

A Comparative Analysis of Fully-Digital and Dynamic Metasurface Antenna Architectures for Energy Beamforming in Wireless Power Transfer

Marco Buseti, Ricardo Souza Senandes, Glauber Brante and Richard Demo Souza

Abstract—This paper investigates trade-offs between fully-digital (FD) and dynamic metasurface antenna (DMA) architectures for energy beamforming in near-field wireless power transfer (NF-WPT). We consider a NF-WPT system in which an antenna array, which can be either an FD or a DMA structure, charges devices at the same time while avoiding transmitting power to specific directions, such as areas where people or animals may be present. Then, we optimize the transmit power to charge the intended devices while strictly avoiding these restricted areas. Results reveal that the FD array offers superior spatial resolution and is able to provide very concentrated energy beams, with low radiated power outside the intended directions. Nevertheless, its hardware complexity is considerably high due to the need of one RF chain per antenna element. Conversely, the DMA enables energy beamforming with a reduced total power consumption, standing out as a highly scalable solution. However, the energy beams provided by the DMA show non-negligible scattering, especially at distances closer to the DMA, thus making the restriction to avoid unintended users more challenging.

Keywords—Energy Harvesting, Dynamic Metasurface Antenna, Fully-Digital, Wireless Power Transfer.

I. INTRODUCTION

Wireless power transfer (WPT) has emerged with the potential to eliminate physical connections and enable continuous operation for the Internet of Things (IoT) [1]–[3]. With the transition to higher operating frequencies in 5G and 6G systems, radiative near-field WPT (NF-WPT) has gained significant attention due to its potential for highly efficient energy delivery over typical IoT distances. Energy beamforming, which concentrates electromagnetic fields at target directions, is a critical component of NF-WPT, whose efficiency depends heavily on the transmitter architecture.

Fully-digital (FD) arrays provide maximum flexibility by enabling independent control of amplitude and phase of each antenna element. However, they require a dedicated RF chain per antenna, yielding high hardware complexity. To mitigate this, dynamic metasurface antennas (DMAs) emerge as a promising hybrid alternative [4]. DMAs utilize a dense group of configurable metamaterial elements fed by a small number of RF chains. While this drastically reduces hardware overhead, the dense spacing introduces mutual coupling, and

the phase shift and gain of each element become correlated, adding non-convex restrictions to the beamforming design [5], [6]. Thus, achieving precise energy focusing with DMAs involves hardware-inherent constraints that increase system design complexity.

The literature has extensively investigated DMAs across various applications, such as massive MIMO communications [7]–[9] and NF localization [10]. While FD arrays provide optimal beamforming flexibility due to their unconstrained degrees of freedom, DMAs offer a highly scalable alternative that may reduce power consumption [9]. However, most works on the DMA focus primarily on information transmission or localization. The explicit comparison of these architectures for NF-WPT, where the goal shifts from data rate maximization to precise spatial energy confinement for IoT networks [11], remains not well explored.

Another aspect investigated by the recent literature is that practical RF-WPT systems must focus beams on IoT devices while strictly limiting electromagnetic exposure to regions occupied by humans or animals [12]. In that sense, the work in [13] addressed this challenge by proposing a bat algorithm (BA)-based energy beamforming approach for DMA-assisted NF-WPT, solving the non-convex problem of maximizing delivered power to intended devices while keeping received power below a safety threshold for unintended targets. While [13] successfully demonstrated the capability of the BA to manage the complex physical constraints of DMAs, a critical question remains regarding how this hybrid architecture fundamentally compares to an unconstrained FD system under the same strict charging and avoidance conditions.

Therefore, this paper bridges that gap by investigating the performance trade-offs between FD and DMA architectures for energy beamforming in NF-WPT. Utilizing the BA optimization framework from [13], we evaluate both structures in terms of beam patterns, total power consumption, and the minimal spatial separation required to isolate intended and unintended users. Simulation results show that the FD architecture achieves superior spatial resolution, successfully isolating users separated by as little as 3.1 mm in the Fresnel region, and 17.3 cm in the Fraunhofer distance. In contrast, the DMA completely fails to isolate users in the Fresnel region due to inherent energy scattering, while user separation must be at least 47.5 cm in the Fraunhofer distance. However, since it operates with significantly fewer RF chains, the total power consumption of the DMA is smaller compared to the FD (51.45 dBm for the DMA versus 59 dBm for FD).

M. Buseti, R. S. Senandes and G. Brante are with Federal University of Technology - Paraná (UTFPR). E-mails: marcovieirabusetti@alunos.utfpr.edu.br, ricardosouzasenandes@gmail.com, gbrante@utfpr.edu.br. R. D. Souza is with the Federal University of Santa Catarina (UFSC). E-mail: richard.demo@ufsc.br. This work was partially supported by CAPES (Finance Code 001), and CNPq (300705/2026-3, 317368/2025-7, Universal 403124/2023-9, INCT STREAM 409179/2024-8).

II. SYSTEM MODEL

We assume a WPT system where a multi-antenna energy transmitter is fixed on the ceiling of a room with dimensions $[x_{\max}, y_{\max}, z_{\max}]$, serving K single-antenna energy harvesting devices. We denote the location of these devices by $\mathbf{p}_k = [x_k, y_k, z_k]$. Furthermore, we assume additional U unintended devices to be avoided by the transmitter, located at $\mathbf{p}_u = [x_u, y_u, z_u]$.¹ Then, to evaluate the performance trade-offs between different antenna technologies, we consider two distinct array architectures: DMA and FD.

To ensure NF propagation conditions, the devices are at a distance from the transmitter array greater than the Fresnel distance $d_{\text{fs}} = \sqrt{\frac{3D^2}{8\lambda}}$, and smaller than the Fraunhofer distance $d_{\text{fr}} = \frac{2D^2}{\lambda}$, where $D = \sqrt{2}L$ is the effective antenna diameter and L the antenna length [14]. Under these NF propagation conditions, the channel is strongly governed by deterministic line-of-sight propagation rather than by multipath effects, in contrast to far-field communications where stochastic multipath fading models are typically required to account for reflections, scattering, and diffraction.

According to [6], the channel coefficient between each element of the antenna array and the device k is

$$\mathcal{C}_{i,l,k} = \mathcal{A}_{i,l,k} \exp \left(-j \frac{2\pi d_{i,l,k}}{\lambda} \right), \quad (1)$$

where the index i, l represents either each antenna element of the FD architecture in a uniform rectangular array (URA), or the l -th metamaterial element in the i -th waveguide in the DMA architecture. In addition, the exponential component represents the phase variation as a function of distance, and $d_{i,l,k} = \|\mathbf{p}_k - \mathbf{p}_{i,l}\|$ represents the Euclidean distance between $\mathbf{p}_k$ and the location of the i, l element of the array $\mathbf{p}_{i,l} = [x_{i,l}, y_{i,l}, z_{i,l}]$. Also, $\mathcal{A}_{i,l,k}$ controls the amplitude of the channel coefficient, given by [15]

$$\mathcal{A}_{i,l,k} = \sqrt{F(\theta_{i,l,k}, \phi_{i,l,k})} \frac{\lambda}{4\pi d_{i,l,k}}, \quad (2)$$

where $(\theta_{i,l,k}, \phi_{i,l,k})$ is the elevation-azimuth pair from the i, l -th element to the k -th user, while the radiation profile of each element is given by

$$F(\theta_{i,l,k}, \phi_{i,l,k}) = \begin{cases} 2(b+1) \cos^b(\theta_{i,l,k}), & \theta_{i,l,k} \in [0, \frac{\pi}{2}], \\ 0, & \text{otherwise,} \end{cases} \quad (3)$$

with b being the boresight gain.

III. ANTENNA ARRAY ARCHITECTURES

A. Dynamic Metasurface Antennas (DMA)

The DMA model is a hybrid antenna architecture in which a group of N_h metamaterial elements is fed by N_v RF chains, as illustrated by Fig. 1. The number of vertical and horizontal elements is determined by the antenna length L and the wavelength λ , with $N_v = \lfloor L/(\lambda/2) \rfloor$ and $N_h = \lfloor L/(\lambda/5) \rfloor$ [6], yielding a total number of elements $N_{\text{DMA}} = N_v \times N_h$.

¹We assume that the position of the users is known to the transmitter, and the method to identify or detect them is out of the scope of this work.

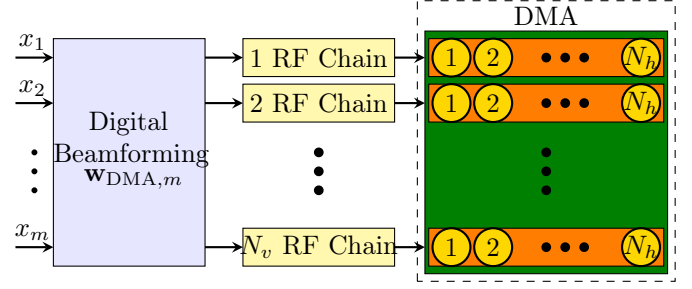


Fig. 1: Transmitter antenna architecture based on DMA.

The signal propagation effects within the waveguide structure are described by the diagonal propagation matrix $\mathbf{H} \in \mathbb{C}^{N_{\text{DMA}} \times N_{\text{DMA}}}$ of the DMA, with $h_{i,l}$ being the $((i-1)N_h + l)$ -th column and $((i-1)N_h + l)$ -th row element of $\mathbf{H}$, where $i = 1, \dots, N_v$ and $l = 1, \dots, N_h$ [4]. In addition, the propagation coefficient for the l -th element in the i -th waveguide can be written as [6]–[10]

$$h_{i,l} = \exp \left[-(l-1)d(\alpha_i + j\beta_i) \right], \quad (4)$$

where d denotes the inter-element distance on the waveguide, α_i is the waveguide attenuation coefficient, and β_i is the propagation constant of the i -th waveguide, where $i = 1, \dots, N_v$ and $l = 1, \dots, N_h$. In addition, the propagation coefficients $h_{i,l}$ are frequency-dependent, as both α_i and β_i vary with the operating frequency [6]–[10].

Let x_m be the m -th energy symbol at the input of the digital beamforming, which is fed to the waveguides, where $m = 1, \dots, M$, and $M = \min(N_v, K)$. Moreover, $\mathbf{w}_{\text{DMA},m} \in \mathbb{C}^{N_v \times 1}$ denotes the precoding vector for x_m . Thus, considering that the energy symbols are normalized and independent, so that $\mathbb{E}\{x_n^H x_r\} = 0, \forall n \neq r$ and $\mathbb{E}\{x_n^H x_n\} = 1$, the transmit signal of the DMA is given by

$$\mathbf{s}_{\text{DMA}} = \sum_{m=1}^M \mathbf{H} \mathbf{Q} \mathbf{w}_{\text{DMA},m} x_m, \quad (5)$$

where $\mathbf{Q} \in \mathbb{C}^{N_{\text{DMA}} \times N_v}$ contains the configurable weights of the metamaterial elements, given by [6]

$$\mathbf{Q}_{(i-1)N_h + l, n} = \begin{cases} q_{i,l}, & i = n, \\ 0, & i \neq n, \end{cases} \quad (6)$$

with $q_{i,l} \in \mathcal{L} = \left\{ (j + e^{j\phi_{i,l}}) / 2 \mid \phi_{i,l} \in [0, 2\pi] \right\}$. This is the Lorentzian-constrained phase model, which captures the dependency between the elements' amplitude and phase. Note that $\mathcal{L}$ denotes the Lorentzian interval in the complex plane [5].

As a consequence, the transmit power of the DMA is $P_{\text{DMA}}^{\text{TX}} = \mathbb{E}\{\mathbf{s}_{\text{DMA}}^H \mathbf{s}_{\text{DMA}}\}$, which can be written as

$$P_{\text{DMA}}^{\text{TX}} = \sum_{m=1}^M |\mathbf{H} \mathbf{Q} \mathbf{w}_{\text{DMA},m}|^2, \quad (7)$$

yielding a total power consumption given by [16], [17]

$$P_{\text{DMA}}^{\text{total}} = \eta^{-1} P_{\text{DMA}}^{\text{TX}} + N_v P_{\text{RF}} + N_{\text{DMA}} P_{\text{meta}} + P_{\text{BB,DMA}}, \quad (8)$$

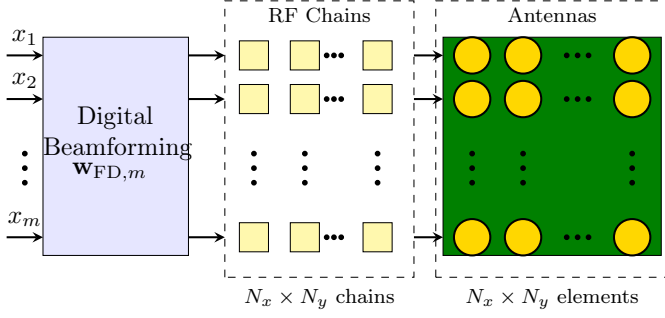


Fig. 2: Transmitter antenna architecture based on FD.

where $\eta \in [0, 1]$ represents the power amplifier (PA) efficiency, P_{RF} is the power consumed by each active RF chain, and P_{meta} is the power required to tune the state of each metamaterial element. Also, the baseband power consumption of the DMA is given by $P_{\text{BB,DMA}} = P_{\text{DSP}} + P_{\text{control}} + N_v P_{\text{ADC}}$, where P_{DSP} is the DSP power consumption, P_{control} is the power consumed by the control logic for metamaterial switching, and P_{ADC} is due to analog-to-digital converters.

Then, the energy signal received by the k -th device depends on the channel coefficient vector between device k and the elements of the DMA. We denote such channel coefficient vector by $\mathbf{c}_{\text{DMA},k} = [\mathcal{C}_{1,1,k}, \mathcal{C}_{1,2,k}, \dots, \mathcal{C}_{N_v, N_h, k}]^T$, encapsulating all $l \in [1, N_h]$ elements of the $i \in [1, N_v]$ waveguides, with respect to the k -th device. Therefore, the energy signal received by the k -th device is $y_k = \mathbf{c}_{\text{DMA},k}^H \mathbf{s}_{\text{DMA}}$, yielding a received RF power of

$$P_{\text{DMA},k}^{\text{RX}} = \sum_{m=1}^M |\mathbf{c}_{\text{DMA},k}^H \mathbf{H} \mathbf{Q} \mathbf{w}_{\text{DMA},m}|^2. \quad (9)$$

B. Fully-Digital (FD) Antennas

The FD architecture is illustrated in Fig. 2, which is composed of N_{FD} active RF chains, each directly connected to a single antenna element. Typically, the inter-element distance is $\lambda/2$, so the number of elements of the FD array in x and y directions is $N_x = N_y = \lfloor L/(\lambda/2) \rfloor$, and the total number of elements is $N_{\text{FD}} = N_x \times N_y$. Notice that for the same L and λ as in the DMA configuration, we have that $N_{\text{FD}} > N_{\text{DMA}}$.

Then, with a slight notation abuse, let x_m be the m -th energy symbol at the input of the beamforming block, where $m = 1, \dots, M$, and $M = \min(N_{\text{FD}}, K)$. Moreover, $\mathbf{w}_{\text{FD},m} \in \mathbb{C}^{N_{\text{FD}} \times 1}$ denotes the digital precoding vector for x_m . Thus, considering normalized and independent energy symbols, $\mathbb{E}\{x_n^H x_r\} = 0, \forall n \neq r$ and $\mathbb{E}\{x_n^H x_n\} = 1$, the transmit signal of the FD array is given by

$$\mathbf{s}_{\text{FD}} = \sum_{m=1}^M \mathbf{w}_{\text{FD},m} x_m. \quad (10)$$

As a consequence, the transmit power of the FD architecture is $P_{\text{FD}}^{\text{TX}} = \mathbb{E}\{\mathbf{s}_{\text{FD}}^H \mathbf{s}_{\text{FD}}\}$, which can be written as

$$P_{\text{FD}}^{\text{TX}} = \sum_{m=1}^M |\mathbf{w}_{\text{FD},m}|^2, \quad (11)$$

with total power consumption given by [16], [17]

$$P_{\text{FD}}^{\text{total}} = \eta^{-1} P_{\text{FD}}^{\text{TX}} + N_{\text{FD}} P_{\text{RF}} + P_{\text{BB,FD}}, \quad (12)$$

where the baseband power consumption of the FD is $P_{\text{BB,DMA}} = P_{\text{DSP}} + N_{\text{FD}} P_{\text{ADC}}$.

Then, we denote the channel coefficient vector between each device k and the elements of the FD array by $\mathbf{c}_{\text{FD},k} = [\mathcal{C}_{1,1,k}, \mathcal{C}_{1,2,k}, \dots, \mathcal{C}_{N_x, N_y, k}]^T$. Therefore, the energy signal received by the k -th device is $y_k = \mathbf{c}_{\text{FD},k}^H \mathbf{s}_{\text{FD}}$, yielding a received RF power of

$$P_{\text{FD},k}^{\text{RX}} = \sum_{m=1}^M |\mathbf{c}_{\text{FD},k}^H \mathbf{w}_{\text{FD},m}|^2. \quad (13)$$

Although the FD architecture offers the highest energy beamforming flexibility by enabling independent amplitude and phase control at each antenna element through the unconstrained complex vector $\mathbf{w}_{\text{FD},m}$, it requires N_{FD} active RF chains. Consequently, it incurs significantly higher hardware complexity compared to the DMA structure for the same number of radiating elements.

IV. NUMERICAL RESULTS

To evaluate the DMA and FD architectures, we consider a WPT system operating at $f = 5$ GHz, with $L = 0.2$ m, within an indoor environment of dimensions $x_{\text{max}} = y_{\text{max}} = 10$ m and $z_{\text{max}} = 3$ m. The energy transmitter is fixed at the center of the ceiling, with its location defined by $\mathbf{p}_{\text{tx}} = [x_{\text{max}}/2, y_{\text{max}}/2, z_{\text{max}}]$. A scenario with $K = 1$ energy harvesting device, positioned at $\mathbf{p}_1 = [4, 5, 1]$ m, and $U = 1$ unintended device to be avoided, at $\mathbf{p}_2 = [6, 5, 1]$ m, is considered. The BA-based solution from [13] is employed to minimize the transmit power P_a^{TX} , $a \in \{\text{DMA}, \text{FD}\}$, subject to $P_{a,1}^{\text{RX}} \geq 350 \mu\text{W}$ (-4.56 dBm) for the energy harvesting device and $P_{a,2}^{\text{RX}} \leq 100 \mu\text{W}$ (-10 dBm) for the unintended device. Both architectures are evaluated in terms of beam patterns, minimum spatial separation between devices, and total power consumption.

A. Beam Patterns

The beam patterns of both architectures are compared by plotting spatial received power heatmaps in the (x, y) plane at height $z = 1$ m, where the devices are located. Fig. 3a presents the received power heatmap, in dBm, for the DMA architecture. The received power is effectively concentrated at the intended location $\mathbf{p}_1$, with $P_{\text{DMA},1}^{\text{RX}} \approx -5$ dBm, while at $\mathbf{p}_2$ the power is reduced to $P_{\text{DMA},2}^{\text{RX}} \approx -12$ dBm, meeting the optimization constraints. However, considerable energy spreading is observed across many other positions in the room, which is inherent to the amplitude-phase coupling of the DMA architecture. To complement the visualization of this effect, Fig. 3b presents the 3D radiation pattern for the same scenario, filtering only the spatial regions where $P_k^{\text{RX}} \geq 10$ dBm. The energy scattering of the DMA is clearly evidenced, which may hinder the simultaneous satisfaction of charging and avoidance constraints depending on the spatial configuration of the devices.

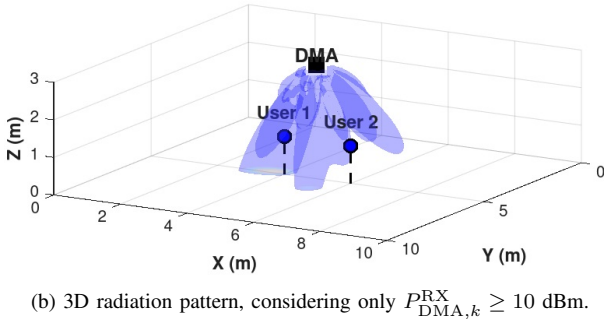
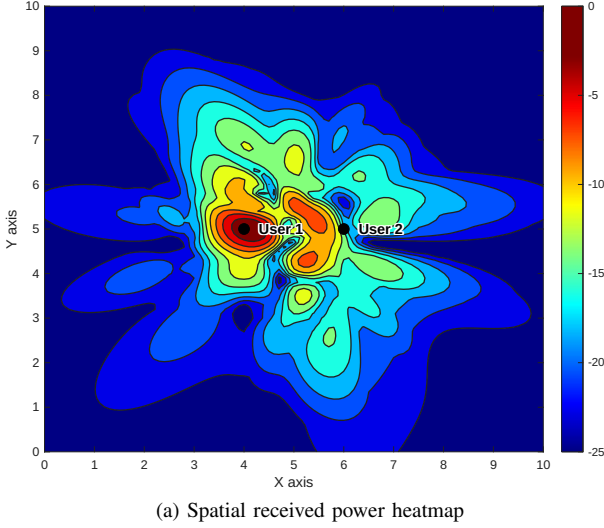


Fig. 3: Spatial received power heatmap and 3D radiation pattern for the DMA architecture.

In contrast, the FD architecture exhibits a different behavior. Fig. 4a shows that the irradiated power is well confined to the vicinity of the intended device, with $P_{\text{FD},2}^{\text{RX}}$ driven towards zero. The 3D visualization in Fig. 4b corroborates this result, showing highly focused beam directivity towards $\mathbf{p}_1$ and negligible radiation towards the unintended device location.

B. Minimal Distance Between Devices

Given the energy scattering inherent to the DMA architecture, we now investigate the minimum inter-device distance required to guarantee $P_{a,1}^{\text{RX}} \geq 350 \mu\text{W}$ and $P_{a,2}^{\text{RX}} \leq 100 \mu\text{W}$. Two evaluation regions are considered: the Fraunhofer boundary ($d_{\text{fr}} = 2.67$ m) and the Fresnel boundary ($d_{\text{fs}} = 0.2372$ m). The Fraunhofer boundary in the 3D space is illustrated by the shaded blue hemisphere in Fig. 5. Then, we place both devices at a fixed height $z = 1.0$ m, which is depicted by the blue circle whose radius is marked as R_{fr} . We start with these devices separated by 180° in this blue circle, progressively reducing their angular separation until convergence of the optimization fails. The optimization for the FD array converges until a minimum angular inter-device separation of 5.625° , equivalent to a linear distance of 17.3 cm. Conversely, the DMA requires a minimal angular separation of 15.469° , equivalent to a linear distance of 47.5 cm, indicating reduced spatial resolution under this architecture.

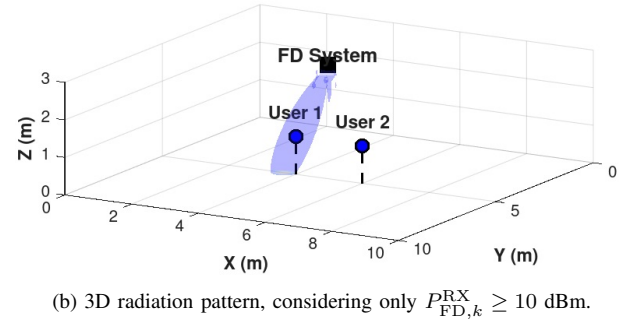
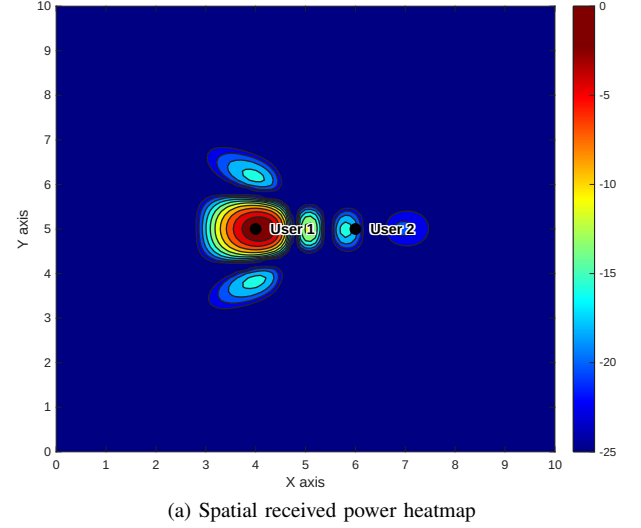


Fig. 4: Spatial received power heatmap and 3D radiation pattern for the FD architecture.

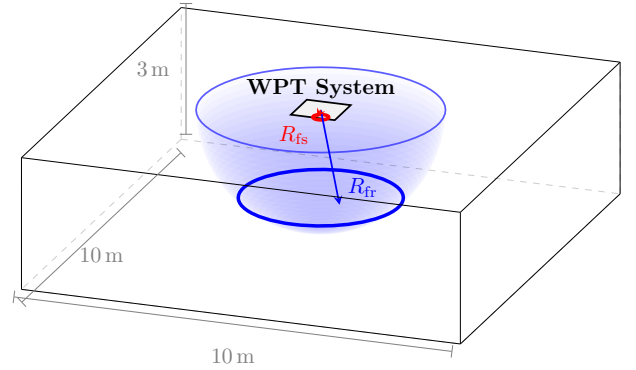


Fig. 5: 3D schematic of the indoor WPT scenario, depicting the transmitter location and the evaluation circles for the Fresnel (red) and Fraunhofer (blue) boundaries.

At the Fresnel boundary we place both devices at the red circle with radius marked as R_{fs} in Fig. 5, with a fixed height $z = 2.834$ m with respect to the floor. In this setup, the FD architecture maintains convergence with an angular resolution as small as 1.055° , equivalent to a linear separation of 3.1 mm. Conversely, the DMA completely fails to satisfy the isolation constraints at this range: even at the maximum angular separation of 180° , the energy scattering prevents

TABLE I: Spatial resolution and minimum distance requirements

Evaluation Region	Arch.	Ang. Sep.	Phys. Dist.
Fraunhofer ($z = 1.0$ m)	FD	5.625°	17.3 cm
	DMA	15.469°	47.5 cm
Fresnel ($z = 2.834$ m)	FD	1.055°	3.1 mm
	DMA	Failed	Failed

TABLE II: Power consumption of FD and DMA architectures

Architecture	Transmit Power	Total Power Consumption
FD	26.44 dBm	59 dBm
DMA	34 dBm	51.45 dBm

the simultaneous satisfaction of the charging and avoidance requirements. These results are summarized in Table I.

C. Power Consumption

The power consumption of both architectures is evaluated using the parameters from [18]: $P_{\text{RF}} = 40$ mW, $\eta = 35\%$, $P_{\text{meta}} = 5$ mW, $P_{\text{control}} = 21.8$ mW, $P_{\text{DSP}} = 40$ mW, and $P_{\text{ADC}} = 22$ mW. For the evaluated scenario, the DMA employs $N_v = 6$ active RF chains, whereas the FD array requires $N_{\text{FD}} = 36$ RF chains. The transmit power values $P_{\text{DMA}}^{\text{TX}}$ and $P_{\text{FD}}^{\text{TX}}$ are obtained from the optimized beam patterns of Figs. 3a and 4a, and the total power consumption is computed according to (8) and (12), respectively. The results are summarized in Table II.

As we observe, the FD array requires lower transmit power ($P_{\text{FD}}^{\text{TX}} = 26.44$ dBm versus $P_{\text{DMA}}^{\text{TX}} = 34$ dBm) due to its superior spatial focusing capability, which effectively suppresses energy leakage. However, despite this advantage in radiated power, the FD architecture incurs a higher total power consumption ($\mathcal{P}_{\text{FD}}^{\text{total}} = 59$ dBm versus $\mathcal{P}_{\text{DMA}}^{\text{total}} = 51.45$ dBm) owing to the considerably larger number of active RF chains. In the DMA, the additional transmit power required to overcome the scattering imposed by the Lorentzian metamaterial constraints is compensated by the reduced number of RF chains, resulting in a lower overall power budget. These results indicate a fundamental trade-off: the FD architecture offers superior spatial precision but at a higher hardware and energy cost, while the DMA provides a more scalable and energy-efficient solution in scenarios where strict spatial isolation is not critical.

V. CONCLUSIONS

In this paper, the performance trade-offs between FD and DMA architectures for energy beamforming in NF-WPT systems were investigated. A BA-based algorithm was employed to minimize the transmit power of the antenna array, subject to energy harvesting thresholds for the intended devices and safety isolation limits for unintended users. The results reveal a contrast in spatial resolution, radiated power, and hardware efficiency. The FD architecture shows superior spatial resolution, successfully isolating users separated by as little as 3.1 mm in the Fresnel region, while confining the radiated energy strictly to the target device. Conversely, the physical

constraints of the DMA's passive elements resulted in broader energy scattering and an inability to isolate users at very close ranges. Nevertheless, its lower hardware complexity in terms of reduced RF chains remains a significant advantage in achieving a lower total power consumption, 51.45 dBm compared to 59 dBm with the FD array.

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