Radiation Analysis in a Gradual 5G Network Deployment Strategy

Conference Paper · September 2020

DOI: 10.1109/5GWF49715.2020.9221314

2 authors:


Ahmad El Hajj
Beirut Arab University


Tarek Naous
American University of Beirut

Radiation Analysis in a Gradual 5G Network Deployment Strategy

Ahmad M. El-Hajj
Electrical & Computer Eng. Department
Beirut Arab University
Beirut, Lebanon
a.elhajj@bau.edu.lb

Tarek Naous
Electrical & Computer Eng. Department
Beirut Arab University
Beirut, Lebanon
tareknaous@ieee.org

***Abstract*—In a world where many overlapping 2G, 3G, and 4G electromagnetic radiation sources already exist, concerns regarding the potential increase in these radiation levels following the roll-out of 5G networks are growing. The deployment of 5G is expected to increase power density levels drastically, given the limitations of mmWave communications that impose a notably higher number of base stations to cover a given area of interest. In this paper, we propose a gradual deployment strategy of a 5G network for a small area in downtown Austin, Texas, using the already existing 4G LTE sites of the area. The radiated power density of the proposed 5G network is then analyzed according to several electromagnetic field (EMF) exposure limits and compared to the radiation levels of the same area where only the LTE network is present. Simulation results for the selected area demonstrate the significant increase in radiation levels resulting from the addition of 5G cell towers.**

***Index Terms*—5G, Network Planning, Radiation Analysis**

I. Introduction

The notably large bandwidth available in the millimeter-wave (mmWave) band and the potential multi-gigabit-per-second (Gbps) data rates that can be achieved for future communication services have made mmWave communications a key part of Fifth Generation (5G) mobile networks. Despite the promising advantages of millimeter wave communications in terms of improved quality of service requirements, its usage for the 5G wireless standards comes at significant costs. First, working with such high frequencies will reduce coverage ranges of base transceiver stations (BTS). For proper coverage of an area, a densification of 5G BTSs is required to achieve the same coverage provided for this same area by today's 4G BTSs. Also, high propagation loss and increased signal blockage occurs, motivating the introduction of multi-antenna approaches such as Massive MIMO [1], [2].

This potential addition of a large number of transmitters gives rise to another problem that needs to be considered, which is the increase in radiation levels in the rolled-out 5G network. Although these transmissions are non-ionizing radiations, they cause thermal heating at the eyes and skin level. Extensive heating for long periods of time is when adverse health effects may occur. These health concerns have stimulated interest in the biological safety of mmWave transmissions. In this respect, several exposure limits have been specified in standards and regulations developed by commissions and organizations that many governments will rely on when future 5G networks are deployed. However, these regulations have contradicting limits, many of which have remained the same before the year 2000. Therefore, designing a 5G network with radiation levels that complies with all the safety limits is a difficult task given the current regulations.

Despite the ongoing standardization of 5G technology, several works in the literature have presented 5G network deployment studies. The cost and coverage implications of deploying a 5G network in Britain has been presented in [3] where it was shown that full coverage had exponentially rising costs due to network densification. Additional 5G network designs for different cities were presented in [4]–[6] without any consideration for the constraints of electromagnetic radiations or the implications of the environment in mmWave propagation. Network design has been studied under such radiation constraints in [7], [8] but for 4G networks. Power density assessment of 5G cellular nodes in an indoor environment has been presented in [9] where results showed that the peak power density remained below the specified threshold and can thus be deemed safe for the general public. However, not all of the guidelines and exposure limits were considered in this work and the simulation did not represent a real-world scenario.

To the best of our knowledge, no work has provided a thorough analysis of the deployment of 5G networks in terms of its impact on the increase in radiation levels. Existing work in the literature has either focused on the cost (e.g., [3]) or radiation levels for older standards (e.g., [7]). To this end, this paper presents a mmWave-based 5G network deployment strategy given pre-existing LTE nodes in a small geographical area in Austin, Texas. We then approximate the power density levels that would be experienced in such outdoor environments and analyze their variations and compliance with the specified exposure limits for different transmission powers and transmit antenna gains. We also compare this radiated power density in the deployed 5G network to the power density levels of the same area when only the pre-existing LTE BTSs are present.

The rest of this paper is organized as follows: Section II presents the 5G simulation environment considered in this work. The proposed deployment strategy of the 5G network in a small area in downtown Austin, Texas is presented in Section III. Radiation analysis of the deployed network is performed in Section IV. Concluding remarks follow in Section V.

II. 5G Environment Setup

A. Pathloss Model

The close-in free space reference distance (CI) path loss model [10] is considered. It is defined by the following equation:

$$PL^{CI}(f,d)[\text{dB}] = FSPL(f,1m) + 10n\log_{10}\left(\frac{d}{d_0}\right) + X_\sigma^{CI} \quad (1)$$

where the free space path loss (FSPL) for a frequency of operation f is given by:

$$FSPL(f,1m) = 20\log_{10}\left(\frac{4\pi f}{c}\right) \quad (2)$$

The CI path loss model can be rewritten as:

$$PL^{CI}(f,d)[\text{dB}] = 20\log_{10}\left(\frac{4\pi f}{c}\right) + 10n\log_{10}\left(\frac{d}{d_0}\right) + X_\sigma^{CI} \quad (3)$$

where:

- n: is the single model parameter or the path loss exponent
- d_0**:** is the reference distance taken as 1 meter
- d: is the distance in meters between the BTS and the mobile station
- X_σ^{CI}: a zero mean Gaussian random variable with standard deviation σ in dB. It represents large scale channel fluctuations due to shadow fading (SF). The standard deviation of this random variable is given by:

$$\begin{aligned}\sigma^{CI} &= \sqrt{\sum X_\sigma^{CI^2}/N} \\ &= \sqrt{(PL^{CI} - FSPL - n10\log_{10}(d))/N}\end{aligned} \quad (4)$$

where N represents the number of measured path loss data points

The values for parameters n and SF vary from one scenario to another. Table I presents the values of these model parameters in different environmental setups, which have been obtained by ray tracing and measurements in [11].

TABLE I: CI Model parameters for different environments [12]

Scenario	CI Model Parameters
UMa-LOS	n = 2.0, SF = 4.1 dB
UMa-NLOS	n = 3.0, SF = 6.8 dB
UMi-S.C.-LOS	n = 1.98, SF = 3.1 dB
UMi-S.C.-NLOS	n = 3.19, SF = 8.2 dB
UMi-O.S.-LOS	n = 1.85, SF = 4.2 dB
UMi-O.S.-NLOS	n = 2.89, SF = 7.1 dB

UMa: denotes Urban Macrocell (Tx Heights $>$ 25 m), **UMi:** denotes Urban Microcell (Tx Heights $<$ 25 m), **LOS:** denotes line-of-sight, **NLOS:** denotes no line-of-sight, **S.C.:** denotes Street Canyon, **O.C.:** denotes Open Square

B. mmWave Specific Attenuation Factors

In mmWave propagation, attenuation due to atmospheric and weather conditions constitutes an important factor to consider [13]. Specifically, we will consider oxygen attenuation $O(d)$ and rain attenuation $R(d)$, which are both dependant on the separation distance d. Oxygen attenuation has been observed to be equal 16dB/km in [14], and hence can be obtained by the following:

$$O(d)[\text{dB}] = \frac{16d}{1000} = 0.016d \quad (5)$$

The rain attenuation factor depends on the climate of the zone under study. The International Telecommunication Union (ITU) have segmented these zones and provide measurements for the rain rates of each zone [15]. Based on these measurements and considering that the area under study in this paper will be in Austin, Texas, the rain attenuation rate will be taken to be 3.5 dB/Km. This loss can then be obtained using:

$$R(d)[\text{dB}] = \frac{3.5d}{1000} = 0.0035d \quad (6)$$

C. Link Budget Estimation

The link budget equation upon which the cell radius will be estimated can now be defined as:

$$P_{Rx}[\text{dBm}] = EIRP[\text{dBm}] - PL^{CI} - O(d) - R(d) + G_{Rx} \quad (7)$$

where P_{Rx} is the power received by the mobile station, G_{Rx} is the antenna gain in dBi of the mobile station, and the effective isotropic radiated power (EIRP) is given by:

$$EIRP[\text{dBm}] = P_{Tx} + G_{Tx} - L_{Tx} \quad (8)$$

where P_{Tx} is the transmission power in dBm of the BTS, G_{Tx} is the transmitting antenna gain in dBi, and L_{Tx} is the cable loss in dB due to possible antenna mismatch. Table II lists the values chosen for each parameter of the link budget equation.

TABLE II: Simulation Parameters

Parameter	Value
Frequency f	28 GHz
Max EIRP	43 dBm
Antenna Gain G_{Tx}	24 dBi
Transmission Power P_{Tx}	19 dBm
Receiver Antenna Gain G_{Rx}	0 dBi
Cable Losses L_{Tx}	0 dB

D. Identifying Cell Ranges

By using the link budget equation in (7) and considering the simulation parameters given in Table II, the separation distance can be found for several receiver sensitivities. The calculated distance constitutes the cell range for a given BTS that satisfies the received power requirement. These calculations are summarized in Table III. A main observation is that the resulting cell ranges become significantly smaller when the receiver sensitivity is higher. Cell ranges that are too small (below 10 meters) are not considered since such small ranges are not desirable for real deployment.

III. Network Deployment

We now consider a small geographical area in downtown Austin, Texas, to deploy the 5G network. A diagrammatic view of our proposed strategy is shown in Fig. 1. The selected area is shown in Fig. 2(a) and delimited in red on the map of Fig. 2(b). This area already contains several locations where LTE sites are already built and which will be the starting points of the gradual 5G network deployment strategy. The initial LTE cell tower locations are obtained from an online cell tower database (www.opencellid.org). We consider a worst case scenario where no line-of-sight components are available.

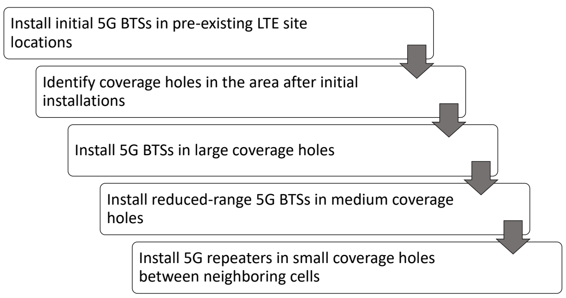
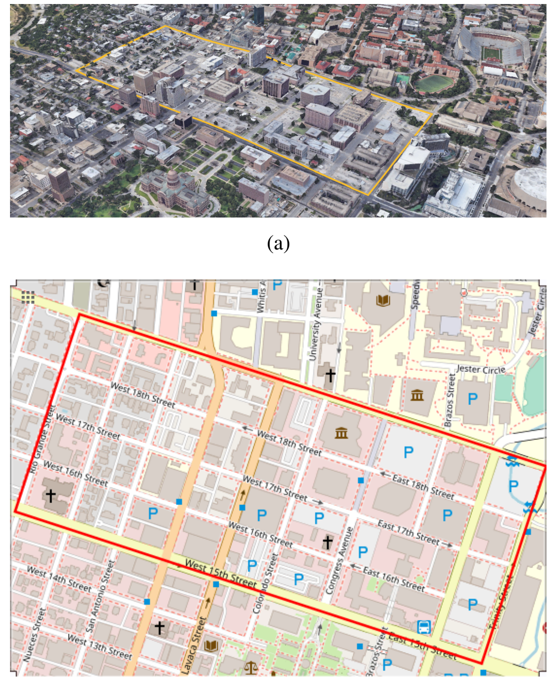


Fig. 1: Gradual Deployment Strategy

The first step of deployment starts by building 5G BTSs in the areas where LTE BTSs already exist, a technique known as co-siting. The main aim of co-siting is to reduce capital expenditures (CapEx) required to erect the 5G sites and minimize the operational expenditures (OpEx) needed to sustain their operation. UMa-NLOS towers will be placed in these locations. The receiver sensitivity is considered to be -78 dBm which, according to Table III, sets the cell range of each UMa to be 53 meters. The coverage of the initial BTSs installed is shown in Fig. 3, after slightly changing the location of the BTS within the same area it is built on, which may be any building rooftop, to lessen interference and provide better coverage. It can be noticed that these initial cells do not provide coverage to the whole area due to the small cell range of each BTS. Theoretically, this range can be increased but would demand the EIRP to be increased above the allowed limit of 43 dBm, by increasing the transmission power and selecting a higher-gain massive MIMO antenna configuration

The next step is the identification of coverage holes, as shown in Fig. 4. Large coverage holes are can be noticed, where several UMa towers can be distributed to provide good coverage. Smaller coverage hole are also be identified. Some of these holes are very small areas between neighboring cells where 5G repeaters, such as the one described in [16], can be placed to cover these small holes. Other small holes are not small enough to be fixed merely by the placement of a repeater, and are neither too big to place a BTS with a cell range of 53 meters. In such locations, reduced-range towers can be placed to provide coverage. The coverage range for these towers can be shrinked by reducing transmission power and choosing smaller MIMO antennas. We calculate the cell range for the reduced-range BTS towers to be approximately 30 meters and estimate the coverage of the 5G repeater to be 15 meters. The final design of the deployed 5G network is shown in Fig. 5. It can be observed that the deployment of a 5G network in an area as small as the one presented requires a densification of cell towers and signal repeaters, which in turn will cause much more radiation.



(a)

(b)

Fig. 2: Geographical area of interest in Austin, Texas (a) Satellite View (b) Map View

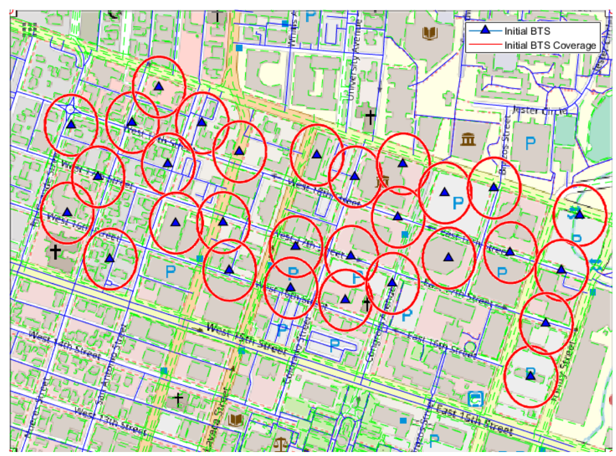


Fig. 3: Coverage of initial 5G BTSs built at the locations of pre-existing LTE cell towers

TABLE III: Calculated Cell Ranges for Several Receiver Sensitivities in Various Environments

	Cell Range (meters) for EIRP = 43 dBm					
Receiver Sensitivity	**UMa-LOS**	**UMa-NLOS**	**UMi-S.C.-LOS**	**UMi-S.C.-NLOS**	**UMi-O.S.-LOS**	**UMi-O.S.-NLOS**
-78 dBm	302	53	334	38.5	385	60
-70 dBm	165	29.7	186	22.3	216	33
-65 dBm	105.5	22	120	15.7	139	22.5
-60 dBm	65	14.1	74.5	11	85	15.3
-55 dBm	38.5	×	44.5	×	55	×
-50 dBm	22.6	×	26	×	27	×
-47 dBm	16.2	×	18.6	×	20	×

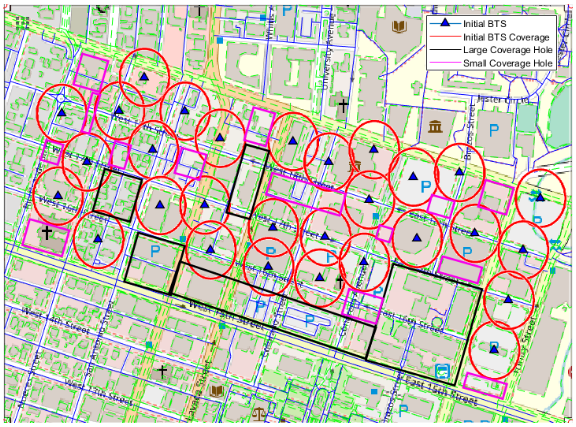


Fig. 4: Coverage holes identified after initial BTS installations

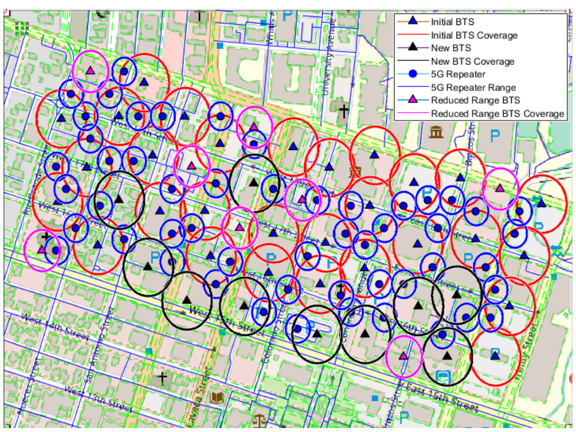


Fig. 5: Deployed 5G Network

IV. Radiation Analysis

A. Exposure Limits

Although mmWave radiation is non-ionizing, the absorption of mmWave energy in the human body causes heating to the skin and eyes. This has caused serious concerns in terms of potential health risks that might come along with the introduction of 5G networks [17]. For this reason, before introducing mmWave devices into the market, they need to comply to several exposure limits that have been specified in several standards and specifications. The specific absorption rate (SAR) has often been used as the metric to determine exposure compliance. The SAR measures the amount of energy absorbed by the human body while using a mobile phone. However, at high frequencies, this absorption is restricted to the skin level and thus it would be difficult to use the SAR as a measure for exposure limits at mmWave frequencies. The power density (P_D) measured in W/m^2 has been the preferred metric in the mmWave domain.

For the frequency range of 2 to 300 GHz, the IEEE C95.1-2019 standard [18] specifies a limit power density value of 10 W/m^2 in restricted environment and 50 W/m^2 in unrestricted environments. These correspond to an averaging time of 30 minutes. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) 2020 guidelines for limiting exposure to electromagnetic fields [19] specify the general public exposure limit at 10 W/m^2 for frequencies between 2 and 300 GHz with the averaging time being 30 minutes. Similar limits are specified by the Federal Communications Commission (FCC) in [20] where a restriction of 10 W/m^2 for the general public has been set. In contrast, the institute for building biology and sustainability (IBN) in Germany have specified the exposure limit to be less than 0.1 $\mu W/m^2$ in their 2015 Standard of Building Biology Measurement Technique (SBM-2015) [21], which is a million-fold lower than what is specified by the aforementioned guidelines. This suggests that negative health effects can occur at levels much lower than 10 W/m^2. Finally, the Chinese ministry of health [22] have set the power density exposure limit to 0.1 W/m^2.

TABLE IV: General Public Power Density Restrictions for the Frequency Range of 2 to 300 GHz

	IEEE C95.1-2019	ICNIRP	FCC	China	SBM-2015
P_D Limit (W/m^2)	10	10	10	0.1	10^{-6}

B. Power Density Assessment

The power density P_D radiated by a transmit antenna can be expressed at a far-field distance d using the following:

$$P_D = \frac{G_{Tx} P_{Tx}}{4\pi d^2} \quad (9)$$

The far-field distance is defined as the Fraunhofer distance expressed by:

$$d_{far-field} = \frac{2D^2}{\lambda} \quad (10)$$

where D is the largest dimension of the antenna and λ is the wavelength that corresponds to a frequency of operation. For distances less than the far-field distance, the power density cannot be computed using (9) and there would be a need to resort to numerical modeling methods such as the finite element method or finite-difference time domain.

C. Results

Fig. 6 shows the value of the power density for several choices of transmission power and transmit antenna gain in the distance range of 1 to 5 meters. For the proposed 5G network, we considered a transmission power of 19 dBm and a transmit antenna gain of 24 dBi. This corresponds to a value of 1.59 W/m^2 at 1 meters which drops to 0.06 W/m^2 at 5 meters. These values comply with the limits set by IEEE, ICNIRP, and FCC, since they are much lower than 10 W/m^2, but do not comply with SBM-2015 and Chinese Ministry of Health regulations. Fig. 7 shows the variations of the power density over the range of 20 to 50 meters. At 50 meters, which is at proximity of the cell edge, the power density drops further to $6.35 \times 10^{-4} W/m^2$ which is still much higher than the limit of the SBM-2015 guidelines. As shown in both Fig. 6 and Fig. 7, increasing the transmission power or choosing an antenna with a higher gain leads to an increase in the radiated power density. To comply with the limit set by China, the total EIRP needs to be dropped to achieve a power density below 0.1 W/m^2 which comes at the expense of a reduced cell range (below 50 meters). This makes it more difficult to plan cost-efficient 5G networks.

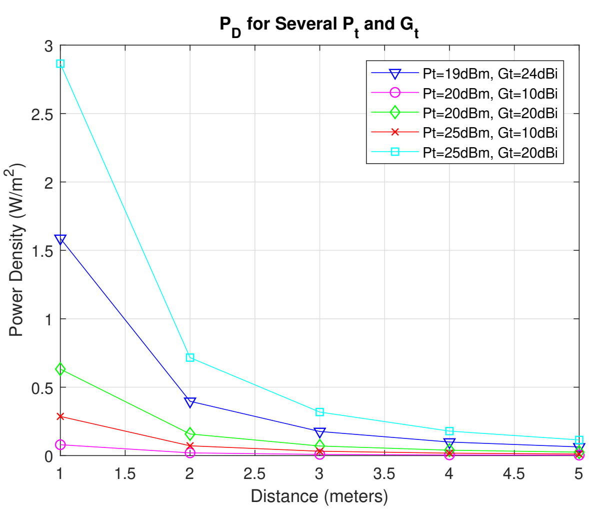


Fig. 6: Power Densities for Several Transmission Powers and Antenna Gains for the range of 1 to 5 meters

Cumulative Distribution Function (CDF) plots for the power density levels experienced in both the pre-existing LTE network and the newly deployed 5G network are shown in Fig. 8. The additional radiations imposed by the 5G network significantly increase the probability of being exposed to power density levels of more than 0.5 W/m^2 and that could reach up to the range of 2 to 2.5 W/m^2, while such power

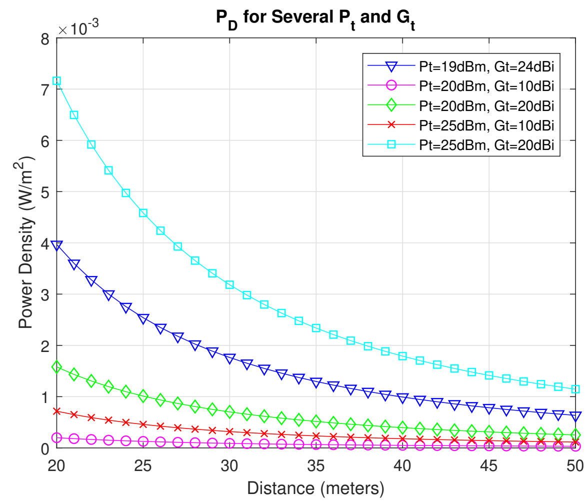


Fig. 7: Power Densities for Several Transmission Powers and Antenna Gains for the range of 20 to 50 meters

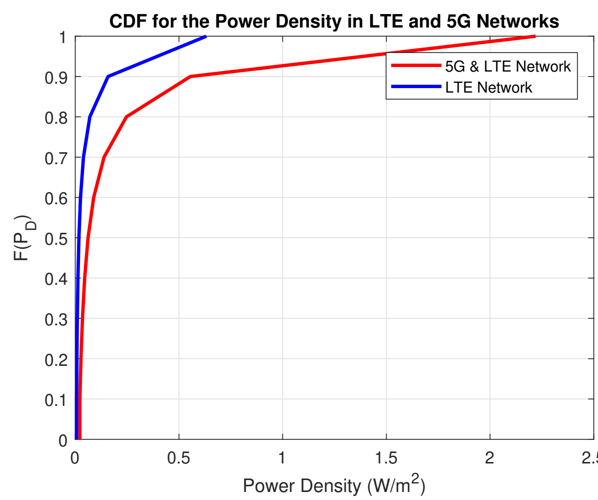


Fig. 8: CDF for the power densities levels for both pre-existing LTE and deployed 5G network

density levels were not experienced in the pre-existing LTE network. This is why the CDF of the power density in the pre-exisitng LTE network reaches the limiting factor of 1 for a power density around 0.65 W/m^2

Fig. 9 shows a heat-map representing the radiated power by the LTE BTSs in the area under study before deploying the 5G network, where a simplified path loss model [23] is considered for an urban macrocell. In Fig. 10, a similar heat-map is shown after the deployment of the 5G network. The remarkable increase in radiation levels after integrating 5G infrastructure with the original LTE network can be easily observed through the predominance of the red color in the heat map.

The presented results clearly show that the potential radiation levels that will be reached upon the roll out of 5G networks do not comply with all of the aforementioned exposure limits. This suggests that 5G mobile networks can not yet be classified as safe for the public, and demands serious considerations before using mmWave communications for 5G networks, given the potential harms it could afflict on the public. This paves the way to the consideration of hybrid transmission techniques including traditional electromagnetic waves, free-space optics and visible light communication

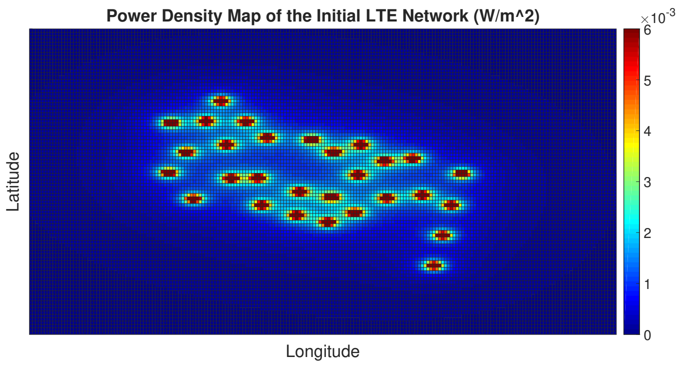


Fig. 9: Power Density Map of the Initial LTE Network

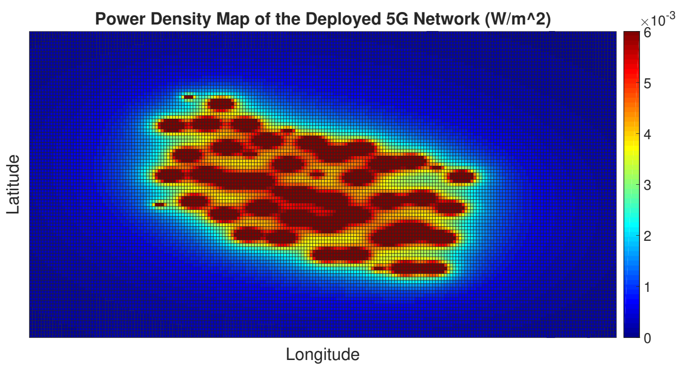


Fig. 10: Power Density Map of the Deployed 5G Network

V. Conclusion

This paper presented an analysis of the radiation levels in a deployed 5G network in an urban outdoor environment. Under the constraints of exposure limits, several challenges face the design and planning of such radiation aware 5G networks. Cell ranges need to be reduced to comply with the maximum allowed radiated power, requiring the densification of small cells in small areas and making it more costly to deploy these radiation-aware 5G networks. Although in this work we considered the maximum allowed EIRP prior to network deployment, results showed power density levels that do not satisfy all the exposure limits set by several sources. In this regard, a positive impact can be imposed by radiation-aware 5G networks on several levels. On a governmental level, the exposure limits for the power density need to be revised using today's data and approaches to bridge the gap between the thresholds specified by the different institutes and commissions. On a technological and scientific level, the radiation exposure constraint can open the door for innovative 5G solutions targeted to limit the health risks and economic barriers associated with this problem. This work can be extended by developing an analytical framework to efficiently rank and rate different cell allocation alternatives to minimize the potential radiations given a carefully chosen list of key performance indicators.

References

[1] M. Xiao, S. Mumtaz, Y. Huang, L. Dai, Y. Li, M. Matthaiou, G. K. Karagiannidis, E. Björnson, K. Yang, I. Chih-Lin, *et al.*, "Millimeter wave communications for future mobile networks," *IEEE Journal on Selected Areas in Communications*, vol. 35, no. 9, pp. 1909–1935, 2017.

[2] H. El Misilmani and A. El-Hajj, "Massive mimo design for 5g networks: an overview on alternative antenna configurations and channel model challenges," *2017 International Conference on High Performance Computing & Simulation (HPCS)*, pp. 288–294, 2017.

[3] E. J. Oughton and Z. Frias, "The cost, coverage and rollout implications of 5g infrastructure in britain," *Telecommunications Policy*, vol. 42, no. 8, pp. 636–652, 2018.

[4] A. A. Al-Mekhlafi, O. M. Al-Kamali, R. Q. Shaddad, and M. A. Abduljalil, "Dense 5g network planning for coastal area at aden city, yemen," *2019 First International Conference of Intelligent Computing and Engineering (ICOICE)*, pp. 1–7, 2019.

[5] N. A. Jazea, H. Alyasiri, and A. H. Saloom, "Planning and optimization of 5g mobile network for al-najaf city (phase i)," *2019 International Engineering Conference (IEC)*, pp. 45–49, 2019.

[6] R. Q. Shaddad, F. S. Al-Kmali, M. A. Noman, N. K. Ahmed, E. M. Marish, A. M. Al-Duais, A. A. Al-Yafrsi, and F. A. Al-Sabri, "Planning of 5g millimeterwave wireless access network for dense urban area," *2019 First International Conference of Intelligent Computing and Engineering (ICOICE)*, pp. 1–4, 2019.

[7] D. Plets, W. Joseph, K. Vanhecke, and L. Martens, "Exposure optimization in indoor wireless networks by heuristic network planning," *Progress in Electromagnetics Research-PIER*, vol. 139, pp. 445–478, 2013.

[8] M. Deruyck, E. Tanghe, D. Plets, L. Martens, and W. Joseph, "Optimizing lte wireless access networks towards power consumption and electromagnetic exposure of human beings," *Computer Networks*, vol. 94, pp. 29–40, 2016.

[9] D. Basu and S. F. Hasan, "Approximating electromagnetic exposure in dense indoor environments," *2018 15th International Symposium on Wireless Communication Systems (ISWCS)*, pp. 1–5, 2018.

[10] G. R. Maccartney, T. S. Rappaport, S. Sun, and S. Deng, "Indoor office wideband millimeter-wave propagation measurements and channel models at 28 and 73 ghz for ultra-dense 5g wireless networks," *IEEE access*, vol. 3, pp. 2388–2424, 2015.

[11] Aalto University, BUPT, CMCC, Nokia, NTT DOCOMO, New York University, Ericsson, Qualcomm, Huawei, Samsung, Intel, University of Bristol, KT Corporation, University of Southern California,, "5G Channel Model for bands up to 100 GHz," *Tech. Rep. [Online]. Available: http://www.5gworkshops.com/5GCM.html*, Dec. 6, 2015.

[12] K. Haneda, J. Zhang, L. Tan, G. Liu, Y. Zheng, H. Asplund, J. Li, Y. Wang, D. Steer, C. Li, *et al.*, "5g 3gpp-like channel models for outdoor urban microcellular and macrocellular environments," *2016 IEEE 83rd Vehicular Technology Conference*, pp. 1–7, 2016.

[13] P. Series, "Propagation data and prediction methods for the planning of short-range outdoor radiocommunication systems and radio local area networks in the frequency range 300 mhz to 100 ghz," *tech. rep., ITU, Tech. Rep. ITU-R*, 2015.

[14] S. Singh, R. Mudumbai, and U. Madhow, "Interference analysis for highly directional 60-ghz mesh networks: The case for rethinking medium access control," *IEEE/ACM Transactions on networking*, vol. 19, no. 5, pp. 1513–1527, 2011.

[15] R. P. Series, "Itu,"characteristics of precipitation for propagation modelling,"," *Recommendation ITU-R P. 837*, vol. 6.

[16] S. K. Sharma, M. Patwary, S. Chatzinotas, B. Ottersten, and M. Abdel-Maguid, "Repeater for 5g wireless: A complementary contender for spectrum sensing intelligence," pp. 1416–1421, 2015.

[17] T. Wu, T. S. Rappaport, and C. M. Collins, "Safe for generations to come: Considerations of safety for millimeter waves in wireless communications," *IEEE Microwave Magazine*, vol. 16, no. 2, pp. 65–84, 2015.

[18] "Ieee standard for safety levels with respect to human exposure to electric, magnetic, and electromagnetic fields, 0 hz to 300 ghz," *IEEE Std C95.1-2019 (Revision of IEEE Std C95.1-2005/ Incorporates IEEE Std C95.1-2019/Cor 1-2019)*, pp. 1–312, 2019.

[19] I. C. on Non-Ionizing Radiation Protection *et al.*, "Guidelines for limiting exposure to electromagnetic fields (100 khz to 300 ghz)," *Health Physics*, vol. 118, no. 5, pp. 483–524, 2020.

[20] F. C. Commission *et al.*, "Report and order: Guidelines for evaluating the environmental effects of radiofrequency radiation," *FCC 96-326*, 1996.

[21] B. Maes, "Institut für baubiologie+ nachhaltigkeit (ibn). building biology evaluation guidelines for sleeping areas (sbm-2015). neuss, rosenheim (de): Baubiologie maes, ibn., 2015 may, 3p."

[22] H. Chiang, "Rationale for setting emf exposure standards," 2009.

[23] A. Goldsmith, *Wireless communications*. Cambridge university press, 2005.