moreover, we report in the Appendix a technical overview of our methodology, including a detailed description on how to reproduce our results.

I. WHAT IS CELLULAR DENSIFICATION AND WHY IS NEEDED BY 5G?

Network densification is realized through the capillary deployment of "small" base stations over the territory. This trend already emerged for 4G networks [6] (and, in particular, with the LTE-advanced technology)—in response to the rapid increase in the data traffic. The basic concept behind cellular densification is the reduction of the coverage area of each base station. In this way, user devices connected to the cellular network experience favorable propagation conditions (due to a limited distance from the base station)—often coupled with a line of sight conditions. In addition, the dense installation of base stations allows massively reusing the radio resources across the territory [7], thus providing better service—especially in densely populated zones. Due to densification, large throughput and low delays can be guaranteed, thus matching the stringent key performance indicators that are often required by the users' applications.

Not surprisingly, base station densification is a key aspect of 5G [8] and also for future wireless generations. The exploitation of higher frequencies (which inevitably increases the impact of propagation losses), coupled also with user device-centric functionalities (such as the dynamic beamforming), naturally requires a dense installation of 5G base stations. However, it is important to remark that most small cells deployed in the world are 4G LTE at the time of writing this article, and it will take some years for 5G small cells to outnumber those for 4G. In addition, we stress the fact that 5G densification will occur only at selected locations of the territory (e.g., the ones with stringent capacity and/or service quality constraints, such as a sports stadium with thousands of users online), while the majority of the territory will continue to be covered by sparse macrocells.

II. HOW DOES 5G DENSIFICATION CHANGE OUR UNDERSTANDING OF EXPOSURE?

Exposure from base stations is typically measured in terms of electric field strength, as users are normally subject to far-field conditions, and therefore, it is sufficient to measure the electric field intensity for a complete exposure characterization. Measurement tools—such as exposure meters and spectrum analyzers—often report the exposure in terms of power density and/or received power, which, however, can be easily transformed into electric field strength by applying fixed and known parameters [9].

In this context, there are some complications that may change our understanding of exposure from dense 5G networks. First, the adoption of "mm-Wave" frequencies is actually an option for the deployment of dense 5G networks [9], especially for very crowded environments, where it is critical to provide gigabits of data traffic to users. "mm-Wave" frequencies interact with the human body differently compared to lower frequencies [10] (mainly because they do not penetrate in depth in the exposed tissues, but they are rather absorbed at the skin level [11]). To this aim, we refer the interested reader to [12] and [13] for detailed evaluations

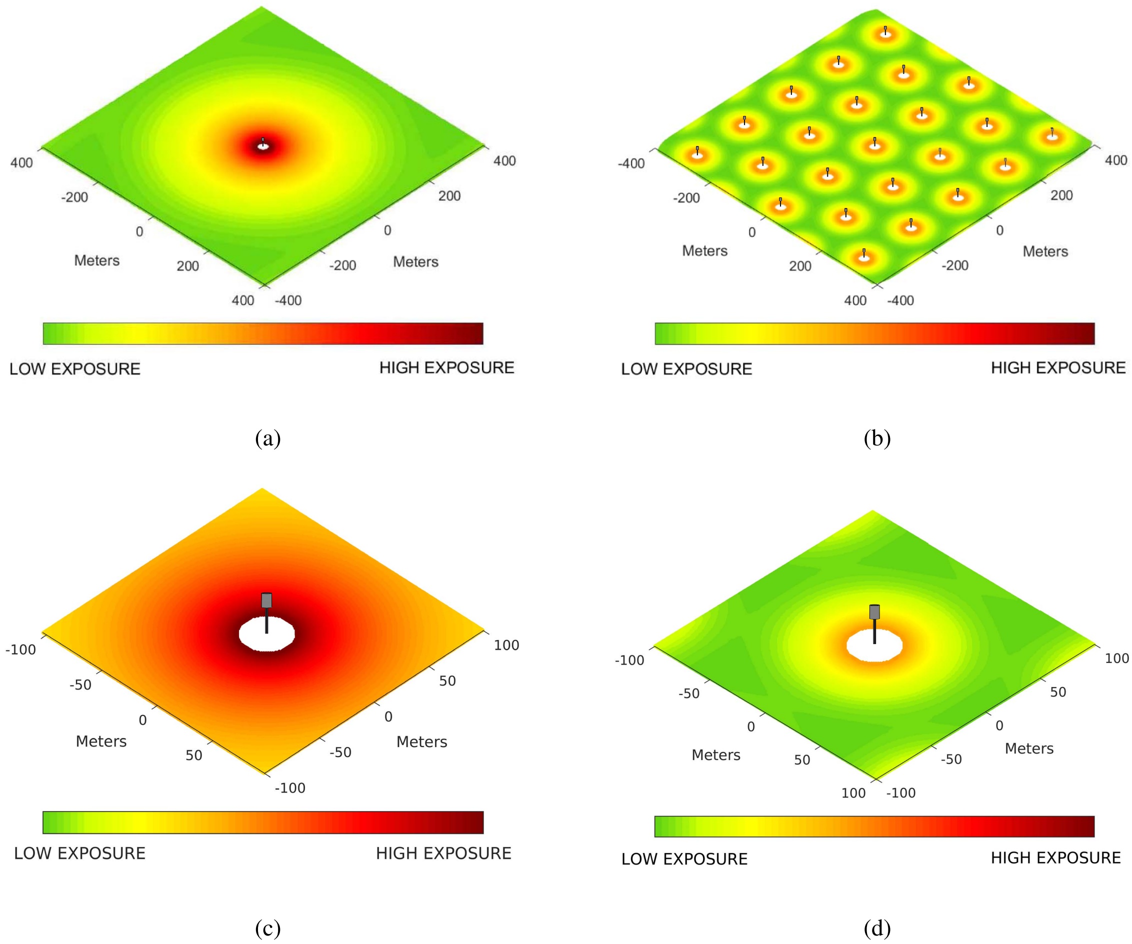

Fig. 1. ***Exposure levels in a sparse versus a dense 5G deployment: densification allows decreasing the level of exposure in proximity to the base stations (figure best viewed in colors). (a) Sparse deployment. (b) Dense deployment: 25× increase in the base stations. (c) Sparse deployment: zoom on one base station. (d) Dense deployment: zoom on one base station.***

of exposure generated by user equipment operating on mm-Wave.

Although heating effects may be observed over tissues/organs exposed to “mm-Wave” frequencies (with sufficiently high enough power), it is important to remark that international guidelines [14] define exposure limits that cover all the frequencies in use by cellular networks, including “mm-Wave” ones. Such limits are defined to prevent any harmful effect (such as heating) on the exposed tissues, as well as to minimize (possible) long-term health effects—still not known at present time. It is clear that the relative lack of well-done research studies focusing on the (possible) long-term health effects due to exposure from “mm-Wave” cellular equipment (both base stations and terminals) suggests that further efforts have to be done in the field [15]. However, we stress the fact that 5G deployments operating on “mm-Wave” frequencies are not so pervasively installed over the world, while most of 5G networks are currently adopting similar frequencies (and also similar exposure patterns) than the ones already in use by previous generations—for which different well-done research studies confirm that exposure below maximum limits is not harmful to health [9].

The second aspect that has to be taken into account when considering the exposure from dense 5G networks is the fact that 5G base stations tend to be composed of a large number of radiating elements, in order to realize massive multiple-input–multiple-output (MIMO) and beamforming functionalities. While the maximum radiated power of a 5G base station is comparable—if not higher—with respect to pre-5G base stations, the exposure directionality is increased [9]. This means that the exposure over the territory from a given base station may not always be uniform, but it may depend, e.g., on the orientation of the antenna elements and the actual synthesis of the traffic beams [9]. Consequently, some zones in the territory may receive exposure peaks, e.g., due to the simultaneous pointing of several beams over the same area, while other ones may be subject to a negligible amount of exposure. However, the latest revisions of the international regulations (see [14]) already take into account the intrinsic "instantaneous" nature of 5G exposure, by differentiating between "long-term" maximum limits that are applied over minutes/hours averages and "short-term" limits that are applied over shorter time scales.

The third aspect related to 5G densification is the fact that, in different countries in the world, exposure regulations stricter than international guidelines are enforced [9]. The rationale of such regulations is to introduce an additional level of precaution, by typically imposing limits that are lower than the ones defined in the international guidelines and/or minimum distances between the installed and specific areas (such as schools, public parks, hospitals, and even residential areas). However, there is actually a debate about the meaningfulness of such regulations. By imposing strict regulations, in fact, the pervasive installation of base stations over the territory may be impaired [16], which may, in turn, result in coverage holes without any 5G signal and/or increased exposure from the user devices. As a result, some countries (such as Poland and Lithuania) have recently harmonized their previously strict exposure limits to the ones reported in the international guidelines [9].

III. HOW DOES 5G DENSIFICATION AFFECT THE EXPOSURE OVER THE TERRITORY?

We tackle this important question by visualizing (and explaining) the exposure levels over one representative area. To this aim, Fig. 1 highlights the exposure at ground level for different 5G densification options. In more detail, Fig. 1(a) shows a sparse 5G deployment, in which the central base station has a circular coverage area of radius 500 m. On the contrary, Fig. 1(b) shows a dense 5G deployment, in which the number of base stations is increased by a factor of 25 than the previous case, *and* at the same time, the coverage of each base station is shrunk to a circular area of radius 100 m. In this way, each portion of the territory is served by the cellular network, while the zones with overlapping coverage (i.e., multiple base stations covering the same area) are always limited. The colors in Fig. 1 are proportional to the exposure level: red and orange for high exposure values, yellow for intermediate exposure levels, and, finally, green for low exposure values. The same exposure scale is used across all the subfigures in Fig. 1.

When the sparse 5G deployment is considered [see Fig. 1(a)], high levels of exposure are achieved in a wide area surrounding the central base station, as marked by orange and red colors. On the contrary, the exposure tends to decrease when the distance from the base station is increased, as highlighted by the green areas toward the border of the area. This effect is triggered by the signal propagation across the air medium, which introduces a decrease in the exposure—proportional to the distance from the base station.

We then repeat the same analysis for the dense deployment, as shown in Fig. 1(b). In this case, despite the increase in the number of base stations, the red and orange zones almost disappear. In simple terms, the more base stations are deployed over the territory, the narrower is the base station coverage, and therefore, the lower is the power radiated by each base station. Consequently, the reduction of exposure around each base station is a direct effect of densification—an aspect often overlooked by the skeptic of 5G.

Let us provide more technical explanations about the aforementioned effect. In principle, the power radiated by each base station is influenced by the size of the area covered by the cell, and therefore, it is not a fixed parameter. It is clear that the power has to be tuned to serve all users in the covered area, including those ones at the cell edge, which generally experiences the highest signal degradation (due to the large distance from the base station) and, consequently, the lowest amount of received power. In general, the amount of base station power that is received by a smartphone has to be higher than a minimum value—often called "sensitivity threshold" [17]. In a dense 5G network, the coverage area of each base station is rather small, and therefore, a limited amount of power is radiated by the base station to guarantee minimum sensitivity for the smartphones at the cell edge. On the contrary, when a sparse deployment is assumed, the coverage area of each base station is pretty large, thus resulting in a huge amount of radiated power to satisfy the sensitivity constraint for the (distant) smartphones.

Up to this point, a natural question can be: why does the base station tune power rather than always radiating at a maximum value? To answer this question, we need to remind that the power in the air should be not excessive, in order to avoid radiation beyond the cell edge and, consequently, interference with the neighboring cells—a major goal pursued by operators to guarantee performance for users. Therefore, the radiated power scales with the size of the area covered by the base station. This effect is evident when we consider a zoom of 100×100 m^2 around one base station, as shown in Fig. 1(c) and (d). In proximity to the base station, a huge decrease in the exposure is experienced in the dense case [see Fig. 1(d)] with respect to the sparse one [see Fig. 1(c)].

However, the skeptic of densification may still raise two objections: 1) we are not quantifying the variation of exposure in specific locations (e.g., at the cell edge and/or close to the base station) and 2) we are not providing any insight about the actual exposure levels on the population. The following sections aim at providing comprehensive answers to such concerns.

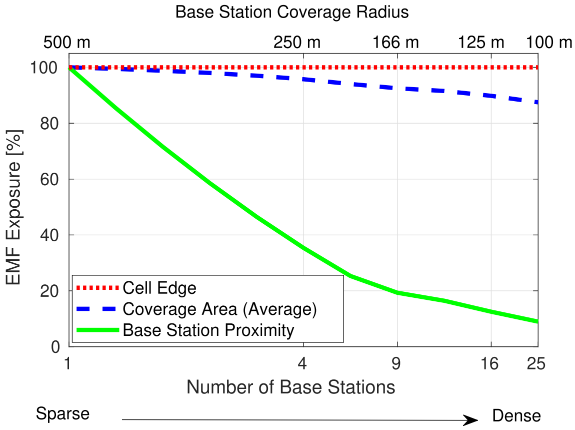

Fig. 2. *Exposure (in percentage) for different numbers of base stations. The exposure evaluation is done: 1) at the cell edge; 2) at base station proximity; and 3) over the whole coverage area (average value). In all cases, densification does not increase the level of exposure.*

IV. WHICH IS THE IMPACT ON THE EXPOSURE AT SELECTED LOCATIONS?

The goal of this step is to quantify the level of exposure in specific zones of the territory. In particular, we focus on the following exposure conditions: 1) base station proximity, i.e., at a distance of around 20 m; 2) cell edge, i.e., at the border of the area covered by the base station; and 3) inside the whole area covered by the cell, i.e., at intermediate distances between the previous two cases.

Fig. 2 reports the exposure (in percentage), for different number of deployed base stations over the same area (bottom x-axis), and different coverage radii for each base station (top x-axis). For each exposure condition (i.e., base station proximity, cell edge, and whole area), we compute the ratio between the exposure with a given number of base stations (from 1 to 25) and the reference case with one base station. This number, which ranges between zero and one, is then multiplied by 100 in order to get an exposure percentage—reported in the figure on the vertical axis.

By observing, in more detail, Fig. 2, we can note that the exposure percentage abruptly decreases in proximity to the base stations when the number of base stations is increased (green line, left to right parts of the figure). In particular, when 25 base stations are deployed in the same territory, the exposure at the base station proximity is reduced by more than 90% with respect to the sparse case with one single base station. Again, we remind that such an effect is triggered by the reduction of the base station radiated power due to densification.

We then move our attention to the exposure percentage at the cell edge (red dotted line in Fig. 2). Since the line is always horizontal, we can conclude that there is no significant variation in the exposure. This is an expected outcome because the power of each base station is tuned to always guarantee a minimum amount of received power at the cell edge—in order to limit the interference with the neighboring cells. Therefore, the exposure conditions do not significantly vary w.r.t. densification levels for the locations at the cell edge.

Eventually, the blue dashed line in Fig. 2 reports the average exposure percentage that is observed over the whole coverage area of each base station. This time, the line presents a decreasing trend, meaning that densification is able to reduce the average exposure levels over the territory. In particular, when 25 base stations are deployed, the average exposure is decreased by more than 10% with respect to the sparse deployment with one single base station.

Finally, Fig. 3 quantifies the exposure levels in terms of EMF strength for different exposure evaluation distances from the base station. Distance 0% corresponds to locations very close to base stations (i.e., around 20 m), while distance 100% denotes locations at the cell edge. It is obvious that the exposure abruptly decreases when the evaluation distance is increased due to the already mentioned degradation effects that are introduced by signal propagation over the air medium. However, 5G densification strongly contributes to further reducing the exposure levels. In particular, when the number of deployed base stations is increased, a huge decrease in the exposure is observed for all locations at distance up to around 50% from the base station, while, for higher distances, the exposure does not substantially change when densification is increased.

V. HOW DOES 5G DENSIFICATION AFFECT EXPOSURE TO THE POPULATION?

Up to this point, we have shown the exposure benefits of densification at specific locations. However, we need to close the loop and demonstrate that 5G densification is beneficial for population exposure. To this aim: 1) we conservatively impose a uniform distribution of people over the territory and 2) we compute the exposure levels for each person under different densification levels. Fig. 4 reports the observed EMF levels for different percentages of the population. Interestingly, the exposure levels from base stations are negligible (less than 0.2 V/m) for 90% of people, as highlighted in the upper left part of the figure. Therefore, densification does not substantially affect the level of exposure for the majority of the population. On the contrary, 10% of people experience a huge decrease

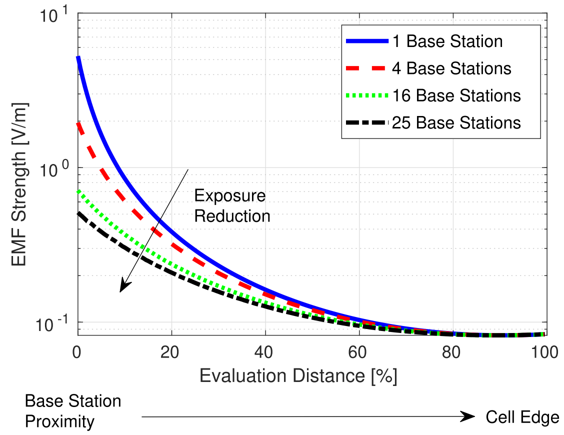

Fig. 3. ***Impact of densification on the exposure for different evaluation distances from the base station. The increase in the number of base stations allows decreasing the exposure up to around 50% of distance from the base station.***

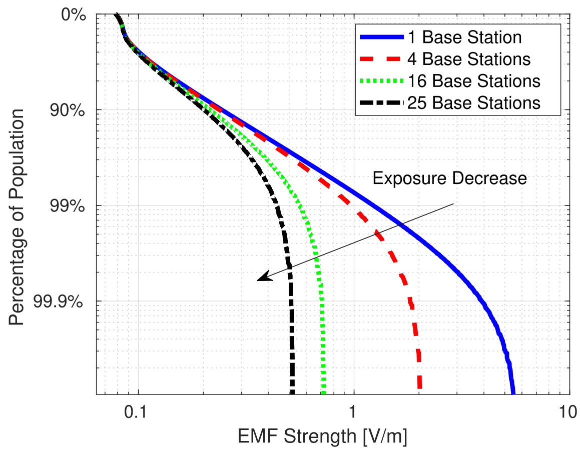

Fig. 4. ***Percentage of population that receives (at most) a given EMF strength value. Densification does not impact the level of exposure for around 90% of the population. However, a huge decrease in the exposure is experienced by the remaining 10%, i.e., those ones living close to base stations.***

in exposure when densification is applied (central and lower part of the figure). This is again an expected outcome, as we have previously demonstrated that the strongest exposure reduction is observed at base station proximity, where such people are located. In addition, the increase in the slope in the exposure curves (bottom part of the figure, right to left) indicates that 5G densification contributes to *democratizing* the exposure conditions, i.e., achieving uniform and low radiation levels over the population.

VI. DISCUSSION

Despite the reduction (or not variation) in radiation that densification can offer, other orthogonal 5G features, such as mm-Wave frequencies, beamforming, and connection of millions of devices per cell, may actually impact the exposure levels presented so far. Hereafter, we discuss why and how such features may actually benefit from densification in further reducing the overall exposure levels. In addition, we shed light on how densification is managed in commercial deployments.

A. Impact of mm-Wave Frequencies

As already introduced earlier in the text, the exploitation of "mm-Wave" frequencies is another big pillar of 5G and one point of discontinuity compared to previous generations. More technically, the frequencies in use by 5G include those ones already close to 4G, typically below 6 GHz and, therefore, denoted as "sub-6 GHz," as well as higher frequencies in proximity to 30 GHz, a.k.a. "mm-Wave." The outcomes presented so far refer to the sub-6-GHz frequencies of 5G. However, when considering mm-Wave frequencies, the degradation of the signal due to propagation effects is stronger than the one observed for frequencies below 6 GHz mainly due to larger propagation losses for non-line-of-sight users and lower penetration capabilities inside buildings [18]. Therefore, it is more challenging to guarantee the minimum sensitivity threshold at the cell edge. As a result, more power has to be radiated in air than the sub-6-GHz case. In this scenario, densification is instrumental in reducing the area that needs to be covered by each base station and, consequently, in limiting the amount of radiated power. In particular, the benefits observed so far with sub-6-GHz frequencies are amplified for the mm-Wave case (due to the increase in the propagation loss at higher frequencies), thus suggesting that base stations with mm-Wave should always operate in a dense deployment.

B. Impact of Beamforming

Another big improvement made available by 5G is the already mentioned beamforming functionality. Rather than hosting a single antenna, a beamforming-based 5G base station is composed of a huge number of radiating elements, able to focus the power into a set of narrow beams. Technically speaking, a cellular architecture based on beamforming allows increasing the user performance, due to many reasons, which include (just to mention a few) increased reuse of radio resources, improved spatial multiplexing, and interference suppression. In our evaluations, we have considered a static case, in which all the beams are simultaneously activated at the same time to cover the whole covered area. However, more dynamic options, which include, e.g., temporal variation of pointing and amplitude of each beam to track the users, may be available with 5G [19]. In all cases, however, densification is useful in limiting the distance between the base station and the user and, consequently, in reducing the amount of power that is radiated by the beams.

C. Impact of Connecting Millions of Devices per Cell

The third big pillar of 5G is the possibility of connecting millions of devices per cell, which are not limited to smartphones but also include the Internet-of-Things sensors/actuators, autonomous vehicles, medical equipment, and many others. It is clear that this step will naturally introduce an increase in the exposure from the devices themselves. However, network densification is instrumental in reducing the signal degradation on the inverse link from the device to the base station and, consequently, in limiting the amount of exposure that is generated by such devices toward the end users. More technically, the better coverage provided by dense networks results in lower uplink power from the devices (a.k.a. adaptive power control), in exchange for higher downlink signals from the base stations. Since the major exposure to the user is from the devices in its close proximity (and not the base stations) [2], this results in a net reduction of exposure brought by densification. Consequently, the more base stations are installed over the territory; the lower is, in general, the radiation from the devices that are experienced by users.

D. Densification in Commercial Deployments

Compared to an ideal scenario—such as the one considered in this work—the operators face multiple constraints over the territory, which include, e.g., a suboptimal placing of 5G base stations with respect to the optimal one (due to the fact that not all base stations can be placed in the desired locations). In particular, the base station positioning may follow an irregular pattern, in which also the coverage area of each base station is not as regular as the one in Fig. 1. However, even in this case, the coverage of each base station is reduced on average as the network is densified, and hence, similar observations, such as the one reported in our work, generally hold.

In addition, any commercial 5G dense deployment has to coexist with base stations implementing other technologies (e.g., 4G)—which may be colocated or not over the same sites hosting 5G base stations—and base stations owned by other operators simultaneously covering the same area. In this case, the composite exposure resulting from all the base stations in the territory has to be always ensured below the maximum limits enforced by laws.

Moreover, a cellular operator may impose other power setting policies than the sensitivity-based one reported in this work. For example, specific signals (such as the ones used as reference/synchronization) may be always transmitted at peak power levels, but, however, the exposure from those signals typically represents a small fraction over the total exposure radiated by the base station.

Finally, specific groups of people may still receive a higher amount of exposure from a dense 5G deployment with respect to a sparse one. For example, cellphone providers may install small cells on utility poles close to buildings, and therefore, people working/living in close proximity to the small cells may receive exposure levels that exceed those from macrocells. Nevertheless, the levels of exposure at distances beyond the compliance distance (e.g., around a meter from a small cell) will be far below accepted safety limits. It is clear that the peak exposure to any member of the population should be always considered.

VII. CONCLUSION

Network densification is a key feature of 5G. In our work, we have provided evidence that 5G densification does not increase the level of exposure, in contrast to a very popular belief. On the contrary, antenna densification does not change the exposure levels for the majority of the population, while, at base station proximity, a huge radiation decrease is experienced when more base stations are deployed in the same territory. Moreover, the increase in the number of base stations helps in reducing the exposure from other relevant 5G features, such as mm-Wave frequencies, beamforming, and connection of millions of devices per cell.

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