

Near-Field Multi-User Beamfocusing with XL-MIMO Arrays for 6G

Wêndria C. da Silva, Gilvan S. Borges, João C. Weyl A. Costa, André M. Cavalcante and Karlo Q. da Costa

Abstract—This paper investigates near-field multi-user beamfocusing using Extremely Large-Scale Multiple Input Multiple Output (XL-MIMO) systems, composed of a 100×100 dipole array operating at 28 GHz. The electromagnetic behavior of the array is modeled using the Method of Moments (MoM), allowing the calculation of the electric field in the near-field region. Eight users positioned in different spatial locations are considered, including scenarios with the same angular directions but different radial distances. The results demonstrate the ability of near-field beamfocusing to promote spatial focusing in both the angular and radial domains, enabling effective user separation. Furthermore, the power received by each user and the signal-to-interference-to-noise ratio (SINR) are evaluated; the results demonstrated improvements on performance of the proposed system.

Keywords—Near-field, XL-MIMO, 6G, multi-user beamfocusing, SINR.

I. INTRODUCTION

The consolidation of fifth-generation (5G) wireless networks has significantly boosted scientific and technological interest in the development of future 6G networks. Unlike previous generations, 6G networks are designed in a more visionary and performance-oriented way, seeking to meet more ambitious requirements for capacity, latency, reliability, and spectral efficiency compared to the current generation.

Historically, wireless communication systems, from 1G to 5G, operate predominantly in frequency bands below 6 GHz. In these bands, the physical constraints associated with the spacing between radiating elements, proportional to the wavelength, limit the number of antennas that can be implemented in an array of practical dimensions [1].

As a consequence, relatively small arrays and lower frequencies limit the near-field region to reduced distances, justifying the classical far-field modeling, where waves are approximated as planar. However, the exponential growth in the number of users, the diversity of services, and the demand for high data rates highlight the saturation of these approaches, since the spectrum is limited and capacity depends on interference management and the efficient use of spatial resources [2].

To overcome these limitations, techniques such as cell division and sectorization have been widely used to increase frequency reuse and improve the signal-to-interference-to-noise ratio (SINR). Although effective, these strategies increase network complexity and impose operational limitations, such

as a greater number of handoffs and less coverage flexibility [3].

In this context, the evolution to 6G requires more profound changes. Extremely large-scale MIMO (XL-MIMO) systems emerge as a promising alternative, allowing advanced spatial control through beamfocusing, dynamic coverage adjustment, and greater interference suppression.

This approach significantly expands the occurrence of near-field scenarios, challenging traditional far-field based models. Unlike the classical regime, near-field propagation requires spherical wave modeling, revealing phenomena such as spatial non-stationarity, tripolarization, evanescent waves, and spatial focusing. These effects introduce new degrees of freedom but also represent challenges for conventional communication algorithms [1].

Thus, antenna arrays operating in the near-field allow precise control of the spatial distribution of energy, adjusting the amplitudes and phases of the elements, favoring the fulfillment of 6G requirements. In this context, this work investigates the electromagnetic behavior of a dipole array operating at 28 GHz, focusing on its ability to serve multiple users simultaneously in the near-field region. The analysis of received power and SINR shows significant performance gains, reinforcing the potential of near-field beamfocusing as an enabling technology for XL-MIMO-based 6G systems.

Unlike most recent studies, which adopt simplified channel models based on spherical waves, this work investigates near-field beamfocusing from an electromagnetic perspective by modeling the antenna array using the Method of Moments (MoM). The proposed approach enables the calculation of the current distribution on each dipole element and the resulting electromagnetic fields prior to the beamfocusing stage, allowing for a more realistic assessment of linear and planar arrays. The main contributions of this work consist of the development of a full-wave MoM model for near-field beamfocusing using dipole arrays—considering spatial focusing and multi-user separation—and the evaluation of beam confinement and user discrimination (in terms of both angle and distance) using large-scale arrays.

II. XL-MIMO AND MULTIPLE ACCESS IN THE NEAR-FIELD

Compared to massive MIMO systems in 5G, the adoption of XL-MIMO in 6G goes beyond simply increasing the number of radiating elements, introducing a fundamental shift in the electromagnetic behavior of the system [1]. In this context, multiple access techniques become essential for the efficient

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utilization of communication resources. In far-field scenarios, schemes such as Space Division Multiple Access (SDMA) primarily exploit angular separation among users, while Non-Orthogonal Multiple Access (NOMA) enables resource sharing in the power or code domains.

In the near-field regime, however, multiple access can simultaneously exploit both angular and radial dimensions. This capability enables spatial focusing in two domains, allowing effective user separation even in scenarios where users share similar angular directions. As a result, inter-user interference is reduced and system capacity is enhanced. Furthermore, studies indicate that XL-MIMO systems can achieve significant SINR gains, improving data transmission performance when appropriate design and deployment strategies are adopted.

III. PROBLEM DESCRIPTION

A. Method of Moments Implementation

A computer program was developed to discretize the antenna array geometry and solve Maxwell's equations in order to calculate the radiated electric field in the near-field region. The Method of Moments (MoM) was employed because it provides an accurate full-wave electromagnetic solution, accounting for mutual coupling between antenna elements. Since only the conducting surfaces are discretized, the number of unknowns is significantly reduced compared to volumetric methods, resulting in lower computational cost and higher simulation efficiency [17].

The proposed implementation is based on the Electric Field Integral Equation (EFIE). Each half-wave dipole is discretized into short segments using sinusoidal basis functions, and the resulting integral equation is converted into a linear system by applying the MoM. The mutual impedance matrix is constructed by considering the electromagnetic interaction between each pair of segments. After solving the linear system $ZI=V$, the current distribution along each dipole is obtained. The near-field electric field is then calculated by superimposing the contributions radiated by all current segments.

For beamfocusing, the exact spherical propagation distance between each antenna element and the desired focal point is calculated. The excitation phase of each element is determined via phase matching, enabling constructive interference at the target position.

The computer program was implemented in Python. Input parameters include the operating frequency, array geometry, number of dipoles, dipole length, inter-element spacing, and target position. Outputs include the current distribution, the near-field electric field, the beam pattern, received power, interference level, and SINR. The general workflow of the developed software is illustrated in Fig 1.

B. Planar Array Design

The dipole array was designed to operate in the near-field region at 28 GHz [7]. Each half-wavelength dipole has a length of 5 mm. The total array size in the y -direction is given by $L_y = (N - 1)d_y$, and in the x -direction by $L_x = (M - 1)d_x$, where the inter-element spacing is $d_y = d_x = 0.55\lambda$. The Fraunhofer distance, which defines the boundary between the

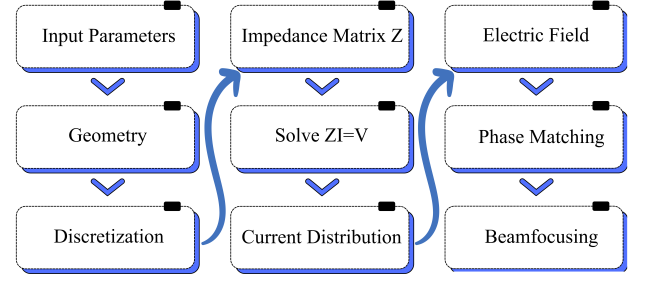


Fig. 1. Flowchart of the proposed Method of Moments, based beamfocusing algorithm for near-field analysis.

near-field and far-field regions, is given in reference [2], as shows below.

$$d_F = \frac{2D^2}{\lambda}, \quad (1)$$

where D is the largest dimension of the antenna and λ is the wavelength. For an operating frequency of 28 GHz, $\lambda \approx 1.07$ cm. Considering a planar array with an approximate size of $D = 0.54$ m, the Fraunhofer distance becomes

$$d_F = \frac{2(0.54)^2}{0.0107} \approx 55 \text{ m}. \quad (2)$$

Therefore, users located at typical distances of a few meters are within the radiative near-field region. In this context, the analyzed array exhibits a sufficiently large aperture to be characterized as an XL-MIMO system, where spherical wavefront propagation effects cannot be neglected.

To enable near-field beamfocusing, the excitation phases $\phi_{m,n}$ were adjusted to focus radiation at the user position, denoted as P_{user} , as illustrated in Fig. 2. The feeding parameters were defined through a progressive phase shift. Each dipole is excited by a voltage source given by

$$V_s(m, n) = V_0 e^{j\phi_{m,n}}, \quad (3)$$

where

$$\phi_{m,n} = -k \Delta_{m,n}, \quad k = \frac{2\pi}{\lambda_0}. \quad (4)$$

The geometric path difference is defined as

$$\Delta_{m,n} = |r_{\text{ref}}| - |r_{m,n}|, \quad (5)$$

where $|r_{\text{ref}}|$ represents the distance between the reference element and the user, while $|r_{m,n}|$ corresponds to the distance between an arbitrary array element and the user.

Consequently, each dipole radiates its own electromagnetic field, determined by the complex phase of its excitation. By the principle of superposition, the total field is obtained as the vector sum of the fields radiated by all elements. The phase differences among them produce regions of constructive and destructive interference: points where waves arrive in phase result in field reinforcement, while out-of-phase contributions lead to partial or total cancellation. This behavior is characteristic of antenna arrays [5].

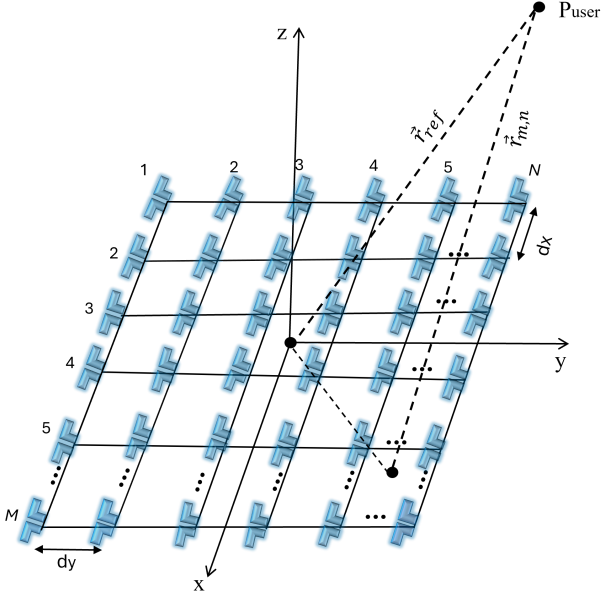


Fig. 2. Geometry of the planar array with $M \times N$ dipoles aligned along x and y . The reference vector r_{ref} is defined from the reference element to P_{user} , and $r_{m,n}$ is the overall distance vector between element (m,n) and P_{user} .

TABLE I
RECTANGULAR COORDINATES OF USER LOCATIONS.

UE	Planes(x, y)	Plane (z)
A, B, C, D	$(0, 0), (L_y, 0), (0, L_y), (L_y, L_y)$	$3L_y$ (1.62 m)
E, F, G, H	$(0, 0), (L_y, 0), (0, L_y), (L_y, L_y)$	$6L_y$ (3.24 m)

IV. NEAR-FIELD BEAMFOCUSING FOR MULTI-USER SYSTEMS

A planar array composed of 10,000 dipoles (100×100) is proposed. The eight users are arranged at the same radial positions (Fig. 2), and the array performs beamfocusing simultaneously toward multiple users. Their locations in the Cartesian plane are presented in Table I, and the corresponding illustrative configuration is shown in Fig 2. All user equipment (UEs) are located in the near-field region, with the first four positioned at a distance of 1.62 m and the remaining four at 3.24 m.

Unlike far-field scenarios, where orthogonality among user channels is primarily achieved in the angular domain and typically requires large antenna apertures, the near-field regime also provides orthogonality in the distance domain. Consequently, users located in the same direction but at different distances can be simultaneously served without significant interference. This enables spatial beamfocusing, with focusing in both angle and distance, which reduces inter-user interference and enhances channel capacity [18].

However, increasing the number of elements for a fixed aperture reduces the inter-element spacing, which may introduce stronger mutual coupling and degrade system performance. To suppress grating lobes, arrays are typically designed with a maximum spacing of approximately half a wavelength ($\lambda/2$). Therefore, one of the main design challenges in near-field communication systems is to extend the near-field region

while avoiding high sidelobe levels, allowing more users to benefit from near-field beamfocusing. As indicated by the Fraunhofer distance expression, the array aperture is the key factor determining the extent of the near-field region.

V. NUMERICAL RESULTS

The results presented in Figs. 3–5 illustrate the distributions of the magnitude of the total electric field $|E|$ in the x , y , and z planes. The array simultaneously steers beams toward eight users positioned at the coordinates defined in Table I. The system is able to spatially distinguish each UE with high accuracy. This is achieved because, beyond conventional angular separation, near-field beamfocusing also exploits the distance domain, enabling two-dimensional focusing, which is not possible under the plane-wave assumption.

It can be observed that even when users are located relatively close to each other in the Cartesian plane, there is no significant energy overlap between beams when their radial distances differ. The array concentrates energy precisely at the target locations, resulting in clear spatial separation among users. This behavior not only confirms the theory of near-field beamfocusing but also reinforces its practical applicability for multiple access in next-generation wireless systems. An additional advantage is that information is directed specifically to the intended UE, suggesting enhanced transmission security, particularly at the physical layer, which is a known limitation in conventional far-field beamfocusing schemes [8].

These results are directly aligned with the evolution of multiple access technologies in modern communications. Traditionally, mobile networks exploit time, frequency, code, and spatial domains to multiplex users. In contrast, the spherical wave-based transmission model introduces an additional degree of freedom by incorporating the distance domain as a multiplexing resource. Beam focusing in both angle and distance significantly increases the number of usable spatial regions for multiplexing, extending the limits of spatial reuse [1].

Thus, unlike traditional SDMA, which is constrained by angular resolution, Near-Field Spatial Division Multiple Access (NS-SDMA) enables the separation of users even when they share nearly the same angular direction, as long as their distances differ. Consequently, incorporating near-field characteristics into the design of multiple access technologies represents a natural pathway to meet the requirements of 6G systems, as it reduces inter-user interference, enhances spatial reuse, and improves overall spectral efficiency.

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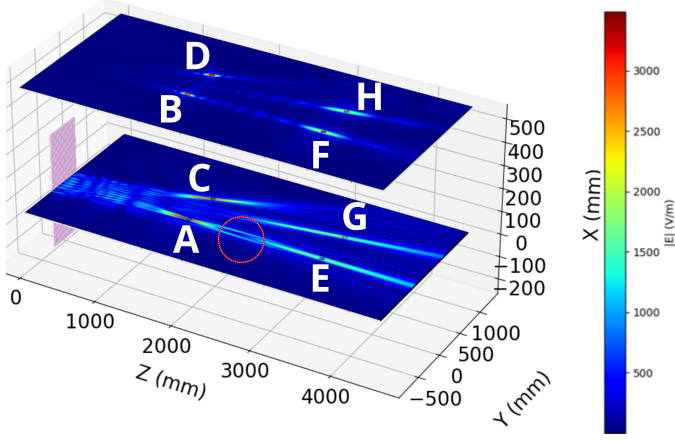


Fig. 3. Near-field beamfocusing for 8 users performed using a 100×100 dipole array, viewed from the $x = 0$ plane.

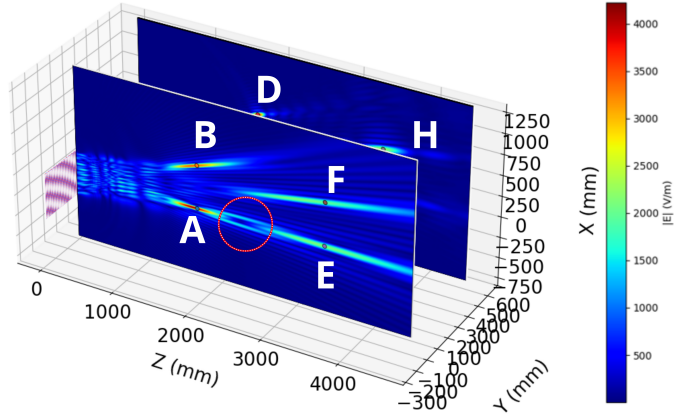


Fig. 4. Near-field beamfocusing for eight users performed using a 100×100 dipole array, viewed from the $y = 0$ plane.

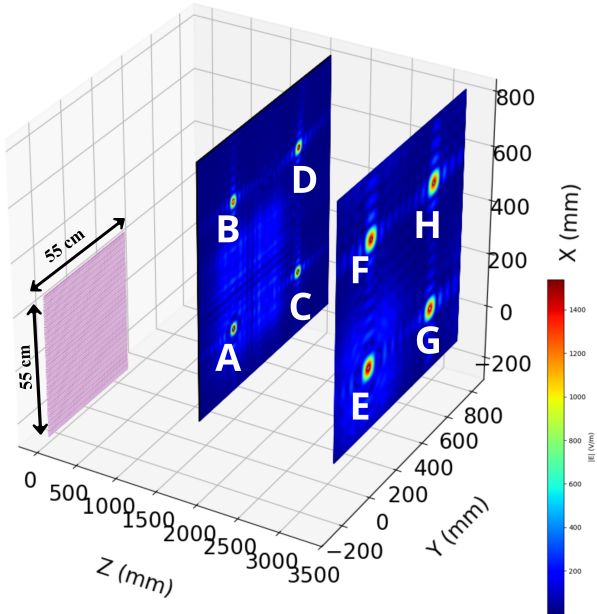


Fig. 5. Beamfocusing in the near-field for eight users, viewed at user height: (a) $z = 1.6$ m and (b) $z = 3.2$ m.

limitation in conventional far-field beamfocusing schemes [10].

Next, the SINR was calculated for each user based on the received power matrix — a metric that quantifies received signal quality by simultaneously considering the desired signal power, interference from other users or transmissions, and system noise—treating the power at the target user as the desired signal and the remaining components as interference [15]. This metric is widely used to evaluate the performance of wireless communication systems, particularly in multi-user scenarios. Therefore, the equation used for this calculation is presented in Equation 6.

$$SINR = \frac{P_{UEtarget}}{\sum P_{interference} + P_{noise}} \quad (6)$$

where $P_{UEtarget}$ represents the power received by the user of interest and $\sum P_{interference}$ corresponds to the sum of the powers from the other simultaneous users. The thermal noise was modeled according to the Johnson–Nyquist formulation [16]:

$$P_{noise} = k_B T_0 B \cdot 10^{NF/10} \quad (7)$$

where B represents the bandwidth (100 MHz), NF is the noise figure (7 dB), $k_B = 1.381 \times 10^{-23}$ is the Boltzmann constant, and $T_0 = 290$ K is the standard temperature. $P_{interference}$ corresponds to the residual power from other users, characterizing the multi-user interference resulting from the imperfect nulling process. The results obtained are presented in Table II and Fig. 6. It can be observed that interference levels remain significantly lower than the received useful power, demonstrating the XL-MIMO system's strong spatial focusing capability when operating in the near-field regime.

Table II also presents the useful power received by each user, considering the multi-user transmission scenario and a total transmitted power of 1 W by the array. The received power was calculated from the current induced in the receiving antenna (5 mm dipole), whose load power is calculated according to the following equation:

$$P_r = \frac{1}{2} |I|^2 \text{Re}(Z_c), \quad (8)$$

where I represents the current induced in the receiving antenna and Z_c corresponds to the load impedance, adopted as $Z_c = 75 \Omega$.

TABLE II
RECEIVED USEFUL POWER AND SINR FOR EIGHT USERS.

UE Target	Useful Power (dBm)	SINR (dB)
A	7.66	25.71
B	6.38	35.71
C	7.30	37.65
D	6.10	35.16
E	1.76	13.59
F	1.41	23.65
G	1.67	23.87
H	1.32	26.79

The behavior of the array is consistent with theoretical expectations, as higher power levels are concentrated on the target users, indicating that each UE receives the largest share

of energy when the beam is focused on its corresponding position. Furthermore, users B, C, and D exhibited the lowest relative interference levels and, consequently, the highest SINR values, indicating greater efficiency in the spatial separation of beams at these positions. Conversely, users A and E showed greater sensitivity to residual interference, reflected in reduced SINR values. This behavior is associated with the spatial dependence of near-field beamfocusing. As observed in Fig. 3 and Fig. 4, the transition of the beam from position A to E resulted in the appearance of grating lobes—highlighted by a red circle—which contributed to increased interference in that region.

Fig. 6 presents a graph based on the values from Table II, clearly illustrating the SINR variation—ranging from 13.59 dB to 37.65 dB—and demonstrating the proposed system’s beamfocusing capability. All SINR values exceed 10 dB, indicating good communication link quality based on existing literature. It is also important to note that, although the system can spatially concentrate energy toward the intended user, physical and electromagnetic limitations—such as mutual coupling and spherical wave propagation—prevent the complete cancellation of radiated power in the directions of other users. Consequently, residual interference between simultaneous users remains.

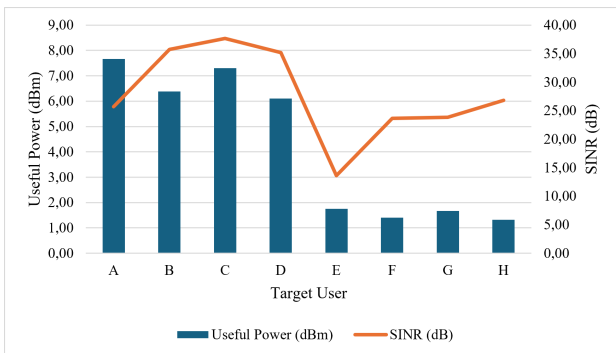


Fig. 6. Received useful power and SINR obtained in a near-field multi-user beamfocusing scenario with XL-MIMO.

This behavior is explained by the fact that, in the near-field region, spatial focusing depends simultaneously on both the radial distance and the angular position of the users. Furthermore, Fig. 6 shows that increasing the number of users tends to reduce the system’s average SINR. This behavior aligns with theory, as a higher number of UEs raises interference levels and makes the spatial focusing process more challenging.

Thus, unlike traditional SDMA (Space Division Multiple Access), which is limited by angular resolution, near-field SDMA allows for user separation even when users share virtually the same angular direction, provided their distances differ. Consequently, incorporating near-field characteristics into the design of multiple-access technologies is a natural path toward meeting 6G system requirements, as it reduces inter-user interference, enhances spatial reuse, and improves overall spectral efficiency. In light of this, we highlight XL-MIMO arrays as a promising alternative for near-field spatial multiplexing, given their ability to simultaneously exploit both angular and radial domains.

VI. CONCLUSIONS

The presented results demonstrate that XL-MIMO arrays operating in the near-field regime represent a promising alternative for next-generation wireless systems. In dense scenarios, characterized by a high concentration of devices and strong demand for spatial reuse, the ability to efficiently exploit spatial degrees of freedom becomes essential. In this context, the near-field regime provides a level of spatial control superior to that achieved by traditional techniques based on the far-field model. The results showed that the proposed array is capable of efficiently concentrating energy on the target user, enabling spatial multiplexing. Consequently, the system can increase channel capacity while supporting more secure connections with improved spatial isolation.

ACKNOWLEDGEMENTS

This work was supported by the Innovation Center, Ericsson Telecomunicações Ltda., Brazil, and the National Council for Technological and Scientific Development (CNPq).

REFERENCES

- [1] IHS Markit, “The 5G Economy: How 5G will contribute to the global economy,” Qualcomm Report, 2019.
- [2] ZHAO, Yajun et al, “6G near-field technologies white paper 2.0”.
- [3] Y. Liu *et al.*, “Near-field communications: A comprehensive survey,” *IEEE Communications Surveys & Tutorials*, 2024.
- [4] H. Zhang *et al.*, “6G wireless communications: From far-field beam steering to near-field beam focusing,” *IEEE Communications Magazine*, pp. 1–3, 2023.
- [5] C. A. Balanis, *Antenna Theory: Analysis and Design*, 4th ed. Hoboken, NJ, USA: John Wiley & Sons, 2016.
- [6] C. A. Balanis, *Advanced Engineering Electromagnetics*, 3rd ed. Wiley, 2024.
- [7] D. G. Dudley, *Mathematical Foundations for Electromagnetic Theory*. New York, NY, USA: IEEE Press, 1994.
- [8] P. Ramezani *et al.*, “Exploiting the depth and angular domains for massive near-field spatial multiplexing,” *IEEE BITS the Information Theory Magazine*, vol. 3, no. 1, pp. 14–26, 2023.
- [9] C. Ouyang, Y. Liu, X. Zhang, and L. Hanzo, “Near-field communications: A degree-of-freedom perspective,” arXiv:2308.00362, 2023.
- [10] H. L. Van Trees, *Optimum Array Processing: Part IV of Detection, Estimation, and Modulation Theory*. John Wiley & Sons, 2002.
- [11] C. Han, W. Gao, N. Yang, and J. M. Jornet, “Molecular absorption effect: A double-edged sword of terahertz communications,” *IEEE Wireless Communications*, vol. 30, no. 4, pp. 140–146, 2023.
- [12] J. An *et al.*, “Near-field communications: Research advances, potential, and challenges,” *IEEE Wireless Communications*, vol. 31, no. 3, pp. 100–107, 2024.
- [13] B. Xu *et al.*, “Resource allocation for near-field communications: Fundamentals, tools, and outlooks,” *IEEE Wireless Communications*, 2024.
- [14] Z. Zhang, Y. Liu, Z. Wang, X. Mu, and J. Chen, “Physical layer security in near-field communications,” *IEEE Transactions on Vehicular Technology*, vol. 73, no. 7, 2024.
- [15] E. Björnson, Ö. T. Demir and L. Sanguinetti, “A primer on near-field beamforming for arrays and reconfigurable intelligent surfaces,” *55th Asilomar Conference on Signals, Systems, and Computers*, IEEE, 2021. p. 105–112.
- [16] H. Nyquist, “Thermal agitation of electric charge in conductors,” *Physical review*, v. 32, n. 1, p. 110, 1928.
- [17] RUSEK, F. et al. “Scaling up mimo: Opportunities and challenges with very large arrays,” *IEEE Signal Processing Magazine*, v. 30, n. 1, p. 40–60, January 2013.
- [18] LU, H. et al. “A tutorial on near-field xl-mimo communications towards 6g. arXiv preprint arXiv:2310.11044,” 2023.