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RESEARCH ARTICLE

EMF-Aware User Association Optimization in 5G Networks

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ABSTRACT Exposure to Electromagnetic Fields (EMF) is one of the main concerns on current mobile wireless deployments, due to the use of active antenna systems and the increase of users connected simultaneously to these systems. In this paper, we evaluate the achievable rate resulting from simultaneous connections from multiple users, along with the signal-to-noise ratio (i.e., SNR), considering existing regulatory constraints on EMF, which is the subject of limitations in several countries. Our approach considers a random deployment of several base stations, according to a Poisson point process, and focuses on exploring the convexity of the achievable rate, as it will increase together with the number of antennas, and decrease with the overhead when a higher number of antennas is used. This article also studies the effects of the placement of new base stations on the overall EMF exposure, ensuring compliance with the current EMF limitations. Results show that due to the narrowness of the beam, the blockage can considerably affect the SNR received. Although several configurations are available from an operator perspective, some flexibility is allowed and the EMF exposure does not affect the average performance dramatically.

INDEX TERMS RF-EMF exposure, 5G, beamforming, resource allocation, network planning optimization.

I. INTRODUCTION

A. FRAMEWORK AND MOTIVATION

Wireless radio communications use Radio-frequency electromagnetic fields (EMFs) to convey information between a transmitter and a receiver. Most of the User Equipment (UE) and base stations in terrestrial communications transmit at low power and therefore the effects of the EMF effects to the human body are usually low [1]. However, one of the features of 5G-and-beyond and 6G mobile wireless generations is the massive device-to-device communications, which implies the massive densification of base stations or devices that will act as base stations, and therefore the increase of EMF exposure levels [2]. In addition, the use of higher frequency bands and beamforming (i.e., to concentrate all the beamforming gain in a narrower beam), is also a debate topic to investigate whether it is more dangerous for human health [3]. EMF assessment is an essential discussion given the densification of base stations, but once the assessment is analyzed, we may need to investigate further to evaluate how to mitigate its effects.

Radio frequencies (RFs) are in the middle of the overall electromagnetic spectrum that ranges from static electricity and magnetic fields to visible light, X-rays, and nuclear radiation [4]. The applications of RFs include radio communications, mobile phone networks, mobile base stations, and smartphones. Due to their flexibility, wireless communications are more common than wired systems, and it is essential to assess RF-EMF exposure when deploying new cellular technologies [5]. The deployment of 5G-and-beyond networks has more requirements and to achieve them, the placement of new base stations will be needed. In a scenario where many sources of RF-EMFs already exist, there is a growing concern that the limits on EMF levels established by each of the country's regulations will severely constrain the planning of 5G networks [6]. The assessment of EMF compliance has always been a significant challenge for deploying new cellular communication technologies [7].

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Moreover, whenever there is a change in cellular network generation, for example, as was seen during the 3G to 4G migration, the deployment of new networks is challenging, as it requires matching the regulatory framework to new technical needs [8].

As we increase the number of base stations, the UEs' EMF exposure will be higher. To the key performance indicators (KPIs) discussed in previous generations, such as the latency, the outage probability, or the link capacity, we need to add now the level of 5G exposure [7]. Our objective is to determine the number of antennas that can be used in a connection to maximize the rate while maintaining the EMF threshold levels. To this end, we ensure a quality level for the connectivity to the UE, and we offer the possibility to increase the number of users served by the operator while maintaining Quality of Service (QoS) 5G standards [9]. To the best of our knowledge, no work evaluates the number of users that can be connected to a 5G-NR (5G-New Radio) station, considering the 5G standards, the EMF exposure, and the placement of new base stations in such an environment.

B. MAIN CHALLENGES

In addition to the usual KPIs optimization based on the connectivity performance, such as the achievable rate or coverage probability, or even more related 5G KPIs such as spectral efficiency or low latency, here we focus on the parameters that affect the EMF emissions. We leave for future work the exploration of the different techniques. Nowadays, ultra-dense scenarios are considered for communications. This fact implies that the UE will be able to select a full range of available resources to attempt a connection.

To this end, we mark two objectives for this paper: Firstly, to optimize the resource allocation to maximize the users that can be connected simultaneously to a certain base station, while ensuring certain QoS in terms of achievable rate and EMF exposure requirements. Secondly, to evaluate the placement of new base stations under the same circumstances.

C. MAIN CONTRIBUTIONS

In line with these requirements, the state-of-the-art analyzed which provides the gap between the literature and our proposed solution, these are the three main contributions of this paper:

- Characterize the optimization problem based on a realistic yet mathematically tractable model.
- To evaluate the interval of the rate that satisfies the constraints and give recommendations both to the use and the operator. Therefore, provide recommendations for the number of users that can be allocated to each 5G-NR station (gNB).
- Compare different scenarios, such as dual connectivity, and single connectivity in different frequency bands, and evaluate different parameters such as antenna configuration, effects of the blockage, and overhead of the connectivity.
- Evaluate EMF-aware limitation of placement of new base stations to achieve the requirements of 5G systems.

D. STRUCTURE OF THE PAPER

The paper is organized as follows: Section II shows the related work of our optimization proposal, such as other optimization techniques and models for EMF exposure levels. Section III describes the stochastic geometry-based system model regarding the distribution of users and base stations and EMF considerations. Section IV illustrates step by step how we will use the system model described to perform the optimization. First, to mitigate the EMF effects, and then to optimize the placement of new base stations. Section V shows the optimization problem to maximize the users connected simultaneously to a certain base station, whilst maintaining values of EMF exposure and rate overhead considerations and shows the placement solution of new base stations under the EMF requirements. In section VI we disseminate the results of both optimization for different technologies (i.e., sub-GHz bands, mmWave, Dual connectivity) and placement. Section VII closes this paper with the main conclusions and points out some directions for future work in this area.

II. RELATED WORK

While there are several works on EMF assessment, in both measurement campaigns and mathematical models of channel propagation and how this affects EMF exposure, there is a gap in the optimization of the user association in different technologies taking into account the EMF exposure as a variable of control on the user association problems. For instance, [10] and [11] provide an in-depth mathematical analysis of how the propagation in MIMO mmWave communications affects the EMF exposure, but it is an assessment problem. The main difference between assessment and optimization is that the assessment considers all the elements to carefully evaluate the EMF exposure, which can be challenging due to different beams and blockage of mmWave links.

On the other hand, some optimization problems focus on improving user association (either increasing the KPIs and/or mitigating the EMF effects. Another interesting aspect to consider is the utilization of the channel, as usually these massive antenna base stations are not used 24/7. This is further evaluated in [12]. Finally, stochastic geometry has proved to be a reliable methodology to mathematically model the deployment of base stations that were unplanned, such as the Small Cells, which were instead deployed ad hoc to increase connectivity at hotspots or provide connectivity where no MCell was available [13]. There are some works that, through stochastic geometry, study the EMF assessment, [14] and [15], but they do not consider any sort of EMF mitigation or optimization.

Several techniques to reduce the EMF while maximizing the performance of the network can be used in current wireless networks. For instance, one could consider the variables that affect EMF exposure and evaluate how we can optimize the connectivity to mitigate its effects. Since EMF exposure is strictly related to received power, most efforts to mitigate its effects are to reduce the received power or sparse it through a larger area, so that EMF exposure to a single user is minimized. Depending on the use case, the prioritization in 5g-and-beyond networks is in the latency of the communications and, on top of that, ultra-dense scenarios serving few users do not need a high received power. Therefore, these works aim to reduce the received power. Towards this direction, in [16] the open loop power control is used to minimize the transmit power. It can adjust the received power, usually used to balance the edge users in a cell radius, but it can also be used to reduce the power once the EMF levels are over the exposure limits. The authors include an Exposure Index-based Power Control Algorithm which maximizes the power control for a set of users to maintain the threshold. In [17], the authors develop an algorithm to evaluate the PD level, and consequently the Specific Absorption Rate (SAR) exposure, and disables the base station (BS) once the threshold is achieved through downlink optimization through PD detection.

Another option considered in the literature is the use of RIS (Reconfigurable Intelligent Surfaces) as a passive Relay. RISs are reflecting surfaces that can improve the wireless channel by creating LoS links [18]. To support a high data rate, mmWave communications are essential. However, the Line-Of-Sight (LoS) path can be blocked, leading to a considerable decrease in the received signal [19]. To this end, the UE must increase its transmission power to reduce the blockage, which increases the EMF exposure. A solution to this problem is to consider a BS acting as a relay to divide the link into two LoS propagation channels: Base station-RIS and RIS-UE [20].

III. SYSTEM MODEL

In this section, we introduce the main system model assumptions for the scenario deployed. We show the base stations' deployment, the channel model between the UE and the base stations (such as propagation LoS and NLoS or the beamforming gain), and the effective rate perceived by the UE. Finally, we show how the EMF within the stochastic geometry scenario is computed.

A. BASE STATIONS AND USER DEPLOYMENTS

We assume a set of base stations whose locations follow a homogeneous Poisson point process (PPP) with intensity λ. In the case of Line-of-Sight (LoS), we may want to connect to the closest base station, which distance follows the distribution [21]:

$$f_x(x) = 2\lambda\pi x \mathrm{e}^{-\lambda\pi x^2}, \tag{1}$$

where x is the distance between the user-centered device and the base station. In this particular case, the PDF shows the distribution to the closest base station. However, in the case of Non-Line-of-Sight (NLoS), we may evaluate the connectivity to a further but LoS gNB. In this case, we show the distance to the n_{th}-closest BS, which can be expressed as [22]:

$$f_d(d_n, n) = \frac{1}{C}\frac{2(\lambda\pi)^n}{(n-1)!}\left(\frac{d_n}{C}\right)^{2n-1}\mathrm{e}^{-\lambda\pi\left(\frac{d_n}{C}\right)^2}, \tag{2}$$

where $n = 1$ means the closest base station, $n = 2$ the second-closest base station, and so on. By replacing n = 1, since it is equivalent to the distance to the closest base station, we will obtain (1). Since this distribution is normalized (i.e., the distance x is between 0 and 1), we add a constant C which represents the real distance between the user and the base station to the PDF distribution to show the effects of distance-related blockage at high frequencies. To better understand this distribution, we need to consider a user-centered device, with all the base stations ordered from the closest one to the furthest.

B. EFFECTIVE RATE

First, let us consider the beamforming gain follows an exponential random variable (as computed empirically in [23]:

$$f_g(g_n) = \mu_n e^{-\mu_n g_n}, \quad \text{where} \tag{3}$$

$$\mu_n \triangleq 0.814(N_T N_R)^{-0.927}, \tag{4}$$

and N_T and N_R refer to the number of transmit and receive antenna elements, respectively. Instead of fixed beamforming gain G, we consider a random variable g_n, which is PDF f_g and it is distributed exponentially. It is randomized due to the misalignment of the beam. To compute the received signal, we consider the attenuation model considered in this study distance-dependent path-loss, and the uplink (UL)/ downlink (DL) received signals are expressed as:

$$S = P_{tx} g_n \left(\frac{4\pi d_n f}{c}\right)^{-\alpha_n}, \tag{5}$$

where S is the average signal received power in both UL and DL, f the network carrier frequency P_{tx} is the transmit power including the antenna gain, the serving cell in the DL case (P), and x is the distance from the device to the target cell affected by the path-loss exponent α. Based on the received power, the SNR can be expressed as:

$$\text{SNR} = \frac{S}{\sigma^2 + I_x}, \tag{6}$$

where σ^2 stands for the noise and I_x for the aggregated interference from the other users. Mathematically, $\tilde{R}_n$ is the effective rate by the UE to the n-th gNB, respectively, which are computed by considering the overhead due to beam-alignment [24], *i.e.*,

$$\tilde{R}_n = \left(1 - \frac{T_t}{T_f}\right) R_n, \tag{7}$$

with

$$R_n = \int_0^{+\infty} \log_2(1 + \text{SNR}_n) f_x(x, n) \mathrm{d}d_n \mathrm{d}g_n \tag{8}$$

and where T_t and T_f are the training and the frame duration respectively.

We can further define the overhead $\nu = \frac{T_t}{T_f}$ as the amount of time dedicated to aligning the beam, while no useful information can be transmitted. The higher the number of antennas used, the higher the overhead, since it takes more time to align the beams. Also, the overall rate will be affected by the overhead. This is the trade-off we will study, and the reason we cannot simply increase the number of antennas *ad infinitum* (or as much as physically possible).

In Fig 1 we show how the achievable rate decreases dramatically when the number of antennas increases, as the overhead for the alignment of the antennas reduces the performance. The resources employed for the alignment (such as the time frame) affect the acceleration of the rate loss. When a lower time frame is used, the resources dedicated to the alignment are lower, and the rate decreases at a slower pace. On the other hand, we can observe that the nominal rate, which do not consider any overhead. In this case, the rate exponentially increases along with the number of antennas.

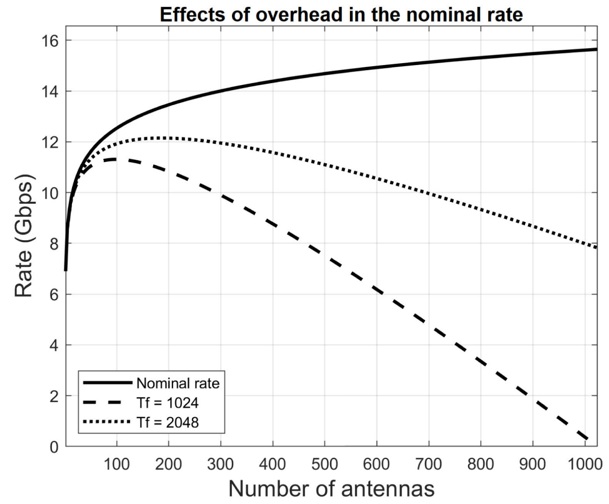

FIGURE 1. Effects of the overhead in the achievable rate, $\alpha = 2.2$.

C. EMF EXPOSURE CONSIDERATIONS

Finally, let us evaluate the EMF exposure in a stochastic geometry scenario deployed. As seen in [14], the Power Density (PD), can be expressed as:

$$S(x) = \frac{A}{(x^2 + h^2)^{(\alpha/2)}}, \tag{9}$$

where A is the channel model considering random small fading, r is the horizontal 2D distance, h is the height of the BS, and α is the pathloss exponent.

However, the authors also modeled how the EMF affected the user in different scenarios. For instance, if we want to compute the expected power density of the closest base station [14]:

$$E[S_1] = (\lambda\pi)^{\alpha/2}\,\overline{A}e^{\lambda\pi h^2}\,\Gamma\left(1 - \frac{\alpha}{2}, \lambda\pi h^2\right), \tag{10}$$

where $\overline{A}$ is an expected value of A and $\Gamma(z, t)$ is the upper incomplete Gamma function. To model the n-th nearest BS, the power density will be evaluated as:

$$E[S_n] = \overline{A}\,(\lambda\pi)^{\alpha/2}\, e^{\lambda\pi h^2}\sigma^n_{-\alpha/2}, \tag{11}$$

$$\sigma^i_x = \sum_0^{i-1} \frac{(-\lambda\pi h^2)^{i-l-1}}{l!(i-l-1)}\Gamma(1+l+t, \lambda\pi h^2), \tag{12}$$

where σ^i_t is the aggregated EMF from the other base stations. Regarding the EMF from the interfering cells, we can use both expressions to determine the EMF exposure for different gNBs. For all the cases exposed in the next section, we will use one of the expressions above in the power density threshold.

IV. METHODOLOGY

To tackle this problem, we propose a resource-allocation algorithm that minimizes the power density and therefore reduces the EMF exposure. Resource-allocation algorithms have been used more frequently since the densification of the scenarios. Therefore, we suggest applying them for EMF mitigation.

There are two concerns about the EMF exposure. First, the assessment evaluates the EMF levels. Then, the mitigation of its effects. This paper covers the latter. To do so, we focus on two different problems: Resource allocation of the existing base stations deployed and the placement of new base stations under those circumstances.

First, we evaluate the EMF-aware user association optimization in three different cases:

- **Single connectivity - sub-6GHz bands:** In this first case, we evaluate the connectivity. We study how many users can connect to a base station simultaneously. We consider the overhead to attempt the connection, which depends on the number of the antennas, and the EMF threshold.
- **Single connectivity - mmWave:** Then, following the same approach for the optimization problem but using mmWave, the link is subject to be blocked.
- **Dual connectivity:** In the last resource allocation problem, we study dual connectivity and its trade-off- We compare the overhead of synchronization of both base stations and its increase of capacity. Moreover, we consider different sub-use cases: for instance, consider both base stations LoS, one LoS, and one nLoS, and then we compare the number of users available with single connectivity in different frequencies.

Secondly, we study the placement of new base stations: The main idea is to identify when and how new stations can be deployed while studying the placement considering the resource allocation optimization proposal. The reason for planning new base stations is out of the scope of this paper and can be due to several reasons: for instance, to increase the connectivity in a certain area for a short period or to provide connectivity where Macro Cells are not feasible. Either way, the placement of new base stations increases the transmit power of these antennas and therefore increases the EMF exposure. The research problem to tackle here is how the placement of these base stations can keep the EMF exposure levels low.

V. OPTIMIZATION PROPOSED

A. MAIN OPTIMIZATION ALGORITHM PROPOSED

In this paper, we aim to provide the operator with a guide for how many users can be simultaneously connected to a gNB. Therefore, it is not a usual optimization proposal that aims to find a maximum rate or an optimal number of users connected. Instead, we study the interval of users which can be served under certain constraints. The effective rate (7) is a convex function. Due to the antennae dependence of the beamforming gain, when we increase the number of antennas, the rate increases along with the beamforming gain. On the other hand, the overhead to connect to all the antennas reduces drastically the rate. Therefore, at some point, the rate will be reduced to 0. Although following the mathematical expression the rate would decrease up to negative values using bigger systems such as 256×256 antennas massive MIMO, practically it would result in a communication breakdown when the rate reaches 0. The control of the number of antennas needed to use can't exceed certain values, to ensure a certain quality of service.

$$\max_{\omega} \; \bar{R}(\omega, \beta)$$
$$\text{subject to } \bar{R}(\omega) \geq R_*, \tag{13a}$$
$$0 < \nu(\omega) < 1 \tag{13b}$$
$$E[S(x)] < PD_\tau. \tag{13c}$$

Finally, we give a couple of notes on these conditions:

- ω is the number of antennas and our variable of optimization.
- $\nu(\omega)$ considers the overhead to switch the antennas.
- E[S(x)] stands for the expected power density in each of the cases.
- R_* ensures the rate according to a certain SNR threshold.
- PD refers to the maximum Power density tolerated, referred to the EMF levels.

Therefore, the objective is, considering the variables and a single connectivity scenario, how many users could be able to connect to the antenna. On one hand, there is a lower limit based on the maximization of the rate of the user to maintain the EMF thresholds and QoS. On the other hand, an upper limit based on the minimum rate of the UE needs to be achieved. The objective is to study this window. This window is determined by the user demand as, for a lower SNR required, the configuration allows for flexibility and the window is wider. On the other hand, for higher SNR requirements, the window is more narrow and the number of users will likely be reduced.

At this point, the objective is to ensure reliable connectivity between the UE and the BS, while maintaining the threshold levels of EMF and considering two variables of control: the number of antennas, and consequently the number of users that will be able to connect simultaneously to a specific base station.

Without loss of generalization, we can apply this algorithm to different configurations, to evaluate, for instance, the effects of the blockage on the number of users. In this regard, we will study the different possible scenarios:

- The closest gNB is available and LoS, so the UEs will connect to this base station.
- The closest gNB is not available, so we will evaluate the users' window when the connection is attempted to the n-th gNB.
- Finally, a combination of both cases will be evaluated. In case the closest base station is blocked (i.e. NLoS), the objective is to compare the window of users when they connect to the closest but NLoS base station.

B. DUAL CONNECTIVITY CASE

It also works for dual connectivity, where we can replace the equation 13a by the sum of the rates of both base stations:

$$R_{DC} = R_{BS1} + R_{BS2}, \tag{14}$$

where each of the rates corresponds to (1) and at the same time, their propagation path can independently be it LoS or nLoS. In the numerical results section, we have simulated the dual connectivity case and the effects on the optimization problem when one or both links are LoS or nLoS. To this extent, the optimization problem can cope with different configurations, and as long as the final rate can be expressed in a single mathematical expression, the same optimization constraints apply as in the single connectivity use case.

C. PLACEMENT OF NEW BASE STATIONS

One of the main challenges of network planning is the placement of new base stations, on top of the existing ones. As we mentioned in the introduction, a key to future mobile networks is to increase the capacity of the network, due to the user demand. Once the assessment of the current network is deployed, and based on the awareness of the EMF threshold. The question is how new base stations can be deployed, ensuring the EMF limitations.

The base station planning is always complicated since we need to take into account many technical aspects, as well as the feasibility of the placement (for instance, due to physical constraints that depend on the surface). The configuration of equipment is based on different QoS requirements. For instance, coverage, capacity, and quality requirements, among others. The right wireless parameters can be chosen to meet the requirements of design considering a wide range of parameters, such as the transmission type, antenna height, antenna angle, carrier frequency, etc. Before the current base station design, it is advised to perform different simulations using different methodologies, such as the Monte Carlo simulation [25].

In our case, since the limitation comes from the EMF, we can randomly place the new base stations, while maintaining that with the new location, x_i and y_i, the sum of the EMF of all and new base stations is lower than PD specified, and the conditions of equation (13) are ratified. In addition, this needs to be valid for every new base station (for all i).

VI. NUMERICAL RESULTS

A. SIMULATION SETUP

In this section, we compare the effects of the pathloss and the density of the base stations to the number of users that can be connected simultaneously. For distributing UEs, we consider uniform distribution in a square area of 2000 m × 2000 m. The gnBs are distributed according to a Poisson Point Process. This work is a preliminary study that focuses basically on a theoretical approach, evaluating how each of the variables affects the optimization problem. This is the first approach using Matlab simulation, which we plan to expand with real data through a platform that is currently being deployed. Joint evaluation of all the variables of control or testing the optimization algorithm in a more realistic scenario is also left for future work, which we are currently planning.

In table 1, we show the numerical values of the simulation, which we have simulated in Matlab using the model detailed in section II, along with the notations used throughout the mathematical analysis of this paper. The values of the time frames, the number of antennas, the transmit power, and the pathloss are obtained from the latest 3GPP standard.

TABLE 1. Simulation parameters.

Parameters	Meaning	Values
f	Network carrier frequency	0.920 / 28 GHz
C	Coverage radius	200 m
P_t	Transmission Power	20 dBm
$G(i,j)$	Total antenna gain	10
N_o	Noise power	-170 dBm
B	System bandwidth per user	20 MHz
α_{LoS}	Path-loss exponent for LoS	2.09
α_{NLoS}	Path-loss exponent for NLoS	3.75
T_t	Total frame time	1024 ms
T_f	Total overhead time	64 ms
N	Number maximum of antennas of each gNB	512 antennas
S	Maximum EMF exposure	3 V/m
λ	Density of gNBs	10 (gnBS/km)
EMF	Threshold on EMF exposure per user	$3v/m$

B. RESOURCE ALLOCATION IN SUB-6GHz FREQUENCIES BANDS

First, we study the number of users in 5G for sub-6GHz. In Fig. 2, we show the number of users that can be connected, with a central frequency of 2.8 GHz, and for different configurations of antennas (i.e., each user connecting to 2,4,8, and 16 antennas). We can observe that by increasing the

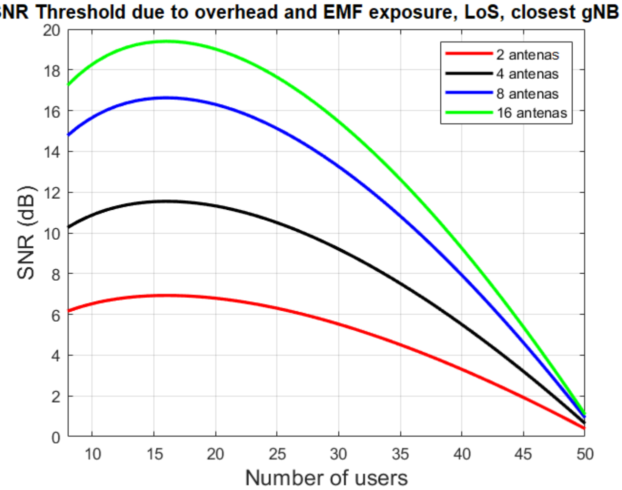

FIGURE 2. Number of users who can connect simultaneously to a single base station in the sub-6GHz bands (f = 920 MHz) for different antenna configurations.

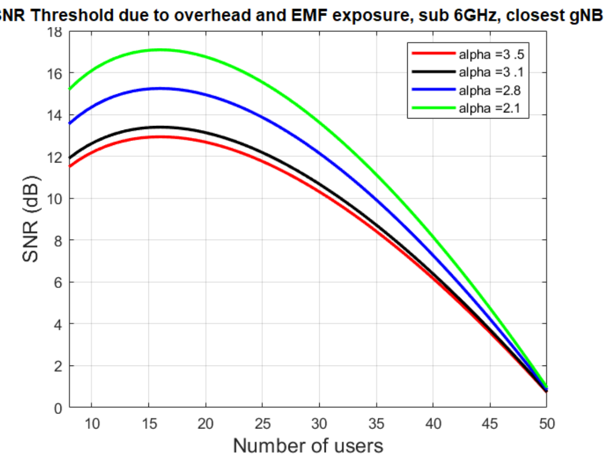

FIGURE 3. Effects of pathloss exponent on the number of users which can connect simultaneously to a base station in the sub-6GHz bands.

number of antennas, we can obtain a higher performance in terms of the SNR for the users connected. However, the increase in the number of antennas escalates the overhead and reduces the number of users that can connect simultaneously. In the end, this will highly depend on the requirements of the user application: if a lower SNR is sufficient, there is more flexibility in the configuration, and more users will be able to connect to the base station. it is also noticeable that the trend remains the same throughout all the configurations. In Fig. 3, we show the effects of the blockage. The blockage of the signal is due to the nLoS link between the user and the base station. This results in an attenuation of the received signal by the user, which directly impacts the SNR. The decrease in the signal received depends on several factors (i.e., how thick the blockage source, the number of blocking sources, among many others). This is reflected by the standard by a pathloss coefficient, α. This coefficient, as it is shown in (5), attenuates the signal exponentially. α values typically

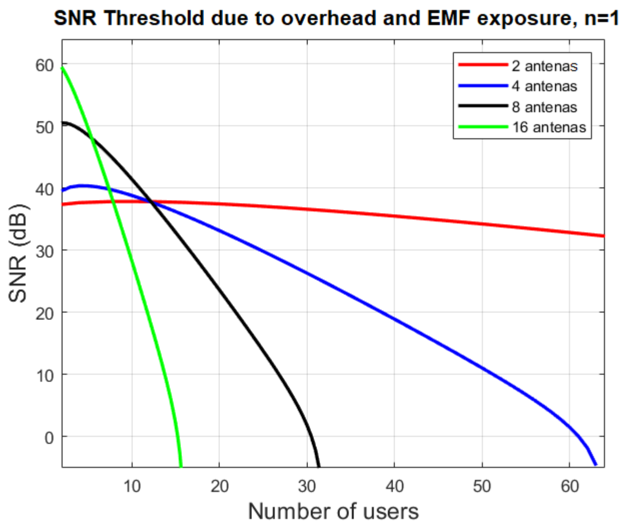

FIGURE 4. Number of users who can connect simultaneously to a single base station in the mmWave bands (f = 28 GHz) for different antenna configurations. Users are connected to the closest base station (n = 1).

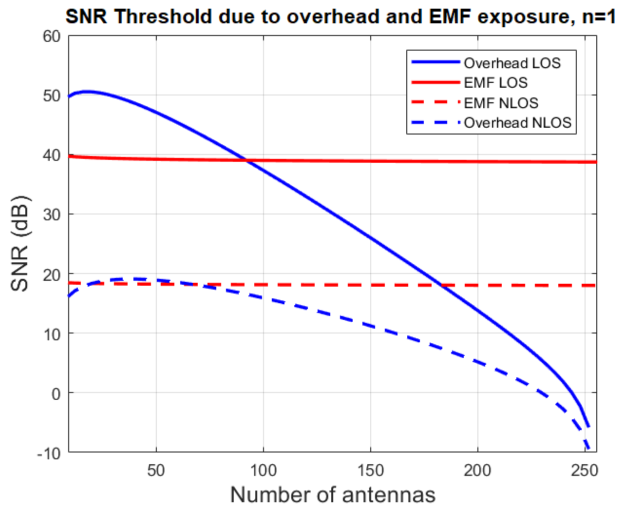

FIGURE 5. SNR depends on the number of antennas and its effects on the EMF exposure and overhead.

go from 2 (free-space) or 2.1 (LoS environment) to 4 which is a huge blockage scenario. In Fig 3, we show the effects of the received SNR for different pathloss coefficients. Although it follows the same trend, it is noticeable that the decrease is not noticeable from $\alpha = 3.1$, meaning that from the environment that produces this pathloss coefficient, the signal will not get worse in a higher blocked scenario. As we will observe, the effects of the blockage are not as critical as in the mmWave frequency bands, as the beam is wider and less subjected to being blocked.

C. RESOURCE ALLOCATION IN mmWave BANDS

Next, we evaluate the resource allocation in mmWave. In Fig. 4, we show the achievable rate for different numbers of users connected simultaneously, assuming that they connect to different numbers of antennas. Our possible configurations allow the users to connect to 2,4,8, and 16 antennas from the gnB. In this case, we also assume the connection to the closest LoS gNB. In detriment to the 920 MHz analysis in 2, we observe a much steeper curve of users we can achieve for a certain SNR. It is strictly related to the narrowness of the beams, which don't allow high performance for many users, but on the contrary, it improves the quality of the signal and the resulting SNR for the ones connected. There is a trade-off between the SNR that one may need to achieve and the number of users that can connect to a particular gNB. For instance, by using 16 antennas the received power from the gNB is higher, and the achievable rate, and consequently the SNR is higher. On the other hand, the overhead provokes a dramatic decrease in the SNR with few users connected. Although the numerology may change depending on the configuration, the general trend is that the higher the number of antennas from the gNB the users may use, the higher the SNR but also the higher the impact of the overhead, so fewer users will be able to use the specific gNB. In the end, it depends on the KPIs needed by every user. The rationale behind this decrease is that, with a higher number of antennas, the amount of the dedicated resources to the beamforming is higher, and results in an increasing overhead.

In Fig. 5, we show the effects of the overhead for line of sight and non-line of sight to the achievable rate, and considering a Luxembourg limitation on the EMF exposure, 3 V/m We can observe that since the received power is lower, the EMF limitation which deviates straight from the received power, is lower. Assuming the connection to the closer base station, we observe a large range of number of antennas available, so we can consider a fairly flexible connection. In the LoS case, even for an SNR of 0 dB which can work for some pilot messages or not-so-demanding download speed, the number of antennas available is quite flexible. In the nLoS scenario, however, it may be restricted. As we will observe in the following studies, it may be beneficial to switch to a further LoS gNB.

In Fig. 6, we show the SNR comparison between closer (n = 1,3) and nLoS to further LoS. We can observe that given some configuration and specific pathloss values (in our case 2.1 and 3.8 for LoS and nLoS respectively), it may be worth it to attempt the connection to the further one. In other words, the decrease of the power due to the distance may affect less severely the connection than the decrease of the power due to the pathloss.

In Fig. 7, we show the effects of the density of the gNBs in a certain area (i.e., how many base stations do we have per square kilometer). We can observe a similar trend in the number of antennas used for each user. Higher densification of the scenario results in a higher SNR achievable, but due to the interference from other base stations, fewer users can benefit from that. On the other hand, if the deployment of the base stations is lower, the average SNR will be lowered (as the average distance from a centered user and the closest gNB will be higher and this is a pathloss distance-dependent model) but more users will have an

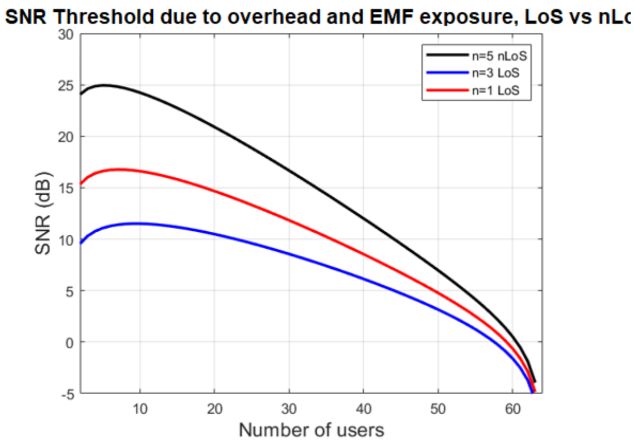

FIGURE 6. **Comparison between the achievable SNR connecting to a further yet LoS base station (5th in this case) and connecting to a closer nLoS (1st and 3rd, respectively).**

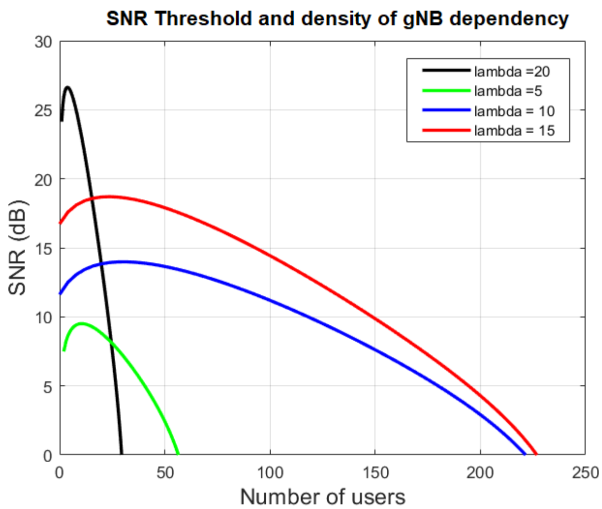

FIGURE 7. **Number of users and achievable SNR depending on the gNBs density per km.**

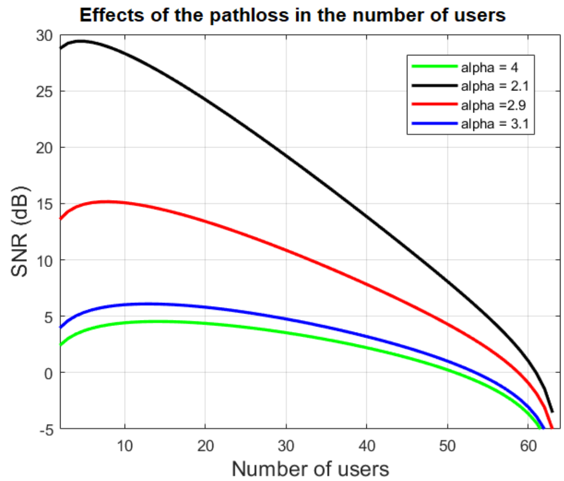

FIGURE 8. **Effects of the pathloss to the number of users and the achievable rate.**

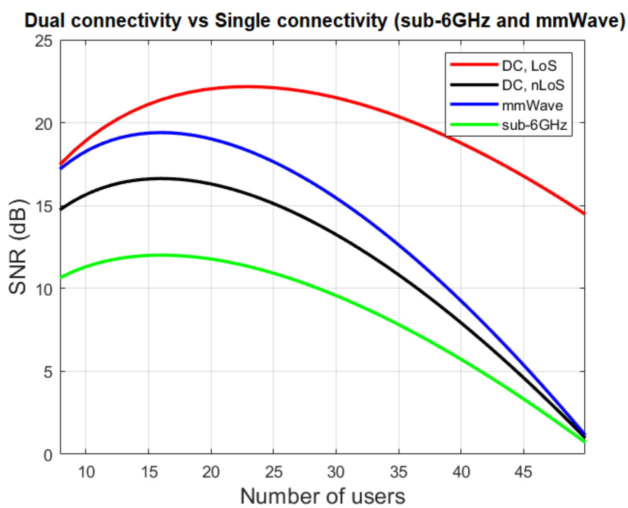

FIGURE 9. **Comparison of the numbers of users available in Dual connectivity and Single connectivity (in both frequency bands).**

acceptable SNR, depending on the use case. Once more, the deployment of the scenario and the configuration used will depend on the demand of the users.

In Fig. 8, we show the effects of the pathloss on the achievable SNR. This study aims to evaluate the effects of the pathloss as a continuous variable, since, rather than LoS or NLoS, the levels of blockage can change. We observe that, naturally, higher blockage and lower SNR are expected. However, there is a blocking point, around $\alpha = 3$ where it does not matter if we increase the thickness of the source of blockage, as the SNR achieved is its minimum. This gives us a good approximation to the maximum tolerable pathloss when considering switching to a further but LoS base station, assuming the higher distance penalization.

Next, we study the possibilities of dual connectivity. In Fig. 9, we show the number of users available increases in detriment to the single connectivity, as long as both base stations are LoS. If one of them is nLoS, mmWave single LoS single connectivity still outperforms the dual connectivity, due to the overhead of connecting to two base stations. However, it still achieves better results than the sub-6GHz bands.

D. PLACEMENT OF NEW BASE STATIONS

Finally, we evaluate the algorithm for the EMF-aware of the placement of new base stations. To do so, we simulate a set of base stations following a PPP (in the figures represented in blue). Based on that, we add 3 base stations (in the figures represented in red) to the original scenario. First, in Figure 10 we observe that when the base stations are randomly located, they may fall not only close to the user but also to some previous base stations, in a way that the EMF threshold may be jeopardized. On the other hand, in Fig. 11, the base stations are placed following the constraints depicted in section III. It is noticeable that they can indeed be close to each other, as there is no distance apart condition, but if this happens it should be far from the user of interest. What threatens the

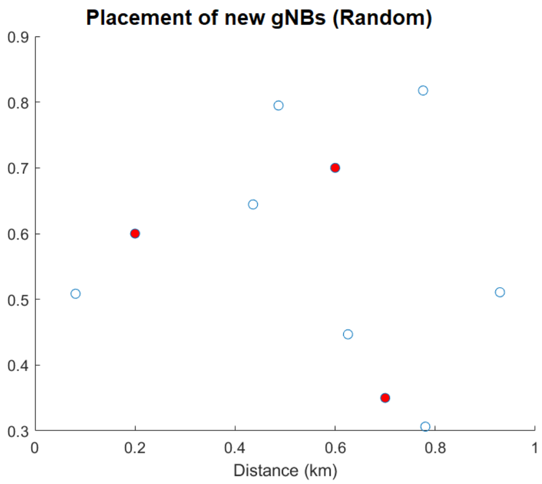

FIGURE 10. Random placement of 3 new base stations in a 1 × 1 square km. Circle dots represent the existing base stations and red dots are the new base stations.

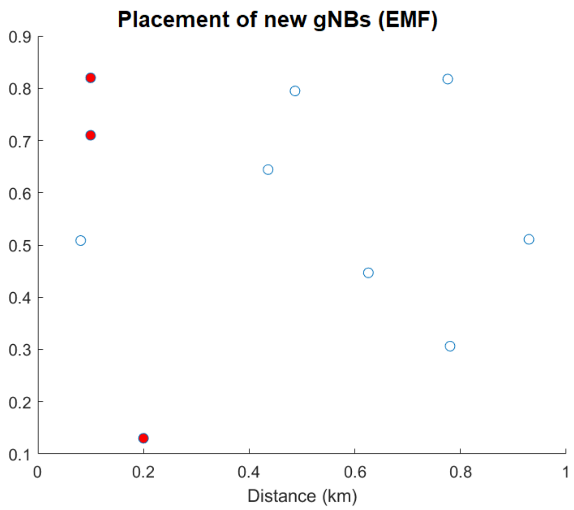

FIGURE 11. Random placement of 3 new base stations in a 1 × 1 square km., considering EMF effects of new base stations. Circle dots represent the existing base stations and red dots are the new base stations.

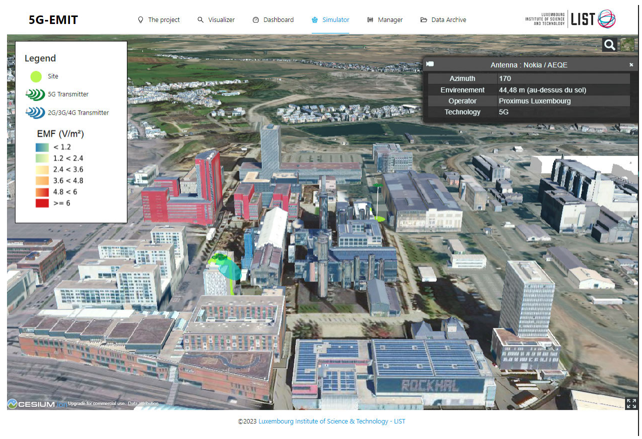

FIGURE 12. EMF assessment in Belval using LIST platform simulator.

EMF exposure levels is the fact of having many base stations together closer to the user. In addition, this is an example that can be set for any scenario (i.e., bigger original scenario or include more base stations in a latter stage, rather than 3). The only logical problem is that if we tend to make the new set of base stations very large, and we are tight on EMF exposition levels, one of the conditions may need to be loose.

This is a theoretical study in the early stage. We have deployed a Matlab simulation using the EMF and rate constraints explored in Section III. However, this still needs to be tested in a real environment. To prove the effectiveness of the algorithm in a realistic scenario, we suggest different alternatives to be evaluated and compared by using:

- Higher-level simulators or network planning solutions, such as Atoll from Forsk. Since it has a function of placement of base stations and an EMF exposure assessment evaluation, it could show the effects in the EMF exposure of our placement algorithm in detriment to the random placement.
- Within the context of the project supporting the present study, we have developed an assessment platform for EMF exposure in Luxembourg. This platform integrates real data obtained from different sensors to accurately measure the EMF exposure, together with infrastructure data (e.g., base station location and radio parameters). In Fig. 12, we show an example of the EMF exposure in Belval, a small region in the cross-border area between Luxembourg and France. Although it shows the base stations that are currently installed, more base stations can be manually added. Therefore, a comparison between the random placement and our approach can be done, to illustrate the benefits of our placement algorithm. Since the assessment of the EMF in the platform considers all the possible fluctuations due to the different elements such as the buildings or the natural subtleties of the terrain, an accurate 3D modeling of an area can be depicted, and therefore an EMF exposure can be compared using different methodologies. In [26] and [27], we show some results about the assessment that we took with the sensors and showed with the platform. In a follow-up project, we plan to extend those measurements and apply the theoretical results of this paper to a real testbed.

VII. CONCLUSION

This paper studies the achievable SNR by a certain number of users that connect simultaneously to a base station. We consider that the gNB has a large number of antennas (massive MIMO) and can therefore allocate different users at the same time. Upon this consideration, we evaluate different use cases considering the overhead to attempt the connection to a bigger number of antennas, and the number of antennas-gain dependencies.

Based on these results, an operator may ask how many users can be allocated to each resource (in our case, the base stations). For different configurations, we study how the blockage, the density of the base stations, or the availability of closer or further base stations affect the decision. We stressed that there is no optimal resource allocation. Instead, it largely depends on the user demand (i.e., minimum SNR or rate for each use case) for the operator to evaluate which is the maximum number of users to allocate (at the minimum rate required by them) and the minimum number of users it can be allocated (considering EMF and overhead constraints) which will obtain their maximum rate. This trade-off is the main purpose of this study.

In addition, we have shown that the placement of new base stations offers also some flexibility within these parameters of the EMF exposure levels. However, we leave for future work to optimize this placement even further, with more tight conditions regarding, for instance, fulfilling those conditions in a multi-user environment or other QoS constraints.

Following this line of research, multi-connectivity with more than two base stations should be considered. This will bring into consideration a higher number of antennas, which, as we have studied, can be beneficial but also have some drawbacks. This trade-off will be part of our future work. Also, heterogeneous networks with different types of frequencies and transmit power (i.e., small cells, macro cells) will need to be considered for the optimization problem. This will need to be considered in the follow-up of the user association problem, considering the EMF exposure. Finally, a joint evaluation of these parameters and an integration of the model into a real test-bed can result in a more realistic approach within the follow-up directions.

Furthermore, we leave for future work an enhancement of uplink communications: In beyond-5G and 6G mobile generations, users are expected to have the same data rate in UL and DL communications. A balanced link is required in applications involving Device-to-device (D2D) communications or Internet-of-things (IoT) applications. Therefore, a similar optimization of the EMF exposures in the UL link could be a potential line of research. Similarly, since transmitting power will increase to balance UL-DL links, the EMF exposure will also increase in the UL link, and consequently the SAR. Therefore, mitigation EMF techniques on the UL link will become specifically necessary.

In addition to that, we aim to introduce an ongoing developing platform for EMF evaluation and mitigation effects, where we will be able to apply these optimization algorithms to a real scenario with real EMF measurements.

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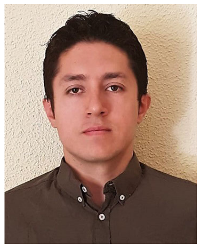

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