How Many Transmission Reception Points to Deploy in a User-Centric Distributed Massive MIMO Network?

Juan F. M. Oliveira, André L. P. Fernandes, Daynara D. Souza, Yasmim K. C. Costa, André M. Cavalcante and João C. W. A. Costa

***Abstract*— User-centric (UC) distributed massive multiple-input multiple-output (D-mMIMO), or cell-free massive MIMO, is a novel wireless technology that improves spectral efficiency and provides uniform coverage in sixth-generation mobile networks (6G). However, properly dimensioning the amount of transmission and reception points (TRPs) for effective network operation is still a challenge. Unlike traditional cellular systems, the user's equipment can connect to multiple TRPs, leading to dynamic connections. This paper presents a methodology to estimate the minimum number of TRPs required in UC D-mMIMO systems, considering realistic user distribution and TRPs' unique coverage constraints. Results are presented for downtown and residential urban scenarios.**

***Keywords*— Cell-free massive MIMO, User-centric networks, TRP dimensioning, 6G mobile networks**

I. Introduction

User-centric (UC) distributed massive multiple-input multiple-output (D-mMIMO) networks, also known as cell-free massive MIMO, are ultra-dense wireless networks where a large number of distributed transmission and reception points (TRPs) cooperate to process, transmit, and receive user equipment (UE) signals. These networks significantly increase the spectral efficiency (SE) and promote a more uniform quality of experience in the mobile network coverage area, making UC D-mMIMOs a key technology for 6G systems. Consequently, solutions have been developed to enable the feasible operation of these networks, including scalable solutions for signal processing and fronthaul deployment [1][2][3].

Despite these advances, most studies on the operation or implementation of UC D-mMIMO assume a fixed number of TRPs, which compromises the feasibility evaluation of these systems [1][2][3]. Proper network dimensioning, which includes TRP count planning to meet user demands and minimum service requirements, is particularly challenging in UC D-mMIMO, where UEs can connect to multiple TRPs, and these connections can change dynamically depending on variable conditions. As a result, there are no fixed coverage areas to individually estimate the demand supported by each TRP in the same way as traditional cellular networks.

Due to this difficulty, even deployment cost analyses, such as the one in [4], often rely on fixed TRP counts. An exception to that is [5], which proposes a more flexible deployment model based on coverage and capacity constraints. However, the coverage side of the dimensioning was estimated by dividing the UE count by the number of pilots at each TRP, disregarding the necessary minimum channel quality for effective service. For instance, in a network with 100 UEs, if a TRP can serve 10 users, the expected minimum number of TRPs required would be 10. However, this is likely underestimated due to geographical factors and user distribution. Some users may not be viable to any TRP, so that additional TRPs will be needed beyond this basic calculation.

This paper proposes a Genetic algorithm (GA)-based methodology to estimate the minimum number of TRPs required to ensure coverage in georeferenced regions, utilizing an approximation of real-world data for user distribution. The GA was chosen due to the large search space and the off-line nature of the problem, which makes metaheuristics like the GA suitable in terms of convergence time and approximation to global optimization. As such, the main contributions of this paper are: (1) a methodology for determining the minimum number of TRPs to operate a UC D-mMIMO network, (2) a technique for evaluating an approximation of the peak user distribution in georeferenced areas using open databases, and (3) a comparison of radio counts for cellular and UC D-mMIMO deployments, considering Capital Expenditure (CAPEX) aspects.

II. Network Dimensioning Methodology

It is assumed a UC D-mMIMO where each TRP can serve up to τ_p UEs, which is equal to the number of orthogonal pilot sequences for channel estimation in the system [5]. Based on that, Fig. 1 illustrates the network dimensioning methodology, comprising four key steps: (i) area definition, (ii) coverage-based dimensioning, (iii) capacity calculation, and (iv) capacity-based dimensioning. The area definition identifies the geographical characteristics and hotspot regions using data from Opencell ID and Google Maps [6] [7]. Coverage-based dimensioning allocates TRPs according to user distribution and limitations per TRP. The goal is to minimize the TRP count

Juan F. M. Oliveira[1], André L. P. Fernandes[1], Daynara D. Souza[1,2],Yasmim K. C. Costa[1], André M. Cavalcante[3] and João C. W. A. Costa[1]. [1]Applied Electromagnetism Laboratory, Federal University of Pará - UFPA, Belém, Brazil, [2]Lappeenranta-Lahti University of Technology, Lappeenranta, Finland, [3]Ericsson Research, Ericsson Telecomunicações Ltda., Indaiatuba, Brazil. E-mails: juan.oliveira@itec.ufpa.br; andrelpf@ufpa.br; daynara.dias.souza@lut.fi; yasmim.costa@itec.ufpa.br; andre.mendes.cavalcante@ericsson.com; jweyl@ufpa.br. This work was partially supported by Ericsson Telecomunicações Ltda, CNPq and CAPES.

required for the UC D-mMIMO network while maximizing user coverage. Subsequently, capacity calculation determines the expected user rate based on the system model. If the network capacity meets user demand, the process concludes. Otherwise, the final step involves determining the necessary TRPs to satisfy user rate requirements by interpolating pre-calculated user data rates for defined TRP counts.

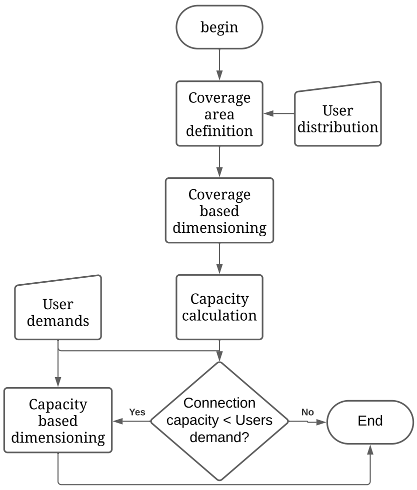

Fig. 1. Network dimensioning methodology.

A. Coverage area definition and user distribution

Algorithm 1: User distribution heatmap based on base stations and hotspot regions

Input: **AREA_COORDS[]**, **OPENCELL_DATA[][]**, **HOTSPOT_INFO[][]**, α_{ope}
FILTER **OPENCELL_DATA** located within **AREA_COORDS**
INITIALIZE U
foreach *filtered radio in* **OPENCELL_DATA do**
  ESTIMATE max users for available resources
  DISTRIBUTE users in the radio coverage
  $U \leftarrow$ Overlap the distribution with current heatmap
foreach *line in* **HOTSPOT_INFO do**
  EXP_USERS $\leftarrow$ (1)
  if HOTSPOT_INFO*[line][user column]* > ***EXP_USERS*** **then**
    MODIFY the U to reflect **HOTSPOT_INFO***[line][user column]*
Output: U

The base scenario is defined by gathering map and satellite information, considering a specified area. Based on this definition, a user distribution heatmap (U) is obtained from Algorithm 1 using Opencell ID and Google Maps data [6] [7]. The algorithm takes as input the following variables: **AREA_COORDS**, **OPENCELL_DATA**, **HOTSPOT_INFO**. The first is a complex array whose size is equal to the number of vertices defining the boundary of the analyzed area. The second is a complex matrix with dimensions equal to the number of radios by three, where each column represents position data as a complex number, coverage range as a real number, and the type of radio as a natural number, respectively. The third is a complex matrix with dimensions equal to the number of hotspots by $N_{vert}^{Max} + 1$, where N_{vert}^{Max} is the maximum number of vertices in any hotspot. Most columns represent the polygon vertices that define the hotspot region as complex numbers, while one column indicates the amount of users associated with that hotspot as a real number.

The OpenCell ID data is filtered to remove the radios located outside the defined area. Then, the maximum number of users each remaining radio can support is estimated based on available resources. This involves setting a target data rate and determining the maximum number of users that can be served while still meeting this rate. For example, according to IMT-Advanced requirements, LTE radios should be able to ensure a data rate of 10 Mbps per user.

Then, each radio's calculated number of users is distributed across its range, which can be done uniformly or radially (concentrating users closer to the radio). Afterward, the user distributions of all radios are overlapped to obtain a 3D heatmap U that describes the users' distribution within the analyzed area.

Then it is possible to estimate the number of users inside any hotspot region delimited by the polygon S that exists in **HOTSPOT_INFO** through the following calculation

$$K = \alpha_{\text{ope}} \cdot \iint_S U \, d\text{A}, \tag{1}$$

where α_{ope} is the operator's market share in the analyzed area, dA corresponds to the infinitesimal element of area, which is given by $d\text{lat} \cdot d\text{lon}$.

This value is compared to the expected value of users in the hotspot from sources outside OpenCell ID, which is previously saved in **HOTSPOT_INFO** before the execution of Algorithm 1 and is calculated by

$$K_h = P(S).\alpha_{\text{mpen}}.\alpha_{\text{ope}}.\alpha_{\text{peak}}, \tag{2}$$

where $P(S)$ represents the peak occupation in amount of persons of the hotspot delimited by the polygon S, α_{mpen} corresponds to mobile network penetration over the population, and α_{peak} accounts for the parcel of active users during peak traffic periods.

If the number of users of the OpenCell ID inside the hotspot region S is significantly smaller than K_h, then U inside the region S is scaled so that (1) returns K_h.

B. Coverage Based Dimensioning

Fig. 2 illustrates the proposed approach for dimensioning limited by coverage in UC D-mMIMO systems. The distribution of TRPs based on the user distribution U. The algorithm estimates the initial quantity of TRPs ($\mathbf{N}_{\text{TRPs}}$) based on the ratio between the total number of users and the number of users that each TRP can serve.

Then, the number of $\mathbf{N}_{\text{TRPs}}$ is spread over the map following the heatmap distribution. After this initial allocation, all users

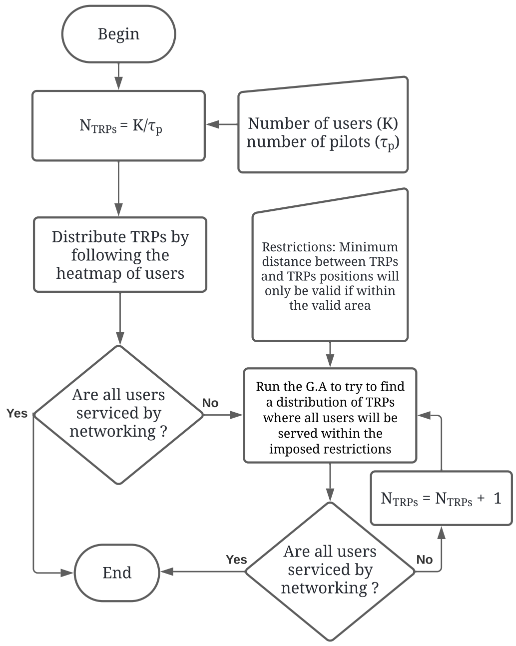

Fig. 2. Coverage Based TRP amount dimensioning methodology, it uses a genetic algorithm to find a valid AP distributions.

are properly checked to be supported by the current TRP configuration, considering the TRP resources and coverage range.

If all users are properly served, the algorithm ends and returns the current TRP configuration. Otherwise, an optimization phase begins. In this stage, a GA is applied to find a valid distribution of the existing $\mathbf{N}_{\text{TRPs}}$. To this end the GA minimizes an objective function representing the amount of users without TRP connections for a given distribution of TRP position, which is given by

$$\begin{aligned}
&\min_{p_\ell=\{p_1,\dots,p_L\}} \quad f_0(K,p_\ell) = K - \sum_{k=1}^{K} \frac{|\mathcal{M}_k(p_\ell)|}{\max(|\mathcal{M}_k(p_\ell)|,1)} \\
&\text{subject to:} \\
&\|p_l - p_{l'}\| \geq \rho_s, \quad \forall l \neq l', \quad l,l'=1,\dots,L \\
&p_l \in \mathcal{A}, \quad \forall l = 1,\dots,L \\
&\beta_{l,k} \leq \beta_{th}, \quad \forall l=1,\dots,L,\ k=1,\dots,K
\end{aligned} \tag{3}$$

where p_ℓ represents the set of TRP positions, K is the total number of users, p_l is the position of TRP l, and p_k is the position of UE k, and $\beta l, k$ denotes the large-scale channel gain between TRP l and UE k. Additionally, the set $\mathcal{M}(p_\ell)$ refers to the collection of TRPs serving UE k for a given set of TRP positions p_ℓ, ρ_s represents the minimum separation distance between any two TRPs, and $\mathcal{A}$ defines the set of all feasible deployment positions for TRPs. This area incorporates the analyzed coverage region while excluding zones where TRP installation is not allowed, such as water bodies and protected environmental areas. Finally, β_{th} denotes the minimum large-scale channel gain threshold for a TRP to be considered operational.

If GA finds a feasible configuration that satisfies all these conditions, the algorithm is terminated. Otherwise, the number of TRPs is incremented ($\mathbf{N}_{\text{TRPs}} = \mathbf{N}_{\text{TRPs}} + 1$) and the process returns to the distribution phase. This cycle repeats until a viable configuration is found. The output of the algorithm is the minimum number of TRP required for network dimensioning.

C. Capacity Based Dimensioning

Capacity-based dimensioning is performed according to the system model and the dimensioning described in Subsection III of [5]. A set of various numbers of TRPs is used to calculate different expected data rates, forming a second set. Each element of the first set is exclusively linked to an element in the second set, allowing for the determination of expected data rates for different TRP quantities. For TRP counts not explicitly defined in the set, the rates are derived by interpolation. In this work, the minimum number of TRPs in the TRP count set is identified based on coverage-based dimensioning. Besides that, the average user data rate is treated as the expected data rate. However, the model presented in this work can also operate based on an agreed-upon data rate parameter from [5].

III. Numerical Results

A. Case Study

The considered scenarios are shown in Fig. 3 and include two 2.25 km^2 areas within Belém city in Pará, Brazil. One area corresponds to a downtown region featuring shopping malls, crowded open markets, and tourist attractions, while the other is a residential neighborhood with no significant points of interest aside from a school and a cemetery. These regions represent two distinct common urban profiles that arise from differences in land use and human activity, which can significantly affect the design of wireless systems. The downtown area includes two hotspot areas poorly covered in the OpenCell ID approximation, marked by blue borders. User distribution in these areas was derived from daily visitor data provided by the municipal government, which was analyzed over the day using information from Google's Popular Times service [7].

Scalable distributed processing for precoding using Local Partial Minimum Mean Squared Error (LP-MMSE) and centralized processing using Partial Minimum Mean Squared Error (P-MMSE) were assumed. A pilot length of 16 was chosen to reflect the current multiuser massive MIMO capabilities in Fifth Generation of mobile networks (5G). Additionally, pilot lengths of 8 and 24 were also considered for some analyses, with the latter representing a realistic capability expansion for current systems. The bandwidth is set to 100 MHz in a single contiguous carrier and the remainder of the radio parameters were the same as in [5].

The calculation of the number of deployed TRPs takes into account a confidence level. Realistically, a single fixed configuration with just one TRP count cannot work in all user configurations, as unexpected user concentrations or isolation may occur. Therefore, a TRP count that supports most scenarios is considered a robust solution. In the analysis, confidence levels of 95% and 99% are utilized. Finally, the GA used 25 individuals, 500 generations, elitism 1, tolerance 10^{-3}, and tournament selection with scattered crossover.

The coefficients α_{mpen}, α_{ope} and α_{peak} were assumed to be 0.859, 0.333 and 0.3491, respectively, which were derived from official demographic and statistical data [8], [9].

Fig. 3. Satellite imagery of the considered scenarios, both located in Belém, Pará: on the left, the Downtown region (Campina neighborhood); on the right, the Residential region (Marambaia neighborhood). The blue polygons indicate hotspot areas that were not well covered by the user distribution method based on OpencellID data.

B. Deployed TRP count Results

Fig. 4 shows the minimum required amount of TRPs needed to effectively operate a UC D-mMIMO network, providing results for the considered pilot counts and confidence levels regarding the adequacy of coverage related to the TRP value shown. Additionally, the gray and dark gray curves represent a naive estimate obtained by simply dividing the number of users by the length of the pilot sequence. An interesting highlight in the figure is that increasing the TRP count confidence levels from 95% to 99% appears to have only significant effects in the downtown scenario. For instance, the largest increase in TRP count for downtown area between the two percentage levels was 80 TRPs, compared to just 21 TRPs for residential areas. Besides that, for the highest considered pilot count, the increase was similar both scenarios. It is also noted that the expected reduction in required TRPs with an increase in pilot count becomes less significant at higher pilot counts. For instance, by taking the downtown 95% confidence results as a baseline, doubling the number of pilots from 8 to 16 reduces the TRP count by 51.4%. However, tripling the number of pilots from 8 to 24 only leads to a 69.8% reduction in TRP count. This suggests that increasing the pilot count to very high values results in diminishing returns.

Fig. 5 shows the minimum number of TRPs needed to support different user demand levels, expressed as achievable UE rates over a 100 MHz contiguous carrier. A 95% confidence level in the adequacy of the presented TRP count and a pilot length of 16 are assumed. The inset highlights the initial points of each curve, where each marker indicates the maximum user rate demand that can be supported with the minimum number of TRPs for each configuration. Due to coverage-limited operation, the TRP count remains constant up to the following user demands: 55.5 Mbps for residential LP-MMSE, 39.6 Mbps for residential P-MMSE, 44.7 Mbps for downtown LP-MMSE, and 71.1 Mbps for downtown P-MMSE. These

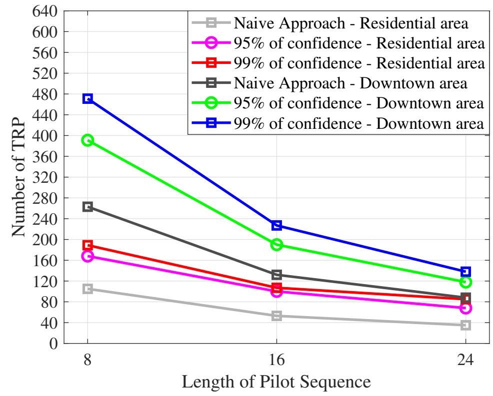

Fig. 4. Minimum number of required TRPs as a function of pilot sequence length, considering 95% and 99% confidence levels for both Downtown and Residential areas.

rates suggest that user demands between 150 and 300 Mbps can be satisfied by carrier aggregation of up to four low-frequency carriers, in line with the 5G experienced user rate targets. To reach 300 Mbps with a single 100 MHz carrier, values between 482 and 5859 TRPs are required depending on the precoder and scenarios. Achieving 500 Mbps under the same conditions is only feasible with centralized P-MMSE, requiring 2103 TRPs downtown and 946 TRPs in residential areas.

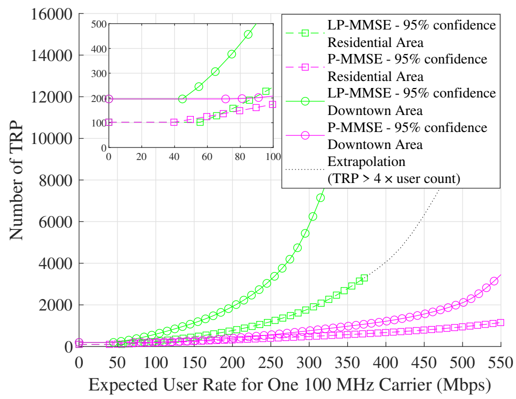

Fig. 5. Minimum number of TRPs to support varying user rates over a 100 MHz carrier, for LP-MMSE and P-MMSE precoders in Downtown and Residential areas (95% confidence, 16-pilot length).

The approximation for UE distribution obtained from the OpenCellID may have some imperfections, as there may be a low correlation between existing cells and user locations in hotspots with poor coverage. However, it is possible to define hotspots manually in Algorithm 1 to circumvent this problem. To verify the impacts of this possible dimensioning imperfection, Fig. 6 compares the results of the minimum TRP count of the downtown scenario with just OpenCellID data and with added hotspots not covered by the original data. Taking into consideration different pilot counts and confidence levels regarding the adequacy of coverage related to the TRP value shown.

The results show the same increase in TRP count for

99% and 95% confidence, and the main takeaway is that the result of the scenario with hotspots under 95% confidence is very similar to the 99% confidence without hotspots. This suggests that if one suspects poor hotspot coverage based on the OpenCellID data, a possible modeling solution is simply to increase the confidence level, instead of performing a detailed area-specific analysis, which is labor-intensive for large regions or when analyzing many regions simultaneously.

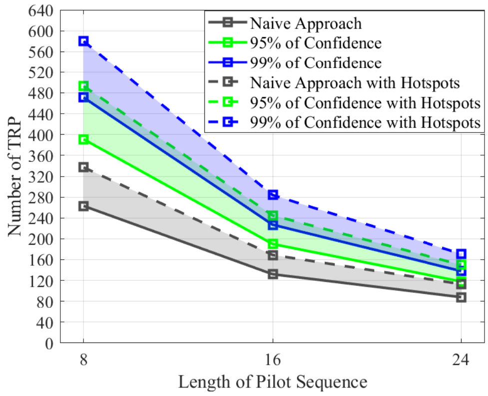

Fig. 6. Minimum TRP count in the Downtown scenario considering only OpenCellID-based user distribution versus including manually added hotspots, across different pilot lengths and confidence levels.

C. Cost Results

Fig. 7 illustrates the total CAPEX as a function of TRP deployment price for the downtown region, all cost are normalized by the maximum small cell deployment price in [10], which is the Cost Unit (CU) of the analysis. The cost calculations for the UC D-mMIMO are proportional to the deployment expenses of a small cell with integrated transport. In the case of cellular deployment, the overall costs include non-radio base station site setup, the cost of upgrading to 5G or initial deployment (which encompasses transport infrastructure), as well as additional frequency bands. A comprehensive breakdown of all considered costs can be found in [10].

The deployment options include brownfield cellular (infrastructure reutilization), greenfield cellular (new infrastructure), and greenfield UC D-mMIMO under two different confidence levels. For brownfield, only the 5G upgrade is considered for base stations installed before 2020, whereas full deployment costs are applied to stations installed after that date.

The curves show that UC D-mMIMO can potentially be more cost-effective than traditional cellular systems, provided that the price of its TRP falls below the maximum costs of current cellular options. Luckily, UC D-mMIMO is expected to have simpler TRPs. The crossover points on the curves represent the thresholds of economic parity between cellular systems and UC D-mMIMO. This suggests that UC D-mMIMO can be more feasible than cellular systems, assuming that TRP costs are reduced by 11% to 35% concerning current systems.

Results are not shown for residential areas, but cellular systems were always more feasible in this case.

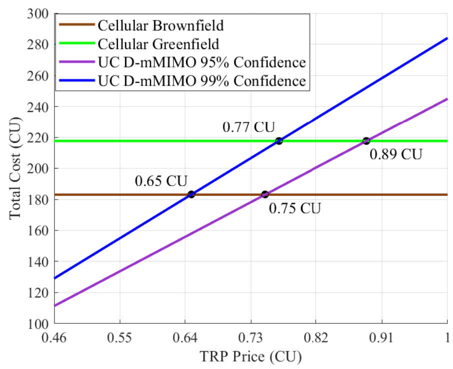

Fig. 7. Total cost analysis between UC D-mMIMO and cellular deployments for varying TRP prices. Crossover points indicate breakeven cost levels.

IV. Conclusions

This paper presented a methodology for estimating the minimum number of TRPs required in a UC D-mMIMO network, factoring in a proposed realistic user distribution estimation method. The methodology employed a GA based optimization for coverage dimensioning. The simulation results showed that previous coverage dimensioning strategies underestimated required TRP counts. It is shown that only centralized processing supports extreme demands under reasonable TRP counts. Additionally, raising the required algorithm confidence level for the deployed TRP count effectively models scenarios where hotspots are not well-covered in the coverage databases used to generate user distributions. Finally, cost results indicate that UC D-mMIMO can be cost-competitive in dense urban areas. Future works include mobility and ray tracing considerations.

References

[1] Ö. Demir, E. Björnson, and Sanguinetti, *Foundations of User-Centric Cell-Free Massive MIMO*. Foundations and Trends® in Signal Processing, 2021, vol. 14, no. 3-4.

[2] H. Q. Ngo, G. Interdonato, E. G. Larsson, G. Caire, and J. G. Andrews, "Ultradense cell-free massive MIMO for 6G: Technical overview and open questions," *Proceedings of the IEEE*, vol. 112, no. 7, pp. 805–831, 2024.

[3] M. M. M. Freitas, D. D. Souza, A. L. P. Fernandes, D. B. da Costa, A. Mendes Cavalcante, L. Valcarenghi, and J. C. Weyl Albuquerque Costa, "Scalable user-centric distributed massive MIMO systems with restricted processing capacity," *IEEE Trans. Wireless Commun.*, vol. 23, no. 12, pp. 19 933–19 949, 2024.

[4] Y. Xiao, P. Mähönen, and L. Simić, "System cost analysis of scalable cell-free massive MIMO architectures for 6G networks," in *Proc. IEEE Globecom Workshops*, 2022, pp. 310–316.

[5] A. L. P. Fernandes, D. D. Souza, C. Natalino, F. Tonini, A. M. Cavalcante, P. Monti, and J. C. W. A. Costa, "A cost assessment methodology for user-centric distributed massive MIMO architectures," *IEEE Open J. Commun. Soc.*, vol. 5, pp. 3517–3543, 2024.

[6] Unwired Labs. OpenCelliD - open database of cell towers. Accessed: April 18, 2025. [Online]. Available: https://www.opencellid.org/

[7] Google LLC. Google maps - mobility and location data. Accessed: April 18, 2025. [Online]. Available: https://www.google.com/maps

[8] Instituto Brasileiro de Geografia e Estatística (IBGE). Population statistics on age distribution and mobile phone usage. Accessed: April 18, 2025. [Online]. Available: https://sidra.ibge.gov.br

[9] Agência Nacional de Telecomunicações (Anatel). Estações do smp – painel de outorga e licenciamento. Accessed: April 18, 2025. [Online]. Available: https://informacoes.anatel.gov.br/paineis/outorga-e-licenciamento/estacoes-do-smp

[10] 5G PPP: METIS-II Project, "Deliverable D1.2: Quantitative techno-economic feasibility assessment," Nov. 2017. [Online]. Available: https://metis-ii.5g-ppp.eu/wp-content/uploads/deliverables/METIS-II_D1.2_V1.1.pdf