CURE: Enabling RF Energy Harvesting using Cell-Free Massive MIMO UAVs Assisted by RIS

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Abstract—The ever-evolving internet of things (IoT) has led to the growth of numerous wireless sensors, communicating through the internet infrastructure. When designing a network using these sensors, one critical aspect is the longevity and self-sustainability of these devices. For extending the lifetime of these sensors, radio frequency energy harvesting (RFEH) technology has proved to be promising. In this paper, we propose CURE, a novel framework for RFEH that effectively combines the benefits of cell-free massive MIMO (CFmMIMO), unmanned aerial vehicles (UAVs), and reconfigurable intelligent surfaces (RISs) to provide seamless energy harvesting to IoT devices. We consider UAVs as access points (APs) in the CFmMIMO framework. To enhance the signal strength of the RFEH and information transfer, we leverage RISs owing to their passive reflection capability. Based on an extensive simulation, we validate our framework’s performance by comparing the max-min fairness (MMF) algorithm for the amount of harvested energy.

Index Terms—Unmanned aerial vehicles, energy harvesting, surface-mount technology, mimo

I. INTRODUCTION

At present, it is estimated that more than 50 billion internet of things (IoT) devices are connected to the internet [1]–[3], including diverse domains such as home and living environment, communication and connectivity, agricultural, healthcare, and medical, transportation and logistics, etc [4]–[7]. These IoT devices employ a variety of methodologies for connecting and sharing data, and most of these methods are wireless by nature [8]. Also, the major portion of the IoT ecosystem is transportable, owing to their applications. So, the charging of these IoT nodes is a crucial factor for the continuous operability of these devices. Moreover, many applications require tiny wireless IoT nodes to be deployed in places that are inaccessible and, there is no permanent power supply either [9]. Although the rechargeable batteries can work as a conventional power source, they can only last for a specific time interval. Afterward, these batteries will also require charging or even replacement, which may incur higher costs. To resolve the problem of stationary charging, a lot of attention had been put to the research works related to finding ways of delivering power wirelessly. The great visionary Nikola Tesla first proposed to transmit energy into free space and convert the energy into usable direct current power [10]. Later, that foresight led to the development of state-of-the-art power supply techniques like Wireless Power Transfer (WPT) and Energy Harvesting (EH).

The cutting edge of the wireless power delivery is the harvesting of energy from radio frequency (RF) signals, providing seamless power to the IoT nodes indoor and outdoor, regardless of whether they are stationary or mobile [11]. However, the conversion efficiency of RF energy harvesting (RFEH) is still low, particularly in long-distance transmissions. For dealing with the distant problem arising from the deployment of access points (APs), many recent works consider adopting a cell-free network system with a central processing unit and fronthaul connection so that there will always be some APs close to each of the IoT nodes. Among them, one group of energy harvesting mechanisms consider the maximization of total RFEH throughput along with the AP selection under transmission power constraints for each AP (e.g., [12]). However, they assume perfect channel state information (CSI) without considering the uplink communications. Another group of works minimize the total transmitted energy for wirelessly-powered cell-free IoT by considering a linear energy harvesting model with only Rayleigh fading (e.g., [13]). Instead, adopting a Rician fading channel model with random phase shifts to each of the antennas of the APs would have been more general like the real environment.

As the massive multiple-input multiple-output (mMIMO) technique has the ability to focus the received signal power with very narrow beams [14], [15], it has been considered in wireless energy and information transfer systems [16], [17]. The practicality of mMIMO’s wireless energy transfer capability for sensor networks energy harvesting was analyzed by Kashyap et al. [18]. Although the mMIMO technology provided better efficiency in data rates compared to the previous technique, there is the issue of inter-cell interference. Consequently, it will fail to provide the desired level of energy transfer efficiency to the IoT devices. To serve all devices in a coherent manner, an improved network infrastructure is considered by authors of [19], [20] with cell-free mMIMOs (CFmMIMO), for APs distributed over the coverage area. Leveraging this infrastructure, we propose CURE, a CFmMIMO-mount Unmanned aerial vehicle (UAV) assisted by Reconfigurable intelligent surfaces (RIS) framework for RF Energy harvesting. The UAV-mounted APs achieve significant performance in data harvesting for IoT devices due to their reachability and mobility [21]. The CFmMIMO UAVs can provide higher average signal strength even in the edge areas of the coverage region. Moreover, the RISs can reflect the
incident signals into the desired direction with the controllable meta elements, which can effectively solve the non-line-of-sight problem and provide constructive interferences to the IoT devices.

In summary, our contributions are three-fold:

- We design and implement CURe, a novel framework for improved RF energy harvesting with the combined benefits of CFmMIMO, UAV, and RIS.
- We verify our framework’s performance by comparing it with the max-min fairness (MMF) algorithm proposed by Demir et al. [22] with respect to spectral efficiency and harvested energy.
- We propose three deployment strategies for the RISs and make empirical comparisons to find out the optimal strategy.

Organization: The rest of the paper is organized as follows: We discuss sufficient preliminary information in Section II. The related works are discussed in Section III. We introduce our proposed CURe framework in Section IV. In Section V, we discuss the technical details of the frameworks and the complete analysis of our algorithms. In Section VI, we explain the evaluation setup along with the empirical analysis and findings. At last, we conclude the paper in Section VII.

II. BACKGROUND

In this section, we discuss the necessary preliminary information that helps to explain the proposed CURe mechanism.

A. Cell-Free Massive Multiple-input Multiple-output

The mMIMO has been receiving paramount interest throughout the last decade or so due to the high spectral efficiency (SE) it offers by the spatial multiplexing of large number of devices on the same time-frequency resource [23]. The basic architecture of the mMIMO is presented in Fig. 1. Although mMIMO has been providing higher data transfer rates than preceding technologies, it suffers from inter-cell interference, especially for the cell-edge-devices [24]. Moreover, the complexity of the symbol detector increases exponentially in the mMIMO uplink receiver, owing to the large number of antennas and RF chain [25]. As an alternative, more advantageous incarnation, CFmMIMO network infrastructure has been proposed by Ashikhmin et al. [19], where a large number of antennas jointly can serve a lower number of IoT devices by relying on time-division duplex (TDD) operations. These antennas are geographically distributed throughout the coverage area and leverage the fronthaul network with CPU operating at the same time-frequency resource. The CPU sends power coefficients and downlink data to the APs, while the APs send back the uplink data received from the IoT devices, to the CPU via fronthaul link. The advantages to CFmMIMO include but not limited to high energy efficiency in terms of mbits/joule because of high array gain, flexible and cost-effective deployment, channel hardening and the favorable propagation conditions, appealingly uniform quality of service (QoS) [26].

B. Reconfigurable Intelligent Surfaces

The RIS is a brand-new concept in the domain of wireless technologies that is drawing a lot of attention from the wireless research community. It is a relaying metasurface, controlled with integrated electronics, and it brings unique wireless communication capabilities [27]. The basic architecture of RIS is presented in Fig. 2. It has a few layers of plane surface that can be fabricated with nano-printing and lithography techniques [28]. The elements can independently provide some changes to the incident signal without consuming any bit of the transmit power. The change can be towards the phase, frequency, amplitude or even polarization [27]. The distinctive characteristic of RISs comes from the capability of controlling the environment via telecommunication operators that shape the EM response of the objects distributed throughout the network [29]. In simpler terms, when direct communication suffers bad qualities, the RIS (generally installed on walls, ceilings, and facades [30]) assists the transmission between sender and receiver by configuring the wireless environment.

C. Unmanned Aerial Vehicle as Access Point

The UAV technology is gaining a lot of interest recently due to its utilization in numerous commercial and military appli-
IV. PROPOSED FRAMEWORK

We discuss our proposed CURE framework in this section. As presented in Fig. 4, our framework provides a downlink radio frequency signal to the battery-limited IoT devices for energy harvesting. The UAVs, mounted with cell-free mMIMO, act as the access points. We consider that the UAVs are tethered with a direct energy source. So, they hover at a point for acting as the access points. They also have an immediate link with the core network, i.e., base station. They provide direct RF signals to the IoT devices.

On the other hand, for enhancing the energy harvesting in the downlink and for providing signals to the non-line-of-sight locations in the coverage areas, reconfigurable intelligent surfaces are utilized. They reflect the RF signal intelligently towards the IoT devices. The combined RF signal from the access points and RISs are harvested at the user end. Then, this power is leveraged for the uplink information transfer from the user devices to the access points. Depending on the location, the uplink signal can be sent directly to either the base station or the UAV/AP and/or via the RIS panel.

III. RELATED WORKS

Downlink RF energy harvesting with mMIMO has become an active research topic in the scientific community in recent years. To mention some, Chen et al. investigated the maximization of energy efficiency for energy harvesting with mMIMO maintaining satisfiable QoS via energy beamforming [34]. Amarasuriya et al. studied the performance of wireless energy transfer for multi-cell multi-way mMIMO relaying by deriving the harvested energy versus the achievable sum rate trade-offs [35]. Zhao et al. investigate the energy harvesting capability of mMIMO by maximizing the minimum harvested energy among the energy-requiring devices subject to a minimum achievable rate for information-requiring-devices [17]. There are a lot of works on investigating energy harvesting using CFmMIMO as well. For example, Ngo et al. explore the performance of CFmMIMO with conjugate beamforming in downlink by considering the joint effect of power control, channel estimation, and nonorthogonality of pilot sequences [19]. Nayebi et al. investigate the downlink performance of CFmMIMO with zero-forcing (ZF) precoding and conjugate beamforming, and propose an algorithm with low complexity power allocation [36]. Unlike the above-mentioned works, Shrestha et al. investigate the performance of simultaneous wireless information and power transfer (SWIPT) for training-based CFmMIMO [37]. However, they considered that information and energy users are located separately. Likewise, Alageli et al. [38] studied SWIPT with CFmMIMO where only the energy users harvest energy, and the information users don’t. Following the methodology of [22], we consider energy harvesting of all the users regardless of their primary requirement by considering power control for maximizing the minimum uplink spectral efficiency for wireless power transfer with CFmMIMO. Moreover, we introduce the idea of leveraging RIS assisting the CFmMIMO mounted on the tethered UAV APs for improved energy harvesting performance. To the best of our knowledge, this is the first work that combines these three technologies for RF energy harvesting.
V. TECHNICAL DETAILS

In this section, we discuss the technical details of our proposed CURedef framework. First, we discuss the underlying system model. Later, we explain our downlink energy harvesting approach. Finally, we provide a detailed description of Algorithm 1.

A. System Model

We consider cell-free mMIMOs mounted on the tethered UAVs as the access points. For serving J number of IoT devices with harvesting capability across the coverage area, we assume U number of APs are distributed. Each UAV-mount CFmMIMO is assumed to be equipped with N number of antennas and they have an error-free fronthaul connection to the central processing unit (CPU). We leverage the implementation scheme proposed by Demir et al. [22]. Accordingly, we assume a time division duplex (TDD) operation, which will force channel reciprocity. We denote the total number of samples per coherence interval by δc. Each of the coherent intervals is split into three phases: (i) uplink training, (ii) downlink wireless power transfer and (iii) uplink wireless information transfer. In the first phase, all the IoT devices send pilot sequences of length δu to the UAV APs, for estimating the channel in order to design the precoding vectors for efficient energy transfer and data reception. For the downlink and uplink transfer, δd and δu samples are used respectively. So, for each coherent interval, the total samples:

δc = δp + δd + δu

(1)

We denote the channel between the jth user and the uth AP by hju, where the channels remain constant in a single time-frequency coherence interval. In the context of CFmMIMO UAVs with multiple antennas, we follow the spatially uncorrelated Rician fading channels proposed by Demir et al. [22] with unknown phase shifts. So the realization of each channel can be expressed as:

hju = eκϕju hju + hju

(2)

Here, eκϕju hju and hju represents the line-of-sight (LOS) and non-line-of-sight (NLOS) components respectively. For NLOS component, the small-scale fading is modeled as NC(0N, γjuIj), with γju representing the large-scale fading co-efficient. In accordance with prior literature, we consider that the UAV APs have perfect knowledge about the LOS component and large-scale fading co-efficient corresponding to the channel between the IoT devices and themselves, describing the long-term channel effects. Unlike the former works that consider the negligence of phase shift ϕju by the Rician fading, we consider the realistic scenario where, due to user mobility, ϕju in the LOS component is unknown. A little amount of random ϕju is induced on both the LOS and NLOS component, constructed by the individual paths, when receiver and transmitter move over distances at the order of the wavelength.

B. Downlink Energy Harvesting

In this phase, all APs start to transmit energy to the IoT devices by utilizing the channel state information (CSI) for the downlink precoding. First, the coherent energy transmission will be analyzed where same energy symbol is transmitted by all the APs for each IoT devices in a synchronous manner, to increase the harvested energy. The signal transmitted by the uth AP can be expressed as:

xjuu = ∑pju sju

(3)

Here, wju denotes the downlink precoding vector for this phase. sju and pju represent the zero-mean unit-variance energy signal for the jth IoT device and the power control coefficient of the uth AP corresponding to the jth device. In the long term, the transmission power for each CFmMIMO AP should satisfy the maximum power limit:

Pu ≤ ρd

(4)

Here, Pu is the average transmitted power for the uth AP and ρd is the maximum power limit. Again Pu can be calculated by:

Pu = E { ∑j=1J √pju wju sju }2 = ∑j=1J pju E { wju }2

(5)

The received signal for the jth IoT device is:

rju = ∑u=1U hju sju + nj E = ∑u=1U m=1 √pmu H H hju sju + nj E

(6)

Here, nj E indicated the additive noise at the jth IoT device. The average input power at the energy harvesting rectifier circuit of the jth device can be expressed as:

Ij = E { ∑u=1U m=1 √pmu H H hju sju }2

(7)
Similar to [39], we will utilize the following non-linear energy harvesting model, as this model correlates with real measured data. For the $j_{th}$ IoT device in $\delta_d$ channel, the total harvested energy can be expressed as:

$$E_j = \frac{\delta_d A_j I_j}{B_j I_j + C_j}$$  \hspace{1cm} (8)

here, $A_j > 0$, $B_j \geq 0$, and $C_j$ are constants determined by curve fitting of the rectifier circuit of the $j_{th}$ device [39].

For the RIS supported transmission, we leverage the expressions from [40]. Fig. 5 presents a detailed view of the RIS assisted energy harvesting. The RIS has $N$ discrete elements and the deterministic channel from source to RIS is presented by $h_{ur}$ ($n_{th}$ component is presented by $[h_{ur}]_n$). The channel in between the destination and the RIS is represented by $h_{jr}$ and the deterministic flat-fading channel is denoted by $h_{ju}$, as mentioned in the earlier equations. The RIS properties are represented by:

$$\Theta = \text{diag}(e^{j\theta_1}, ..., e^{j\theta_N})$$  \hspace{1cm} (9)

here, $\Theta$ represents the diagonal matrix, $\alpha \in (0,1]$ and $\theta_1, ..., \theta_N$ represent the fixed amplitude reflection coefficient and the phase-shift variables respectively. The received signal at the destination can be expressed as:

$$S_r = (h_{ju} + h_{ur}^T \Theta h_{jr})\sqrt{xy} + n$$  \hspace{1cm} (10)

here, $x, y,$ and $n$ represent the transmit power, unit-power information signal and receiver noise respectively. The channel capacity of the RIS-supported network can be expressed as:

$$R_{\text{RIS}}(N) = \max_{\theta_1, ..., \theta_N} \log_2 \left( 1 + \frac{x|h_{ju} + h_{ur}^T \Theta h_{jr}|^2}{\sigma^2} \right)$$  \hspace{1cm} (11)

$$= \log_2 \left( 1 + \frac{x||h_{ju}|^2 + \sigma^2 \sum_{n=1}^{N} |[h_{ur}]_n[h_{jr}]_n|^2}{\sigma^2} \right)$$  \hspace{1cm} (12)

The maximum rate is achieved when the phase-shifts are set as $\theta_n = \arg(h_{ju}) - \arg([h_{ur}]_n[h_{jr}]_n)$. For brevity, the above equation can be re-written with:

$$|h_{ju}| = \sqrt{\beta_{ju}}, |h_{ur}| = \sqrt{\beta_{ur}}, |h_{jr}| = \sqrt{\beta_{jr}}$$  \hspace{1cm} (13)

$$= \frac{1}{N} \sum_{n=1}^{N} |[h_{ur}]_n[h_{jr}]_n| = \sqrt{\beta_{\text{RIS}}}$$  \hspace{1cm} (14)

The re-written equation would be:

$$R_{\text{RIS}}(N) = \log_2 \left( 1 + \frac{x(\sqrt{\beta_{ju}} + N\alpha\sqrt{\beta_{\text{RIS}}})^2}{\sigma^2} \right)$$  \hspace{1cm} (15)

We utilize this equation for calculating the rates for our RIS assisted energy harvesting.

**Algorithm 1:** Harvested Energy

```
1 Param_sys = [Realizations, Pow_transmit, Pow_noise, Block_coher, Param_rectifier, Carrier];
2 Param_sys ← Initialize;
3 AllSetups ← Number of setups;
4 Matrix_rate ← φ;
5 for each setup ∈ AllSetups do
6    rates ← φ;
7    while TRUE do
8        Gain_Channel, Realization_Channel ← SetupFunc(Param_AP, Param_RIS);
9        Stat_Terms, Harvested_Energy ← Channel_Estimation(Gain_Channel, Realization_Channel, Param_sys);
10       rates ← Spectral_Efficiency(Stat_Terms, Harvested_Energy, β);
11       Solution ← Feasibility(rates);
12       if Solution is Feasible then
13           Matrix_rate.append(rates);
14           break;
15       else
16           continue;
17       end
18    end
19 end
```

**C. Implementation of the Energy Harvesting Model**

Finally, in this section, we provide an elaborated description of the energy harvesting algorithm that we considered in this work, represented by Algorithm 1. First, we initialize the necessary system parameters (Param_sys) like realization, transmit power (Pow_transmit), block coherence (Block_coher) etc., according to the requirements of different experiments. Necessarily, we keep the values of some of the parameters fixed across all the experiments, which are provided in Table I. We consider random placement for the client IoT devices in the coverage area, which are represented by each of the setups. We consider multiple setups so that we do not get biased performance results from a particular placement. For saving and later averaging the achieved rates of the energy harvesting model, we maintain a matrix of rates across the setups. For each setup, we calculate the channel gain and realization of the channel through the SetupFunc function, where parameters of the APs (Param_AP) and RISs (Param_RIS) are passed as arguments. Then come up with the statistical terms and amount of harvested energy through the Channel_Estimation function. Here we pass the system parameters, channel gain and realization of the channel as argument. Depending on the value of large-scale fading co-efficient ($\beta$), statistical terms and amount of harvested energy, the final rates are calculated by Spectral_Efficiency function. Then we check the feasibility of the rate solutions and terminate the iteration for a particular setup when feasible solutions are achieved. As mentioned
earlier, we store the rates of different setups and calculate the average harvested energy for the model.

**TABLE I**
VALUES OF DIFFERENT PARAMETERS FOR THE CURE FRAMEWORK.

| Parameter Name                  | Value Assigned |
|---------------------------------|----------------|
| Pilot transmit power (W)        | 10 (+7)        |
| Total power limit per AP (W)    | 10 (U)         |
| Compute noise power (dBm)       | -96            |
| Length of coherence block       | 200            |
| Pilot Length                    | 5              |
| Number of downlink samples      | 25             |
| Carrier frequency (GHz)         | 3.4            |
| Standard deviation of shadow fading for LOS (dB) | 3 |
| Standard deviation of shadow fading for NLOS (dB) | 4 |

VI. EVALUATION RESULTS AND DISCUSSION

In this section, we present the experimental setup and necessary evaluation metrics to assess the energy harvesting performance of the proposed CURE framework. We leverage the implementation of MMF optimization from [22], to calculate the downlink RF energy harvesting from the CFmMIMO UAVs. We further extend it by introducing RIS-assisted energy harvesting. We validate the claim of achieving an increased amount of harvested energy with RIS assistance through comparison with regular MMF and RIS assisted MMF, with respect to empirical cumulative distribution function value of the harvested energy. Later, we experiment with a variable number of meta elements in each RIS and try out with different number of access points to assist in order to find out the optimal number of meta elements for a given number of access points. Also, we try with different number of antennas in an AP with a variable number of RISs and try to find out the optimal number of antennas for a given number of RISs. Finally, we experiment with three different deployment strategies for the RISs and try with different numbers of APs to come up with the best deployment strategy.

A. Spectral Efficiency per user

In this section, we evaluate the performance of CURE framework by comparing the empirical cumulative distribution function of individual spectral efficiency per user, achieved by the regular MMF mechanism and RIS-assisted MMF mechanism, as represented in Fig. 6. We compare the spectral efficiency for all the combinations of coherent, non-coherent and linear, non-linear energy transmission. For the coherent linear energy transmission in Fig. 6(a), it can be seen that RIS-assisted MMF is achieving a higher amount of spectral efficiency compared to standard MMF. Similarly, from Fig. 6(b), Fig. 6(c), Fig. 6(d), it is observed that RIS assisted MMF achieved higher spectral efficiency per user for other types of signal as well. Both the models show similar distributions; for coherent linear signal,
the distribution is more skewed than the non-coherent non-linear signal. The upper tail of the curves represents the users with good channel conditions, who achieve higher spectral efficiency than the other users because of their operation in the saturation region. Fig. 7 represents the comparison of performance between the MMF and proposed CURie framework with respect to the harvested energy. It is evident from Fig. 7(a) and Fig. 7(c) that CURie achieves substantially more harvested energy than MMF for both coherent linear and non-coherent non-linear energy transmissions. To get a concrete idea about the improvement, we increased the number of RISs leveraged for both types of signal in Fig. 7(b) and Fig. 7(d). It is observed that the improvement is exponential with the increased number of RISs.

B. Optimal number of meta-element and antennas

In this part, we experiment with different numbers of meta-elements in the RISs, assisting variable number of APs and different number of antennas in the APs assisted by a variable number of RISs to come up with the optimal choices, as shown in Fig. 8. We keep the number of RISs and APs fixed for the variable meta elements and variable antennas case, respectively. From Fig. 8(a), it is observed that with 9 access points, the amount of harvested energy is very low, even with a higher number of meta elements in each of the 9 RISs. On the other hand, with 16 access points, the amount harvested energy seems to have an upward trend with the increasing number of meta elements in the RISs. On the other hand, in Fig. 8(b), a more steep curve is observed with 16 access points as the number of RISs is increased to 16. In Fig. 8(c) and Fig. 8(d) it is seen that varying the number of RISs doesn’t have that much impact compared to a varying number of APs. In both the figures, for 4 RISs, the incremental number of antennas incurred a higher amount of harvested power. For 9 RISs, the trend is similar, but the magnitude of the downlink power is lower.

C. Best deployment strategy

We experiment with three different deployment strategies for the RISs and try with different numbers of APs to come up with the best deployment strategy. The strategies include: edge deployment, central deployment, and hybrid deployment, as shown in Fig. 9. In the edge deployment (Fig. 9(a)), all the RISs are placed at the edges of the coverage area. In the second deployment strategy, the RISs are placed in between the access points, as presented in Fig. 9(b). In the final deployment strategy, the RISs are deployed in a mixed manner, where half of them are placed at the edge and the other half are placed in the middle of the access points (Fig. 9(c)). From Fig. 10, it can be observed that the hybrid deployment is optimal strategy for all different choices of RIS with 16 APs (Fig. 10(a)), 25 APs (Fig. 10(b)) and 36 APs (Fig. 10(c)). One interesting trend can be found from the figures, that is, with the increase of APs in the coverage areas, the hybrid deployment strategy is becoming exponentially prominent than the other strategies.

VII. Conclusion

In this work, we have presented a comprehensive RF energy harvesting framework that leverages the combined benefits of
UAV mounted CfmMIMO and RIS. The tethered UAVs, operating in a cell-free fashion, provide strong LoS signal in the general coverage area, while untethered ones provide service in peak areas for their flexible deployment. We have devised a mechanism to utilize RISs for directive signals towards the target devices, which will assist both energy harvesting and information transfer. The empirical evaluation results have validated our framework can achieve an increased amount of energy harvesting can be achieved than the MMF [22]. We have also studied different deployment strategies for the RISs, and after comparing their energy harvesting performance, we have found the best strategy properties. In our future work, we will try to optimize the deployment positions and heights of both the UAVAPs and RISs for even improved energy harvesting than the best deterministic strategy.

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