

Learning-Based BD-RIS Architecture Design for WET Systems

Natália Pereira Batista e Victoria Dala Pegorara Souto

Abstract—This paper investigates a wireless energy transfer (WET) system assisted by a beyond-diagonal reconfigurable intelligent surface (BD-RIS), in which the BD-RIS topology, its scattering matrix, and the transmit beamforming are jointly optimized. To address the resulting non-convex problem, an unsupervised learning approach based on two neural networks trained in two stages, followed by local refinement, is proposed. The proposed solution aims to maximize the harvested energy while reducing the architectural complexity of the BD-RIS. Simulation results show energy performance close to that of the *Fully Connected* architecture, but with a significantly smaller number of active connections.

Keywords—BD-RIS, Wireless Energy Transfer, Machine Learning.

I. Introduction

Sixth-generation (6G) networks require solutions that support massive connectivity, distributed intelligence, and energy efficiency. In this context, the Internet of Things (IoT) enables large-scale applications, but the continuous operation of battery-limited devices remains a key challenge. Radio frequency wireless energy transfer (RF-WET) is a promising alternative to remotely power IoT devices, although its efficiency is strongly affected by propagation losses and channel conditions [1].

To address these limitations, beyond-diagonal reconfigurable intelligent surfaces (BD-RISs) have emerged as a generalization of conventional RISs, enabling reconfigurable interconnections among their elements through impedance networks [2]. This additional flexibility increases the degrees of freedom for electromagnetic signal control, but also introduces challenges related to implementation complexity, control overhead, and architecture selection [3], [4], [5].

In the context of RF-WET, recent works have explored the use of BD-RISs to increase the harvested energy in different scenarios, including multicarrier systems, nonlinear energy harvesting models, wireless sensor networks, and wirelessly powered mobile edge computing [6], [7], [1]. These studies report relevant gains over diagonal RISs, especially in non-line-of-sight environments and frequency-selective channels.

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Nevertheless, the literature remains limited regarding the joint design of the BD-RIS architecture and the beamforming at the energy transmitter.

Motivated by this gap, this paper investigates a BD-RIS-assisted RF-WET system for IoT applications, in which the surface architecture and the beamforming at the power beacon (PB) are jointly optimized to maximize the energy harvested by the devices. Based on this formulation, we aim to evaluate the trade-off among structural flexibility, implementation complexity, and energy performance, contributing to the design of more sustainable and efficient IoT networks.

II. System Model

We consider an RF-WET system composed of a PB equipped with a uniform linear array of N antennas, a BD-RIS with M elements, and K single-antenna IoT devices. Due to the energy constraints of the system, analog beamforming is adopted at the PB, generating one beam at a time. For the k -th device, $\mathbf{w}_k \in \mathbb{C}^{N \times 1}$ denotes the beamforming vector, $\mathbf{H}_{\text{RP}} \in \mathbb{C}^{M \times N}$ denotes the PB-BD-RIS channel, $\mathbf{h}_{\text{R},k} \in \mathbb{C}^{1 \times M}$ denotes the BD-RIS-device channel, and $\mathbf{h}_{\text{P},k} \in \mathbb{C}^{1 \times N}$ denotes the direct PB-device channel. The BD-RIS scattering matrix is denoted by $\Theta_k \in \mathbb{C}^{M \times M}$, and it is assumed that $\|\mathbf{w}_k\|^2 = P_{\text{T}}$, where P_{T} is the transmit power of the PB.

The wireless links are modeled using Rician fading combined with a log-distance path-loss model. Thus, the channel between element $\ell \in \{\text{P}, \text{R}\}$ and the k -th IoT device is given by $\mathbf{h}_{\ell,k} = \lambda^2 d_{\ell,k}^{-\alpha_{\ell,k}} (16\pi^2)^{-1} \left[\sqrt{\frac{\kappa_{\ell,k}}{1+\kappa_{\ell,k}}} \bar{\mathbf{h}}_{\ell,k} + \sqrt{\frac{1}{1+\kappa_{\ell,k}}} \tilde{\mathbf{h}}_{\ell,k} \right]$, where $\bar{\mathbf{h}}_{\ell,k}$ and $\tilde{\mathbf{h}}_{\ell,k}$ represent the line-of-sight and non-line-of-sight components, respectively, $\kappa_{\ell,k}$ is the Rician factor, $d_{\ell,k}$ is the link distance, and $\alpha_{\ell,k}$ is the path-loss exponent. The link between the PB and the BD-RIS, described by $\mathbf{H}_{\text{RP}}$, is modeled analogously.

The BD-RIS is characterized by the scattering matrix Θ_k , which is related to the admittance matrix $\mathbf{Y} \in \mathbb{C}^{M \times M}$ by $\Theta_k = (\mathbf{I} + Z_0 \mathbf{Y})^{-1} (\mathbf{I} - Z_0 \mathbf{Y})$, where Z_0 is the reference impedance. Considering a reciprocal and lossless network, we assume $\mathbf{Y} = j\mathbf{B}$, with $\mathbf{B} \in \mathbb{R}^{M \times M}$ and $\mathbf{B} = \mathbf{B}^T$, yielding $\Theta_k = (\mathbf{I} + jZ_0 \mathbf{B})^{-1} (\mathbf{I} - jZ_0 \mathbf{B})$. The admissible structure of Θ_k depends on the BD-RIS interconnection architecture, which defines the avail-

able degrees of freedom for controlling the reflected signal.

Based on the direct and reflected links, the RF power received by the k -th device is expressed as

$$P_k = |(\mathbf{h}_{R,k}^H \mathbf{\Theta}_k \mathbf{H}_{RP} + \mathbf{h}_{P,k}^H) \mathbf{w}_k|^2. \quad (1)$$

Hence, the energy harvested by the k -th device is linearly modeled as $E_k = T_c \eta_k P_k$, where T_c is the channel coherence time and η_k is the energy conversion efficiency.

A. Proposed Optimization Problem

The objective of this paper is to jointly design the PB beamforming, the scattering matrix, and the BD-RIS interconnection architecture in order to maximize the energy harvested by the IoT devices while reducing the structural complexity of the surface. The architecture is represented by a binary connectivity matrix $\mathbf{C} \in \{0,1\}^{M \times M}$, where $[\mathbf{C}]_{i,j} = 1$ indicates a connection between elements i and j . We assume $\mathbf{C} = \mathbf{C}^T$ and $[\mathbf{C}]_{i,i} = 0$. The architectural complexity is defined as $\Psi(\mathbf{C}) = \frac{1}{2} \sum_{i=1}^M \sum_{j \neq i} [\mathbf{C}]_{i,j}$, while the total harvested energy is given by $E_T = \sum_{k=1}^K E_k$. Thus, the problem is formulated as

$$\begin{aligned} & \max_{\{\mathbf{w}_k, \mathbf{\Theta}_k, \mathbf{B}_k\}_{k=1}^K, \mathbf{C}} [E_T, -\Psi(\mathbf{C})] \\ \text{s.t. } & E_k \geq E_k^{\min}, \quad \|\mathbf{w}_k\|^2 \leq P_T, \\ & \mathbf{\Theta}_k = (\mathbf{I} + jZ_0 \mathbf{B}_k)^{-1} (\mathbf{I} - jZ_0 \mathbf{B}_k), \\ & \mathbf{B}_k = \mathbf{B}_k^T, \quad \mathbf{\Theta}_k \in \mathcal{S}(\mathbf{C}), \\ & [\mathbf{C}]_{i,j} = 0 \Rightarrow [\mathbf{B}_k]_{i,j} = 0, \quad \forall i \neq j, \forall k, \\ & [\mathbf{C}]_{i,j} \in \{0,1\}, \quad \forall i, j, \end{aligned} \quad (2)$$

where $E_k^{\min}$ is the minimum required energy for the k -th device and $\mathcal{S}(\mathbf{C})$ represents the set of physically feasible scattering matrices for the architecture induced by $\mathbf{C}$. The problem is non-convex and mixed continuous-discrete due to the coupling among beamforming, electromagnetic configuration, and BD-RIS topology.

III. Proposed Solution

To solve the problem in (2), an unsupervised learning approach based on two neural networks is proposed, as illustrated in Fig. 1. The input vector consists of the IoT device positions and the channel coefficients $\mathbf{H}_{RP}$, $\mathbf{h}_{P,k}$, and $\mathbf{h}_{R,k}$, previously normalized using standard scaling. The first network generates a continuous representation of the BD-RIS connectivity matrix, from which the binary topology $\mathbf{C}$ is obtained through thresholding and the straight-through estimator mechanism. Then, the second network receives the feature vector concatenated with the inferred topology and estimates the susceptance admittance matrix $\mathbf{B}$ and the beamforming vectors $\mathbf{W} = [\mathbf{w}_1, \dots, \mathbf{w}_K]$. From $\mathbf{C}$

and $\mathbf{B}$, the effective matrix $\mathbf{C} \odot \mathbf{B}$ is constructed and used to obtain the scattering matrix $\mathbf{\Theta}$.

Training is carried out in two stages, followed by a refinement phase. In the first stage, a relaxed formulation is adopted, in which the topology is learned continuously while annealing strategies are applied to the sigmoid temperature and to the binarization and complexity penalty weights, promoting initial stability and progressively more defined structural decisions. In the second stage, the inferred binary topology is fixed, and the network responsible for estimating $\mathbf{B}$ and $\mathbf{W}$ is fine-tuned. Finally, a local per-sample refinement is performed with the topology kept fixed, aiming to improve the electromagnetic configuration of the surface and the beamforming vectors.

The trainable parameters are optimized by minimizing the multi-objective loss function given by

$$\mathcal{L} = -\lambda_e E_T + \lambda_c \mathcal{P}_c + \lambda_s \mathcal{P}_s + \lambda_b(t) \mathcal{P}_b + \lambda_f \mathcal{P}_f + \mathcal{R}, \quad (3)$$

where $\mathcal{P}_c$ penalizes the architectural complexity of the BD-RIS, $\mathcal{P}_s$ represents the structural symmetry term, $\mathcal{P}_b$ promotes binarization of the inferred topology, $\mathcal{P}_f$ corresponds to the energy fairness term, and $\mathcal{R}$ aggregates the network parameter regularization terms. The coefficients λ_e , λ_c , λ_s , $\lambda_b(t)$, and λ_f control the trade-off among energy performance, architectural complexity, and structural feasibility.

IV. Simulation Results and Discussion

This section evaluates the performance of the proposed solution for the joint design of the BD-RIS topology, the admittance matrix, and the beamforming vectors. The *Fully Connected* architecture is adopted as a benchmark, since it represents the case with the highest connectivity among the surface elements. Unless otherwise stated, we consider $N = 2$, $K = 5$, $f = 915$ MHz, $T_c = 1$ s, $\eta_k = 1 \forall k$, $P_t = 10$ W, and $Z_0 = 50 \Omega$. The PB and the BD-RIS are located at $[0, 0]$ m and $[0, 20]$ m, respectively, while the IoT devices are uniformly distributed within a circular region of radius 5 m. All links follow Rician fading with factor 1 and path-loss exponent 2. Results are presented for $M \in \{25, 50, 100\}$.

Fig. 2 presents the total harvested energy E_T as a function of the number of BD-RIS elements. It can be observed that E_T increases with M for both solutions, due to the larger number of degrees of freedom available for controlling the reflected signal. Although the *Fully Connected* architecture provides slightly higher performance, the proposed solution maintains E_T close to the benchmark. Furthermore, Fig. 3 shows the number of active BD-RIS connections. As expected, the *Fully Connected* architecture exhibits a sharp increase with M , whereas the proposed solution uses only a reduced subset of connections. Therefore, the proposed

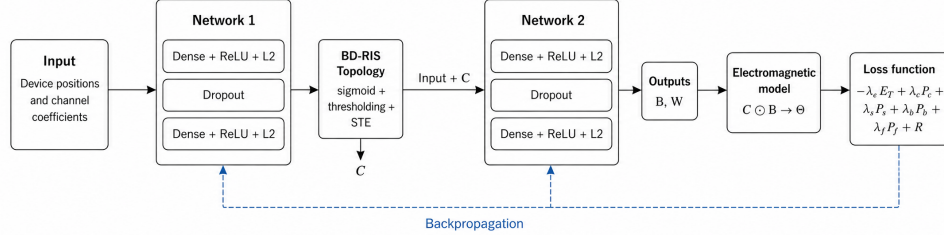
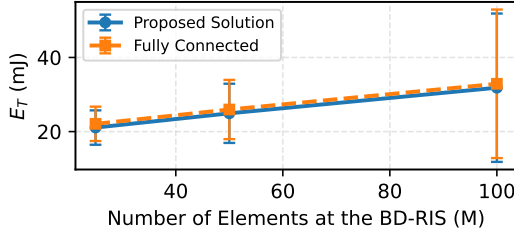


Fig. 1: Architecture of the proposed solution.


 Fig. 2: Analysis of E_T versus M .

approach preserves competitive energy performance with lower architectural complexity.

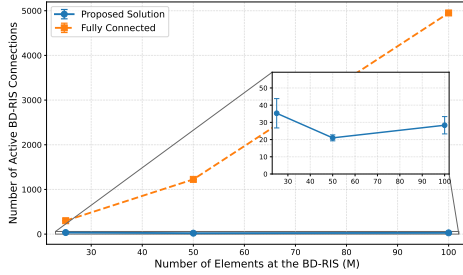


Fig. 3: Analysis of the number of active BD-RIS connections.

The results indicate that the proposed solution provides a favorable trade-off between energy performance and implementation complexity. Although the *Fully Connected* architecture offers an upper reference in terms of structural flexibility, its high number of connections may significantly increase control complexity, the consumption associated with reconfigurable circuits, and practical implementation difficulty. In contrast, the proposed solution drastically reduces the number of active connections while maintaining E_T close to that achieved by the fully connected architecture. Thus, the learning-based approach is promising for the design of BD-RISs in RF-WET systems, especially in scenarios where architectural simplicity and scalability are important requirements.

V. Conclusions

This paper proposed an unsupervised learning approach for the joint design of the BD-RIS topology, the admittance matrix, and the beamforming in RF-WET

systems. The results showed that the proposed solution achieves energy performance close to that of the *Fully Connected* architecture while using significantly fewer active connections. Therefore, the proposed approach provides an efficient trade-off between harvested energy and architectural complexity.

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