

# Assessment of Radiofrequency Electromagnetic Field (RF-EMF) Potential Exposure in Buildings

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**Abstract**—Building upon a methodology previously established by the authors, this study uses publicly available Base Station (BS) deployment records from the Mosaico database, maintained by the Brazilian National Telecommunications Agency (ANATEL), to characterize buildings directly exposed to Radiofrequency Electromagnetic Fields (RF-EMF) in four cities in Northeastern Brazil. Demographic indicators from the Brazilian Institute of Geography and Statistics (IBGE) were incorporated to support comparative analyses of the factors associated with these exposure scenarios. A total of 34, 29, 13, and 19 target buildings were identified in Natal, Maceió, Aracaju, and João Pessoa, respectively. The results show that the occurrence of target buildings is driven by multiple factors rather than solely by BS density or urban verticalization, also depending on subscriber profile distribution and operators' BS deployment strategies. Furthermore, the findings highlight the importance of neighborhood-level disaggregated data for statistical analyses of the factors associated with this exposure scenario.

**Keywords**—Non-Ionizing Radiation, Electromagnetic Fields, Buildings, 5G.

## I. INTRODUÇÃO

The most recent auction of frequency bands for fifth-generation (5G) mobile networks in Brazil has accelerated the deployment of new radio access infrastructure [1] and expanded the operator licensing landscape [2] in Brazil. The entry of new operators into the market, combined with incumbent carriers' reconfiguration of existing radio access infrastructure to meet network coverage and capacity requirements, has resulted in a substantial increase in BS deployment across highly urbanized areas. As a result, new scenarios of Radiofrequency Electromagnetic Field (RF-EMF) exposure have emerged, along with a rise in already known exposure cases.

In this context, the International Commission on Non-Ionizing Radiation Protection (ICNIRP) and the Brazilian National Telecommunications Agency (ANATEL)

play central roles in establishing safety limits [3] and regulating RF-EMF exposure [4], respectively.

However, although the ANATEL guidelines [4] comprehensively define the locations for RF-EMF exposure assessment, these evaluations predominantly occur at street level through drive tests [5], [6]. Such an evaluation approach disregards the higher exposure potential on the upper floors of buildings directly exposed to emissions from BS antennas.

Previous investigations conducted by [7] and [8] identified significantly higher exposure levels on building floors directly exposed to antenna emissions compared with those measured at street level. These studies also highlighted the existence of critical exposure cases, in which the target building is situated along the boresight direction of the transmitting antenna, within the intersection of the vertical and horizontal Half-Power Beamwidth (HPBW) planes, thereby being subject to the maximum radiated power density of the main lobe.

According to data from the Brazilian Institute of Geography and Statistics (IBGE), the Northeast region experienced a 2.87-fold increase in the number of occupied apartment-type dwellings between 2000 [9] and 2022 [10], indicating a regional verticalization trend, particularly in the state capitals. Therefore, this article constitutes a direct extension of the work reported in [7], broadening its methodological scope to encompass a systematic assessment of the potential RF-EMF exposure scenario of buildings across four municipalities in the Brazilian Northeast (Aracaju, João Pessoa, Maceió, and Natal), and introducing an analysis of the demographic and network-technical parameters that influence the occurrence of such scenarios.

The remainder of this paper is organized as follows. Section II reviews related work and outlines the contributions of this study. Section III describes the dataset origin and investigation methodology. Section IV presents and discusses the results, while Section V summarizes the main conclusions and presents further investigations.

## II. RELATED WORKS

Large-scale RF-EMF exposure assessments in indoor building environments have been conducted in several studies in the literature. Some studies have conducted measurements to develop exposure estimation models for indoor environments [11]–[13], while studies such as [14]–[16] have conducted measurements to identify the contribution of each radio technology to RF-EMF exposure levels. Other studies, such as [17], have explored the correlation between RF-EMF exposure and epidemiological indicators in neighborhoods surrounded by multiple BSs.

In previous works, we analyzed the general population's exposure to RF-EMF from different sources and across

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multiple environments. Among the studies, in [18], we measured the exposure levels of distributed antenna systems (DAS) and Wi-Fi networks in a shopping center. Considering residential indoor exposure, we evaluated the exposure levels of Wi-Fi access points and microwave ovens in dwellings [19] as well as an atypical case of high exposure involving a microwave oven [20].

In [21], we conducted outdoor measurements in the city of Natal, while in [22], we investigated RF-EMF exposure over a 24-hour period in buildings located at different distances from radio, television, and cellular BSs. In [7], we proposed a methodology for selecting buildings directly exposed to BS antennas emissions using publicly available data, which served as the foundation for the present work. Most recently, in [8], we performed a vertical assessment across all floors of a 20-story building classified as a critical case according to the methodology established in [7].

Despite the large body of related work, to the best of our knowledge, no prior study has analyzed the relationship between demographic and network technical data and worst-case exposure scenarios in buildings. Therefore, the main contributions of this work are:

- Application of the target-building selection methodology proposed in [7] to four cities in the Brazilian Northeast, including three which had not previously been analyzed.
- Improvement of the methodological procedures previously introduced.
- Measurement-ready identification of new cases of RF-EMF potential exposure in buildings across different cities.
- Analyses of the multifactorial factors leading to the occurrence of target buildings in different cities.

### III. METHODOLOGY

We selected four cities in Northeastern Brazil as study objects: Natal, João Pessoa, Maceió, and Aracaju. Then, we collected urban indicators for the cities from the 2022 Demographic Census conducted by IBGE, as presented in Table I. The subsequent stages of the methodology were based on the approach established in [7], as explained in the following subsections.

#### A. Data Collection and Processing

On March 12, 2026, we downloaded the BSs dataset for each of the four cities via ANATEL's Mosaico platform [24]. For the subsequent analyses, we used the geographic coordinates (latitude and longitude), as well as the azimuth, elevation, height, and horizontal HPBW information associated with the BSs emissions.

Since the Google Street View imagery for most streets in Aracaju and Maceió dates back to 2024, before the deployment of most Brisanet 5G FWA support BSs, we excluded this operator's stations from the study and evaluated only stations from Claro, TIM, and Vivo mobile operators. This represents a methodological limitation of the present study, since recently deployed BSs may generate additional target buildings that could not be verified using the available Google Street View imagery. Therefore, the reported results should be interpreted as conservative estimates.

#### B. Visualization of the Horizontal Zones of Interest

Using Google Earth aerial imagery as the cartographic base and information collected from ANATEL's platform, we developed a Python application that overlays 100-meter-radius circles centered at each BS coordinates and graphically represents the azimuths and horizontal HPBW for the station, as shown in Fig. 1. Unlike [7], which performs this stage in two separate steps, we improved this procedure into a single application for this study.

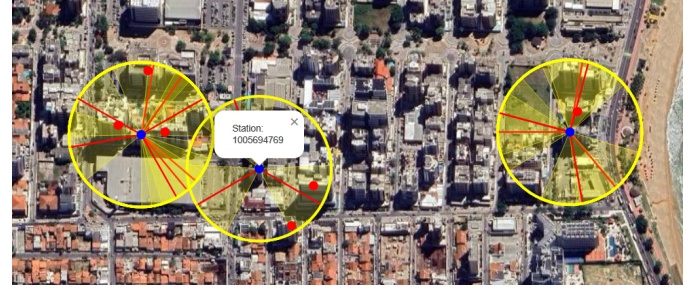


Fig. 1: Visualization of the BSs configuration with the developed application.

In this stage, we cataloged the target buildings located within the area covered by the horizontal HPBW of the BS emissions. These areas, highlighted in yellow in Fig. 1, were defined as horizontal zones of interest. In locations where multiple BSs share the same infrastructure, we configured the application to overlap the horizontal zones of interest.

#### C. Target Building Selection and Exclusion Criteria

To qualify as study objects, target buildings must not only lie within the horizontal zone of interest of a target BS, but also have at least one floor directly exposed to emissions from the respective target BS.

Therefore, the height relationship between the target building and the target BS antenna plays a relevant role in determining whether this criterion is satisfied. We identified three arrangement scenarios involving the height of the target building and the height of the target BS antennas:

- 1) The height of the target building exceeds the height of the antennas.
- 2) The height of the target building and the antennas are equal.
- 3) The height of the target building is lower than the height of the antennas.

When arrangement 1) occurred, the evaluated building was directly maintained as a study object because at least one floor was located above the antenna height. For arrangements 2) and 3), we performed an additional geometric verification to determine whether the antenna main beam, oriented toward the azimuth directed to the target building, intersected its facade. We used the antenna height ( $h_1$ ) and antenna elevation angle ( $\theta$ ) registered on ANATEL's platform, the geodesic distance between the BS and the target building ( $d$ ), and the estimated building height ( $h_2$ ), obtained using Google Earth Pro. Fig. 2 illustrates the adopted geometry.

According to the procedure established in [7], when Google Earth Pro does not provide the estimated height of the target building due to the absence of a 3D city map, we counted the building's floors and assumed each floor was 3 meters high to

TABLE I: Urban indicators of the evaluated cities.

| Metric                                                 | City     |          |          |             |
|--------------------------------------------------------|----------|----------|----------|-------------|
|                                                        | Natal    | Maceió   | Aracaju  | João Pessoa |
| Population (thousands) [23]                            | 751.30   | 957.916  | 602.757  | 833.932     |
| Territorial Area (km <sup>2</sup> ) [23]               | 167.40   | 509.30   | 182.16   | 210.04      |
| Population Density (inhabitants/km <sup>2</sup> ) [23] | 4488.03  | 1880.77  | 3308.89  | 3970.27     |
| Occupied Houses (thousands) [23]                       | 211.066  | 258.291  | 151.832  | 173.772     |
| Occupied Apartments (thousands) [23]                   | 58.901   | 77.440   | 66.649   | 122.441     |
| Percentage of Vertical Housing (%) [23]                | 21.82    | 23.07    | 30.51    | 41.34       |
| Average Salary (Minimum Wages) [23]                    | 2.80     | 2.40     | 2.60     | 2.70        |
| Municipal Human Development Index (MHDI) [23]          | 0.76     | 0.72     | 0.77     | 0.76        |
| Urbanized Area (km <sup>2</sup> ) [23]                 | 99.32    | 115.08   | 84.57    | 110.82      |
| Gross Domestic Product (GDP) per Capita (R\$) [23]     | 41477.50 | 35232.29 | 36983.19 | 34106.06    |

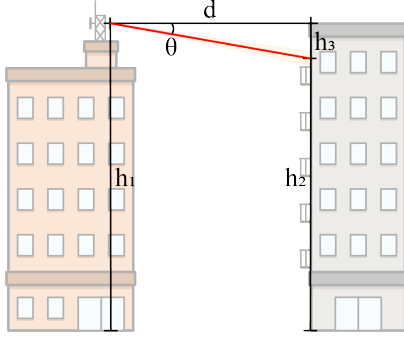


Fig. 2: Assessment of the target BS emission incidence on the target building.

estimate the building's height. This assumption represents an approximation, as floor-to-floor heights may vary depending on the building use and construction standard, particularly for commercial and high-end residential buildings. Consequently, the estimated incidence height may be affected by a small uncertainty, which could alter the classification of buildings whose beam incidence occurs close to the rooftop.

To determine whether the main beam intersected the target building facade, we first calculated the beam vertical displacement relative to the antenna height as

$$h_3 = d \cdot \tan(\theta), \quad (1)$$

where ANATEL reports downward antenna tilts as negative elevation angles. Therefore, the beam incidence height at the building facade is given by

$$h_{inc} = h_1 + h_3 = h_1 + d \tan(\theta). \quad (2)$$

The target building was considered a study object when the incidence height satisfied  $h_{inc} < h_2$ , indicating that the beam intersected the building facade. Otherwise, when  $h_{inc} > h_2$ , the beam passed above the rooftop and the building was excluded from the study. In addition, for all cases corresponding to arrangement 3) with an antenna elevation angle equal to zero degrees, we excluded the respective target building from the study because the main beam passes above its rooftop, without intersecting the facade.

#### IV. RESULTS

The analyses presented in this section are descriptive and exploratory in nature. Owing to the limited number of evaluated cities, no formal statistical inference or correlation analysis was performed. Therefore, the observed relationships between demographic indicators, network deployment characteristics, and the occurrence of target buildings should

be interpreted as qualitative trends rather than statistically validated associations.

Table II presents a set of telecommunication infrastructure parameters for the evaluated cities, either directly retrieved from the ANATEL database or readily derived from it, together with the corresponding results yielded by the application of the methodology, the latter of which are highlighted in bold for clarity.

Natal stands out as the city with the highest number of target buildings, totaling 34, although it presents the lowest number of apartment-type residences, as indicated in Table I. In contrast, João Pessoa, the city with the highest number of apartment-type residences, presented 19 target buildings. Maceió and Aracaju, in turn, presented 29 and 13 target buildings, respectively.

The same behavior occurred for the number of critical cases, with Natal reporting 12 cases, equivalent to 35.29% of the target buildings. Maceió, Aracaju, and João Pessoa presented 10, 4, and 3 critical cases, respectively, corresponding to 34.48%, 30.76%, and 15.79%.

The aggregate results across the four evaluated cities indicate that neither the absolute number of target buildings nor the proportion of critical exposure cases can be adequately explained by urban verticalization metrics or apartment-type residence density alone.

João Pessoa has the highest proportion of rooftop BSs per total BSs number among the evaluated cities, but it has only 9 target BSs in this category. This result can be mainly explained by two factors: (i) João Pessoa has taller buildings compared with the other analyzed cities; and (ii) the deployment profile adopted by operators in the city prioritizes the installation of BS on the tallest buildings in the region, favoring the occurrence of arrangements 2) and 3), described in Section III-C. Table II shows that both the average height of target buildings (82 m) and rooftop-type target BSs (58.08 m) are higher in João Pessoa than in the other cities.

Maceió is the only city where the average height of rooftop-type target BSs (33.80 m) falls below that of greenfield-type installations (36.43 m), which may have reduced the geometric advantage of rooftop deployments over surrounding buildings, limiting their associated target building count (13). This effect is contrasted by João Pessoa, where the higher rooftop-type average antenna height (58.08 m) correlates with a proportionally greater rooftop-type target BS count (9 out of 16 target BSs). Nevertheless, Maceió recorded the second-highest number of target buildings (29), suggesting that the higher count of greenfield-type target BSs (11) and their comparatively greater height compensated for the rooftop geometric limitation by sustaining favorable

TABLE II: Telecommunications infrastructure metrics of the evaluated cities.

| Metric                                                           | City  |        |         |             |
|------------------------------------------------------------------|-------|--------|---------|-------------|
|                                                                  | Natal | Maceió | Aracaju | João Pessoa |
| Number of BSs [24]                                               | 491   | 520    | 398     | 460         |
| Number of 5G BSs [24]                                            | 451   | 430    | 333     | 409         |
| Percentage of 5G BSs (%) [24]                                    | 91.85 | 82.69  | 83.67   | 88.91       |
| Total Number of Rooftop BSs                                      | 54    | 62     | 27      | 61          |
| BSs per km <sup>2</sup> of Urbanized Area                        | 4.94  | 4.52   | 4.71    | 4.15        |
| <b>Number of Target BSs</b>                                      | 31    | 26     | 14      | 16          |
| <b>Number of Target BSs with 5G</b>                              | 29    | 20     | 12      | 13          |
| <b>Number of Target BSs Rooftop-type</b>                         | 17    | 13     | 7       | 9           |
| <b>Number of Target BSs Greenfield-type</b>                      | 14    | 11     | 7       | 7           |
| <b>Number of Target Buildings</b>                                | 34    | 29     | 13      | 19          |
| <b>Number of Critical Cases</b>                                  | 12    | 10     | 4       | 3           |
| Average Target BSs Rooftop-type Antennas Height (meters) [24]    | 48.44 | 33.80  | 38.71   | 58.08       |
| Average Target BSs Greenfield-type Antennas Height (meters) [24] | 38.23 | 36.43  | 26.29   | 32.18       |
| Average Target Buildings Height (meters)                         | 62.02 | 41.50  | 41.50   | 82.00       |

line-of-sight conditions toward nearby buildings.

Natal has the highest density of BSs per km<sup>2</sup> of urbanized area (4.94), while João Pessoa has the lowest (4.15). Although Aracaju has a lower number of BSs, it exhibits a higher BS density than Maceió, with values of 4.71 and 4.52 BSs per km<sup>2</sup>, respectively.

All evaluated cities presented high percentages of 5G-enabled BS, with Natal and João Pessoa standing out at 91.85% and 88.91%, respectively. Maceió, the city with the lowest level of 5G coverage, also has the lowest percentage of 5G-enabled target BSs, corresponding to 76.92%.

Fig. 3 shows the distribution of target buildings across the cities, highlighting the neighborhoods with the highest concentrations. Additionally, Table III presents the average monthly income of household heads in the neighborhoods of each city, as well as the citywide average for this metric.

TABLE III: Average monthly income of people responsible for permanently occupied private households [25].

| City        | Citywide Average (R\$) | Neighborhood          | Neighborhood Average (R\$) |
|-------------|------------------------|-----------------------|----------------------------|
| Natal       | 4164,75                | Tirol                 | 12251,79                   |
|             |                        | Lagoa Nova            | 8365,86                    |
|             |                        | Capim Macio           | 8234,11                    |
| Maceió      | 3328,45                | Ponta Verde           | 11035,76                   |
|             |                        | Jatiúca               | 7934,04                    |
|             |                        | Pajuçara              | 7658,78                    |
| Aracaju     | 3783,51                | Jardins               | 16152,54                   |
|             |                        | 13 de Julho           | 12374,34                   |
|             |                        | Salgado Filho         | 7624,82                    |
|             |                        | São José              | 7460,52                    |
|             |                        | Atalaia               | 7020,19                    |
| João Pessoa | 3889,64                | João Agripino         | 14042,89                   |
|             |                        | Brisamar              | 10849,30                   |
|             |                        | Altiplano Cabo Branco | 10294,15                   |
|             |                        | Manaíra               | 8737,30                    |

All evaluated cities presented a higher concentration of target buildings in neighborhoods where the average income of the household head exceeds the citywide average, as shown in Table III. During the execution of the methodological procedure adopted in this study, we also observed that these neighborhoods have a higher concentration of buildings than other neighborhoods in the same city.

The neighborhoods of Lagoa Nova and Jatiúca, located in Natal and Maceió, respectively, had the highest concentrations of target buildings, with 11 each. Aracaju had the lowest concentration of target buildings per neighborhood, a behavior that may have resulted from the lower total number of target

buildings identified in the city.

Taken together, these findings underscore that the spatial distribution of BS deployments and the infrastructure configuration strategies adopted by network operators constitute more determinant factors in the characterization of RF-EMF exposure scenarios than demographic or verticalization indicators, highlighting the necessity of incorporating network-technical parameters into urban RF-EMF exposure assessments.

## V. CONCLUSIONS

This work presented an evaluation of potential RF-EMF exposure scenarios in buildings across four cities in the Brazilian Northeast and compared the results with IBGE demographic data at both the city and neighborhood levels.

Although the correlation between a higher number of BSs, a greater degree of urban verticalization, and a larger number of target buildings appears intuitive, the obtained results revealed that these metrics alone are insufficient to explain the number of target buildings identified in the evaluated cities. The observed results suggest that other factors, such as the regional income profile and the BS deployment strategy adopted by network operators, may also influence the occurrence of target buildings.

By analyzing neighborhoods with the highest concentration of target buildings, we identified city-level data granularity as a limitation of this study, as broader citywide indicators do not accurately capture the specific characteristics of each neighborhood.

Therefore, future work aims to expand the number of cities evaluated to enable more reliable statistical analyses and to complement the results presented in this article. We also intend to increase the territorial granularity of the analyses to the neighborhood level by gathering data from other sources, since the concentration of buildings in specific neighborhoods tends to bias statistical analyses conducted for the city as a whole.

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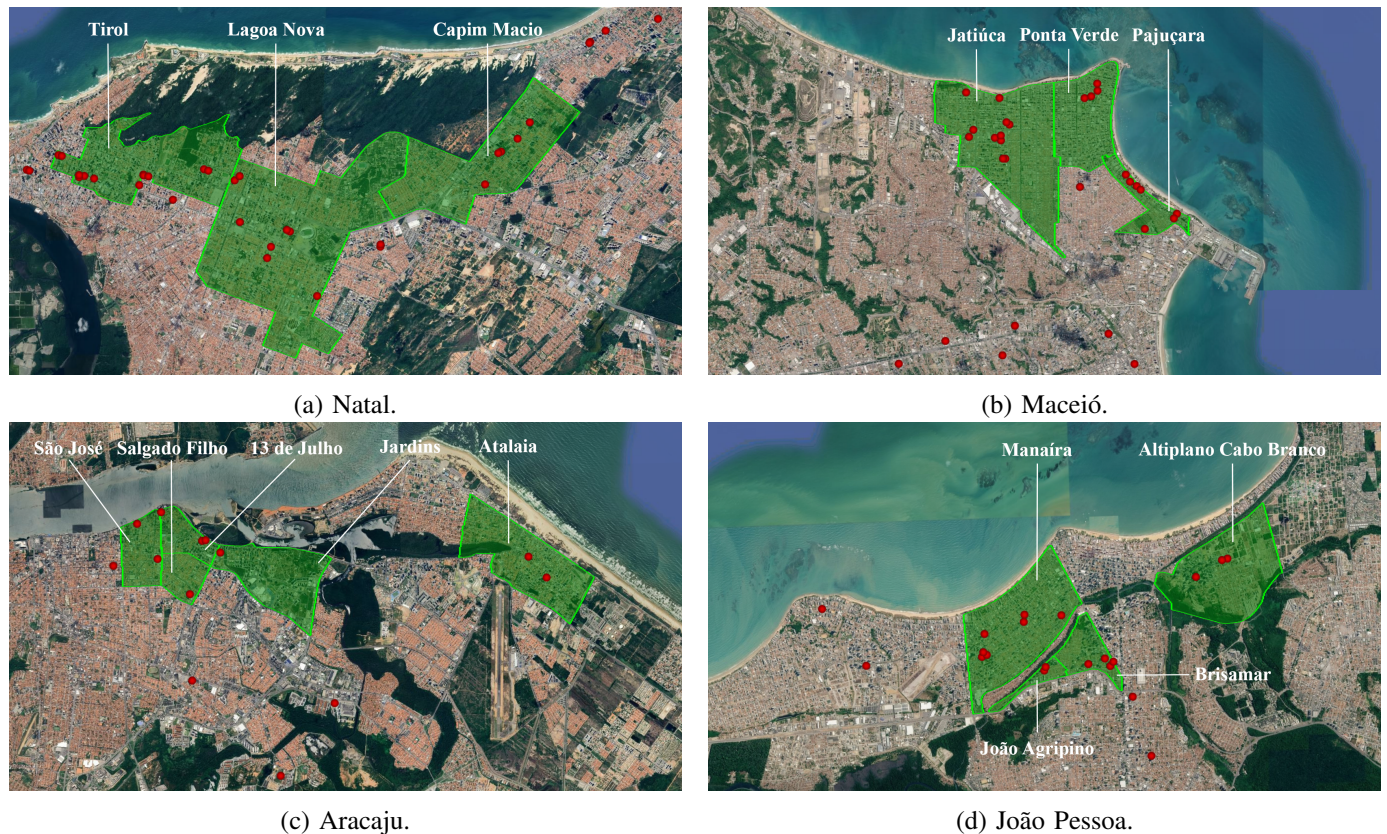


Fig. 3: Distribution of target buildings in the cities evaluated.

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