Adding Active Elements to Reconfigurable Intelligent Surfaces to Enhance Energy Harvesting for IoT Devices

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***Abstract*—Reconfigurable intelligent surface (RIS) panels with passive and active elements significantly enhance Internet of Things (IoT) systems performance by, respectively, reflecting and amplifying incident signals to receiving entities. However, RIS panel active elements consume more energy than passive elements due to the signals reflection property of passive elements and the signals reflection and amplification properties of active elements. In addition, IoT devices may require harvesting energy from radio frequency (RF) signals from a nearby base station (BS) when they do not have enough operational energy. This paper investigates a trade-off between RIS panels containing active and passive elements energy consumption and energy harvested from RF signals of a nearby BS by a power-hungry IoT device. We consider all possible links via the RIS panel between transmitting and receiving nodes. In our model, the RIS panel is powered by harvesting energy from BS RF signals. We consider a fixed-length time frame that is divided into two optimal time slots. In the first time slot, the IoT device harvests energy from the BS RF signals with the help of the RIS. Using harvested energy from the BS RF signal, the IoT device transmits bits to the BS in the second time slot, also with the help of the RIS. We achieve the optimal number of RIS active and passive elements, therefore, reducing the RIS energy consumption for both time slots subject to RF energy harvesting and bits transmission. An optimization problem is formulated as a non-convex mixed-integer nonlinear problem. We propose a robust iterative algorithm to solve the problem. Finally, we present results to show the improved performance of our proposed model.**

I. Introduction

Reconfigurable Intelligent Surfaces (RISs) are potential candidates to improve the channel performance and emerging as possible 6G technology. RISs may be mounted on buildings, or tall objects, which enable the scattering of the transmitted signals to the receiving nodes [1]. Having low hardware implementation and maintenance costs, RIS introduces reflection coefficients and phase shifts to reflect the incident signals. Next-generation wireless communications mandates enhanced mobile broadband traffic, ultra-low-latency communications, and energy-efficient wireless networks. RISs efficiently support those future wireless communications requirements by enhancing channel conditions based on the transmit signals reflection and amplification to the receiving entities [2].

In Internet of Things (IoT) systems, it is imperative to ensure that IoT devices harvest energy from external power sources when the devices do not have internal power sources to operate. Harvesting energy from external sources, such as solar or wind energy, is not always a viable solution. Therefore, harvesting energy from radio frequency (RF) sources, such as nearby base stations (BSs), is a promising solution to meet the energy demands of power-hungry IoT devices due to low cost and less hardware complexity [3]. Moreover, RIS panels may have active elements performing amplification in addition to the incident signals reflection or passive elements performing the incident signals reflection only. Therefore, in addition to passive elements, adding active elements to RISs enhances IoT systems performance significantly. However, active elements consume more energy due to additional amplification properties than passive elements. This suggests that finding the optimal number of active elements is vital to reducing the overall RIS energy consumption and cost.

RISs have recently received intensive studies covering many topics, such as channel estimation and modeling, passive elements optimization, resource allocation, and localization [4] - [9]. Most of the work focuses on RIS passive elements optimization instead of the possibility of adding both active elements to the RIS panel. For example, the authors in [5] proposed RIS panel-based wireless networks, where each active element is assisted by active loads that reflect and amplify the incident signals instead of only reflecting it with the adjustable phase shift as in the case of RIS passive elements. The authors in [6] proposed a novel energy-efficient RIS architecture, where all the RIS elements are passive except for a few non-uniformly distributed active elements. The authors in [7] added RIS passive elements to enhance wireless spectral efficiency. They maximized the minimum SINR subject to transmit power and the RIS phase shift. In [8], the authors enhanced the performance of the wireless networks by leveraging only RIS passive elements via incident signals reflection adjustment subject to signal to interference plus noise ratio (SINR) constraint and active and passive beamforming. Finally, authors in [9] proposed a novel concept of hybrid relay-reflecting intelligent surface, in which a single RIS is deployed with power amplifiers to serve as active relays. In contrast, the remaining elements are passive and only reflect the incident signals.

We summarize the contribution of this paper as follows:

We propose a multi-purpose use of the RIS panel, powered by the harvested BS RF signals, for a fixed duration time frame divided into two optimal time slots, as shown in Fig. 1, including 1) *assisting energy harvesting:* RIS active and passive elements assist an IoT device, S, to harvest RF signals energy from a BS in the first optimal time slot. A power efficiency factor defines the fraction of energy harvested from the BS RF signals, and 2) *assisting transmissions of IoT measurement bits:* In the second optimal time slot, RIS active and passive elements assist the optimal bits transmissions from S to the BS. We achieve optimal RIS active and passive elements energy consumption in both time slots subject to minimum harvested energy by S, bits transmission, and BS/IoT device S power budget. The formulated problem is a non-convex mixed-integer nonlinear problem (MINLP), which is challenging to solve. We, therefore, propose an iterative algorithm to solve the problem. We use the Taylor series approximation and the Dinkelbach method, etc., to develop the solution algorithm. Finally, we present results based on the proposed optimization formulation.

II. System Model

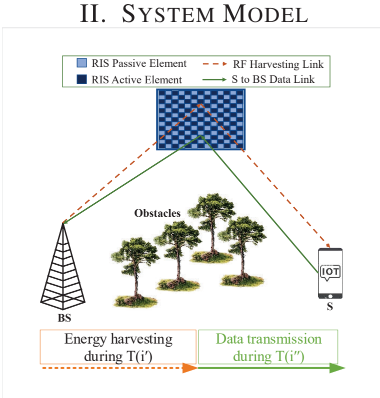

Fig. 1: System model

We assume a BS and an IoT device, S contributing to wireless communications, as shown in Fig. 1. We assume each node is equipped with a single antenna. There is a significant blockage in the network that disrupts the direct links between BS and S. An RIS panel equipped with active and passive elements assists S in harvesting energy from the BS RF signals. Using the harvested energy, the same RIS panel also assists S to transmit bits to the BS. The total time is divided into time frames of fixed length with time frame, $T(i)$ is divided into two slots, $T(i^{'})$ and $T(i^{''})$, where $T(i) = T(i^{'}) + T(i^{''})$. Energy is harvested during $T(i^{'})$ and S sends bits to the BS during $T(i^{''})$.

A. RIS Elements

The RIS element has a size that is smaller than a wavelength. It was shown that the RIS element size can be as small as $\frac{\lambda}{8} \times \frac{\lambda}{8}$ in [10], where λ is the wavelength. The element scatters the incident signal with almost the same gain in any of a number of directions of interest. As shown in Fig. 1, RIS panel has a number of discrete elements, N. We define m as number of RIS active elements, where $m \leq N$. We also define k as number of RIS passive elements, where $k \leq N$. Note that $m + k = N$. Active elements have both reflection and amplification properties, while passive elements only have the reflection property. An amplification factor defines the active elements amplifying the incident signals.

1) Energy harvesting: The IoT device, S harvests energy from BS RF signals with the help of the RIS. We express the RIS elements properties assisting in harvesting energy by S as an $N \times N$ diagonal matrix as follows:

$$\begin{aligned}\mathbf{\Theta} =&\text{diag}(\alpha_1 e^{j\theta_1}, \alpha_2 e^{j\theta_2}, .., \alpha_k e^{j\theta_k},\\ &\alpha_{k+1} e^{j\theta_{k+1}}, \alpha_{k+2} e^{j\theta_{k+2}}, .., \alpha_N e^{j\theta_N})\end{aligned} \tag{1}$$

where $\{\alpha_1, \alpha_2, ..., \alpha_k\} \in [0, 1]$ is the fixed amplitude reflection coefficient and $\{\theta_1, \theta_2, ..., \theta_k\}$ is the phase-shift of the RIS passive elements. $\{\alpha_{k+1}, \alpha_{k+2}, ..., \alpha_N\} \geq 1$ is fixed amplitude reflection and amplification coefficient. $\{\theta_{k+1}, \theta_{k+2}, ..., \theta_N\}$ is active elements phase-shift.

2) Bits transmission: We express the RIS elements properties assisting transmitting bits from S to the BS as an $N \times N$ diagonal matrix as follows:

$$\begin{aligned}\mathbf{\Phi} =&\text{diag}(\beta_1 e^{j\phi_1}, \beta_2 e^{j\phi_2}, ..., \beta_k e^{j\phi_k},\\ &\beta_{k+1} e^{j\phi_{k+1}}, \beta_{k+2} e^{j\phi_{k+2}}, ..., \beta_N e^{j\phi_N})\end{aligned} \tag{2}$$

where $\{\beta_1, \beta_2, ..., \beta_k\} \in [0, 1]$ is the fixed amplitude reflection coefficient and $\{\phi_1, \phi_2, ..., \phi_k\}$ is the phase-shift of the RIS passive elements. $\{\beta_{k+1}, \beta_{k+2}, ..., \beta_N\} \geq 1$ is fixed amplitude reflection and amplification coefficient. $\{\phi_{k+1}, \phi_{k+2}, ..., \phi_N\}$ is active elements phase-shift.

B. Channel Gain

We denote the channel gain for BS-to-RIS link by $\mathbf{h_{br}} \in \mathbb{C}^{N \times 1}$. On the other hand, the RIS-to-S channel gain is defined as $\mathbf{h_{rs}} \in \mathbb{C}^{N \times 1}$. Recall that S harvests energy from BS RF signals in the first time slot. S uses the harvested energy to transmit bits to the BS in the second time slot. During the bits transmission phase, the gains are the conjugate transpose of gains achieved from the RF signals harvesting phase. The RIS-to-BS gain for active elements is $\mathbf{h_{rb}} \in \mathbb{C}^{1 \times N}$. These gains are modeled as fading with $n \sim \mathcal{CN}(0, 1)$. We consider the frequency flat quasi-static block fading model. Thus, the destination knows them correctly. Under this model, we assume that channel is coherent during transmission phases.

C. Energy Harvesting from BS RF Signals

We encounter channel gains between the BS-to-RIS link and the RIS-to-S link. The received signals [11] from BS to S is $s_{bs} = \mathbf{h}_{\text{rs}}^{\dagger} \mathbf{\Theta} \mathbf{h}_{\text{br}} \sqrt{p_b} s + n$, where s is the unit-power information signals and p_b is the BS transmit power to S. $\mathbf{h}_{\text{rs}}^{\dagger}$ is the transpose matrix of channel gain from S and RIS. $\mathbf{h}_{\text{br}}$ is the channel gain from the BS to S. For a given $\mathbf{\Theta}$, we achieve the capacity of the additive white Gaussian noise for gains as $\mathbf{h}_{\mathbf{rs}}^{\dagger}\mathbf{\Theta}\mathbf{h}_{\mathbf{br}} = \sum_{n=1}^{N}(\alpha_n e^{j\theta_n}[\mathbf{h}_{\mathbf{rs}}^{\dagger}]_n[\mathbf{h}_{\mathbf{br}}]_n)$. The maximum rate is achieved, if phase shift θ_n is optimally selected to maximize each term in the sum in $\mathbf{h}_{\mathbf{rs}}^{\dagger}\mathbf{\Theta}\mathbf{h}_{\mathbf{br}}$. θ_n is expressed as $\theta_n = -\arg([\mathbf{h}_{\mathbf{rs}}^{\dagger}]_n[\mathbf{h}_{\mathbf{br}}]_n)$. In this model, the RF signals harvesting is expressed using the power-in-power-out relation wireless charging technology. The harvested energy at S during $T(i^{'})$ is expressed as follows:

$$e = \zeta T(i^{'})p_b((a_f m(i^{'}) + k(i^{'}))|\mathbf{h_1}|)^2 \tag{3}$$

where $\mathbf{h_1} = [\mathbf{h}_{\mathbf{br}}]_n[\mathbf{h}_{\mathbf{rs}}^{\dagger}]_n$ and a_f is the active elements amplification factor. ζ is the efficiency factor within $[0, 1]$. Higher ζ means S harvests proportionally more energy from BS RF signals. $m(i^{'})$ and $k(i^{'})$ are the number of the RIS active and passive elements used during energy harvesting phase, respectively, where $m(i^{'}) \leq m(i)$ and $k(i^{'}) \leq k(i)$. Using (3), S transmits the bits to the BS during $T(i^{''})$.

D. Bits Transmission to BS

Recall that RIS panel has m and k number of active and passive elements, respectively. The maximum number of bits transmitting from S to the BS with the help of RIS panel active and passive elements is:

$$\begin{aligned} B &= \max_{\phi_1,\ldots,\phi_N} T(i^{''})W\log_2\left(1 + \frac{p_s((a_f+1)|\mathbf{h_2}|)^2}{\sigma^2}\right) \\ &= T(i^{''})W\log_2\left(1 + \frac{p_s((a_f m(i^{''}) + k(i^{''}))|\mathbf{h_3}|)^2}{\sigma^2}\right) \end{aligned} \tag{4}$$

where W is the bandwidth of the carrier frequency, σ^2 defines the Additive White Gaussian Noise (AWGN) power at the receiver. $|\mathbf{h_2}| = \mathbf{h}_{\mathbf{sr}}^{\dagger}\mathbf{\Phi}\mathbf{h}_{\mathbf{rb}}$ and $|\mathbf{h_3}| = |[\mathbf{h}_{\mathbf{sr}}^{\dagger}]_n[\mathbf{h}_{\mathbf{rb}}]_n|$. p_s is the S transmit power, where $p_s \leq \frac{e}{T(i'')}$. $m(i^{''})$ and $k(i^{''})$ are the number of the RIS panel active and passive elements used during bits transmission phase at the second time slot, respectively, where $m(i^{''}) \leq m(i)$ and $k(i^{''}) \leq k(i)$.

E. RIS Elements Energy Consumption in both Time Slots

We investigate the RIS panel energy consumption model for both time slots, i.e., during energy harvesting from BS RF signals and bits transmission phases. We consider that the number of RIS panel active and passive elements is fixed in both phases. We calculate the energy consumption of both RIS element types. Active elements reflect and amplify the incident signals, while passive elements only reflect the incident signals. Passive elements consume energy due to the switch and control circuit of the corresponding elements. Besides the energy consumption for switch and control circuits, the active elements consume energy due to the additional functionality, such as power dissipation due to active loads and power consumption due to power amplification. Active elements, therefore, consume more energy than passive elements.

1) Power consumed by passive elements: Recall that in the proposed model, RIS panel has k passive elements. The passive elements consume energy due to control and switch circuits at the reflecting elements. The RIS passive elements power consumption is expressed as follows:

$$p_{ss}(i) = k(i)p_{sc} \tag{5}$$

where p_{sc} is the power consumption due to switch and control circuits for each RIS passive elements.

2) Power consumed by active elements: To analyze the active element power consumption, we consider power dissipation due to DC circuit loss, the output power of the RIS active elements. The negative resistance tunnel diodes at RIS active elements amplify the reflecting signals with the help of the DC biasing source, which results in DC circuit power loss. The output power of active elements includes switch and control circuit power consumption. RIS panel active elements power consumption is expressed as follows:

$$p_{ct}(i) = m(i)(p_{sc}+p_{dc}) + \zeta_1(p_b\mathbf{C_1}+\mathbf{C_2}) \tag{6}$$

where p_{dc} is the power consumption due to DC circuit power consumption. ζ_1 is defined as v^{-1}, where v denotes amplifier efficiency. $\mathbf{C_1} = ||(\mathbf{h}_{\mathbf{1}}^{\dagger}\mathbf{\Phi} + \mathbf{h_3}^{\dagger}\mathbf{\Theta})||^2$ and $\mathbf{C_2} = \sigma^2||(\mathbf{\Phi} + \mathbf{\Theta})\mathbf{I}_m||^2$, where $\mathbf{I}_m$ is the identity matrix of size $m \times m$. $\zeta_1(p_b\mathbf{C_1}+\mathbf{C_2})$ is the RIS panel active elements output power consumption. p_{sc} is the power consumption due to switch and control circuits for each RIS passive element.

3) RIS elements energy consumption: The RIS panel, containing active and passive elements, energy consumption for both time slots can be expressed as follows:

$$e_{ris} = \sum_{i\in\{i',i''\}} T(i)\Big[p_{ct}(i) + p_{ss}(i)\Big] \tag{7}$$

III. Optimization Problem

In this section, we formulate an optimization problem that minimizes the RIS panel energy consumption at both time slots subject to energy harvesting from BS RF signals, bits transmission and their corresponding time slots, and power budget. The optimization problem is expressed as follows:

$$\min_{m,k,p_b,p_s,T(i'),T(i'')} \sum_{i\in\{i',i''\}} T\Big[p_{ct}(i) + p_{ss}(i)\Big] \tag{8a}$$

$$\text{s.t. } e_m \leq \zeta T(i^{'})p_b\left((a_f m(i^{'}) + k(i^{'}))|\mathbf{h_1}|\right)^2, \forall i^{'} \tag{8b}$$

$$p_s \leq \frac{\zeta T(i^{'})p_b((a_f m(i^{'}) + k(i^{'}))|\mathbf{h_1}|)^2}{T(i'')}, \forall i \tag{8c}$$

$$\frac{B_t}{W} \leq T(i^{''})\log_2\left(1 + \frac{p_s((a_f m(i^{''}) + k(i^{''}))|\mathbf{h_3}|)^2}{\sigma^2}\right), \forall i^{''} \tag{8d}$$

$$m(i) + k(i) = N, \quad \forall i \tag{8e}$$

$$m(i^{'}) \leq m(i), \quad m(i^{''}) \leq m(i) \tag{8f}$$

$$k(i^{'}) \leq k(i), \quad k(i^{''}) \leq k(i), \tag{8g}$$

$$p_s \leq p_b. \tag{8h}$$

Note that (8) is a non-convex due to coupling of optimizing variables in (8a) - (8d). The objective function minimizes the RIS panel energy consumption for both time slots and is described in (8a). Moreover, (8b) defines amount of energy is harvested from BS by S during $T(i^{'})$, where e_m is a threshold. In (8c), we define the energy causality constraint and S transmit power to operate the D2D communications. We define the minimum bits are transmitted during $T(i^{''})$ in (8d), where B_t is threshold. In (8e) - (8g), we show the number of RIS panel active and passive elements in two time slots. The relation between BS and S power is shown in (8h).

IV. Proposed Solution

We divide (8) into three sub-problems due to their complexity and then solve them iteratively. Firstly, we optimize RIS elements, given power budget and time slots. In this step, we introduce slack variables and achieve feasible points using the first-order Taylor series expansion. Secondly, we retain the number of optimal RIS elements to optimize BS, and S transmit power. We also introduce feasible points to approximate the optimization problem as convex. Finally, we find the optimal time slots using the achieved optimal variables. We apply the Dinkelbach method in this step to approximate the convexity. Three sub-problems, which are solved iteratively, are investigated in turn in the next three following sub-sections.

A. Optimal RIS Panel Active and Passive Elements

We optimize the number of RIS panel active and passive elements, m and k, respectively, given the BS transmit power and time slots. We reformulate the problem as follows:

$$\min_{m,k} \sum_{i\in\{i^{'},i^{''}\}} T\Big[m(i)(p_{sc}+p_{dc})+\mathbf{C_3}+k(i)p_{sc}\Big] \tag{9a}$$

$$\text{s.t. } e_m \leq \zeta T(i^{'})p_b\left((a_f m(i^{'})+k(i^{'}))|\mathbf{h_1}|\right)^2, \forall i^{'} \tag{9b}$$

$$p_s T(i^{''}) \leq \zeta T(i^{'})p_b((a_f m(i^{'})+k(i^{'}))|\mathbf{h_1}|)^2, \forall i \tag{9c}$$

$$\frac{B_t}{W} \leq T(i^{''})\log_2\left(1+\frac{p_s((a_f m(i^{''})+k(i^{''}))|\mathbf{h_3}|)^2}{\sigma^2}\right), \forall i^{''} \tag{9d}$$

$$(8e) - (8g)$$

where $\mathbf{C_3}=\zeta_1(p_b\mathbf{C_1}+\mathbf{C_2})$. We tackle non-convex energy harvesting from BS RF signals constraint in (9b) by introducing feasible points $m^*(.)$ and $k^*(.)$ as follows:

$$e_m \leq c_2\left(a_f m(i^{'})+k(i^{'})\right)\left(a_f m^*(i^{'})+k^*(i^{'})\right) \tag{10}$$

where $c_2 = \zeta T(i^{'})p_b|\mathbf{h_1}|^2$. Similarly, we tackle (9c) by linearizing at feasible points $m^*(.)$ and $k^*(.)$ as follows:

$$c_3 \leq c_2\left(a_f m(i^{'})+k(i^{'})\right)\left(a_f m^*(i^{'})+k^*(i^{'})\right) \tag{11}$$

where $c_3 = p_s T(i^{''})$. Note that (9d) needs to be convex. We reformulate (9d) as follows:

$$\frac{(2^{\frac{B_t}{W}}-1)\sigma^2}{p_s|\mathbf{h_3}|^2} \leq \left(a_f m(i^{''})+k(i^{''})\right)^2 \tag{12}$$

We expand the RHS as follows:

$$\text{RHS} = \underbrace{a_f^2 m^2(i^{''})}_{\text{non-linear 1}} + \underbrace{2a_f m(i^{'})k(i^{''})}_{\text{non-linear 2}} + \underbrace{k^2(i^{''})}_{\text{non-linear 3}} \tag{13}$$

RHS is non-convex due to the quadratic terms. We linearize the three non-linear terms at feasible points, where $a_f^2 m^2(i^{''}) = a_f^2 m^*(i^{''})m(i^{'})$, $2a_f m(i^{''})k(i^{''}) = 2a_f\frac{m^*(i^{''})k(i^{''})+m(i^{''})k^*(i^{'})}{2}$, and $k^2(i^{''}) = k^*(i^{''})k(i^{''})$. We can reformulate (12) as follows:

$$\frac{(2^{\frac{B_t}{W}}-1)\sigma^2}{p_s|\mathbf{h_3}|^2} \leq 2a_f\frac{m^*(i^{''})k(i^{''})+m(i^{''})k^*(i^{''})}{2} + a_f^2 m^*(i^{''})m(i^{''}) + k^*(i^{'})k(i^{'}) \tag{14}$$

The reformulated problem is expressed as follows:

$$\min_{m,k} \sum_{i\in\{i^{'},i^{''}\}} T\Big[m(i)(p_{sc}+p_{dc})+\mathbf{C_3}+k(i)p_{sc}\Big] \tag{15}$$

$$\text{s.t. } (8e) - (8g), (10), (11), (14)$$

Note (15) is a convex problem. Feasible points m^* and k^* are initialized at any point. At every iteration, the feasible points are updated, and this process continues until it reaches convergence and the optimal solution of (9) is achieved.

B. Optimal Transmit Power of BS and IoT Device, S

In this sub-section, we adopt the optimal m and k from Section IV-A to achieve optimal BS transmit power, p_b and S transmit power, p_s. We reformulate the optimization problem from (8) as follows:

$$\min_{p_b,p_s} \sum_{i\in\{i^{'},i^{''}\}} T\Big[c_4+\zeta_1(p_b\mathbf{C_1}+\mathbf{C_2})\Big] \tag{16a}$$

$$\text{s.t. } e_m \leq c_5 p_b, \forall i^{'} \tag{16b}$$

$$p_s T(i^{''}) \leq p_b c_5, \tag{16c}$$

$$p_b \leq p_m^{bs}, \quad p_s \leq p_m^{iot}, \tag{16d}$$

$$B_t \leq WT(i^{''})\log_2(1+c_6 p_s), \forall i^{''} \tag{16e}$$

where $c_4 = p_{sc}+p_{dc}+k(i)p_{sc}$, $c_5 = \zeta T(i^{'})\left((a_f m(i^{'})+k(i^{'}))|\mathbf{h_1}|\right)^2$, and $c_6 = \frac{1}{\sigma^2}\left((m(i^{'})a_f+k(i^{'}))|\mathbf{h_3}|\right)^2$. We tackle $\log_2(.)$ term from (16e) as follows:

$$\left(2^{\frac{B_t}{W}}-1\right)\frac{1}{c_6} \leq p_s \tag{17}$$

The newly optimized problem can be expressed as follows:

$$\min_{p_b,p_s} \sum_{i\in\{i^{'},i^{''}\}} T\Big[c_4+\zeta_1(p_b\mathbf{C_1}+\mathbf{C_2})\Big] \tag{18}$$

$$\text{s.t. } (16b) - (16d), (17)$$

Note that (18) is a convex problem. Feasible points p_s^* and p_b^* are initialized at any point. At every iteration, the feasible points, including m and k, are updated, and this process continues until it reaches convergence and optimal solution of (16).

C. Optimal Time Slots

We optimize energy harvesting time $T(i^{'})$ and bits transmitting time, $T(i^{''})$ using the optimal m, k, p_b, and p_s. We rewrite the optimization from (8) as follows:

$$\min_{T(i^{'}),T(i^{''})} \sum_{i\in\{i^{'},i^{''}\}} [(T(i^{'})+T(i^{''}))(p_{ct}(i)+p_{ss}(i))] \quad (19a)$$

$$\text{s.t. } p_s \leq \frac{\zeta T(i^{'}) p_b \left((a_f m(i^{'})+k(i^{'}))|\mathbf{h_1}|\right)^2}{T(i^{''})}, \quad \forall i \quad (19b)$$

$$(8b),\ (8d)$$

We tackle the fractional nature of (19b) by applying Dinkelbach method and approximating it to be a convex problem. We briefly explain the Dinkelbach method in the following. Here, $f(r)=\frac{P(r)}{Q(r)}$ is described as $f(r){=}P(r){-}\gamma_d Q(r)$ under all convex constraints, where γ_d is a constant. This value is iteratively updated by $\gamma_j{=}\frac{p_{r_j}}{Q_{r_j}}$, where j is the iterative index. We reformulate (19b) as follows:

$$p_s \leq \zeta T(i^{'}) p_b \left((a_f m(i^{'})+k(i^{'}))|\mathbf{h_1}|\right)^2 - \gamma_j T(i^{''}) \quad (20)$$

where γ_j is constant. Reformulated optimization problem is:

$$\min_{T(i^{'}),T(i^{''})} \sum_{i\in\{i^{'},i^{''}\}} (T(i^{'})+T(i^{''}))(p_{ct}(i)+p_{ss}(i)) \quad (21)$$

$$\text{s.t. } (8b),\ (8d), (20)$$

Note that (21) is a convex problem and follows the same iterative process mentioned in the previous two sub-sections.

The process continues, followed by an iterative approach until convergence. The iterative solution guarantees the convergence [12]. We summarize the proposed solution in an algorithm as follows:

Algorithm 1

1: **Optimization**:
2: **repeat**
3: Find the optimal RIS panel elements using (15)
4: Obtain optimal m and k
5: Find the optimal transmit power using (18)
6: Obtain optimal p_b, p_s
7: Find the optimal time slots using (21)
8: Obtain optimal $T(i^{'})$, $T(i^{''})$
9: **until** convergence

V. Simulation Results

In this section, we present results based on the proposed optimization formulation in (8). The BS, S, D, and RIS panel are deployed at fixed locations. The distance between two communicating nodes determines their corresponding gains. To perform the simulation, we use Gams, which is used to solve nonlinear optimization problem [13]. The list of parameters, used in the simulation setup are $N \in \{50, 100, 150, 200\}$, $T \in \{150, 200, 250, 300\}$ ms, $\sigma^2 = -94$ dBm, $\zeta = [0, 1]$, $e_m = 0.1$ mJ, $p_{sc} = -10$ dBm, $p_{dc} = -5$ dBm, $a_f = 5$, $p_m^{bs} = 0.8$ W, and $p_m^{iot} = 0.2$ W.

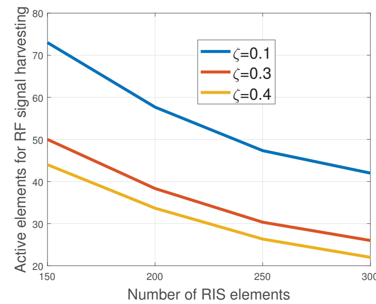

Fig. 2: RIS panel active elements during energy harvesting

Fig. 2 and Fig. 3 show the optimal number of RIS panel active elements required for energy harvesting and bits transmission, respectively. In Fig. 2, the number of RIS panel active elements decreases with the increment of the total number of RIS elements. Since RIS panel active elements consume more energy than RIS passive elements, our proposed model finds the optimal number of active elements. The RIS panel uses more passive elements and aims to find a smaller number of active elements. When S harvests a small fraction of energy from the BS RF signals, the optimal number of active elements is still lower side. In the case of a larger RIS panel, say $N = 300$, and small power-efficiency factor, $\zeta = 0.1$, only 14% of the RIS elements are used as active elements. On the other hand, RIS panel uses only 7% of 300 RIS panel elements as active, when S harvests a higher fraction, i.e., $\zeta = 0.4$, of energy.

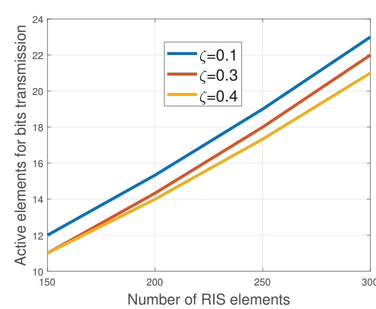

Fig. 3: RIS panel active elements during bits transmission

Fig. 3 shows the RIS panel active elements used in the bits transmission from S to the BS. As shown in Fig. 3, the number of RIS panel active elements increases when the increment of RIS elements. For example, around 8% of the RIS elements are used as active elements when RIS panel has 150 elements (a lower number in our simulation setup). On the other hand, around 7% of the RIS elements are used as active elements when RIS panel has 300 elements (a higher number in our simulation setup). The change of the number of RIS panel active elements is not significant even for the higher number of RIS elements. Fig. 4 shows the

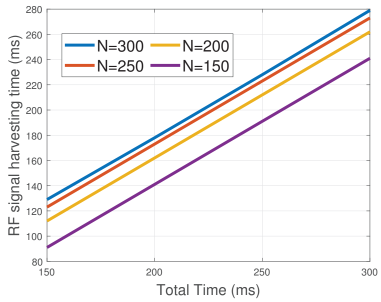

Fig. 4: Optimal time during energy harvesting

time, $T(i^{'})$ required for harvesting from the BS RF signals. Recall that $T(i) = T(i^{'}) + T(i^{''})$. So, the remaining time, $T(i^{''})$ is used during bits transmission from S to the BS. The energy harvesting from BS RF signals time increases for the larger number of RIS elements. Energy harvesting time proportionally increases with the incremental of the RIS elements number. In short, energy harvesting from BS RF signals time is higher than the time required for bits transmission. Fig. 5 shows convergence of the optimization problem is fast, and happens after the third iteration.

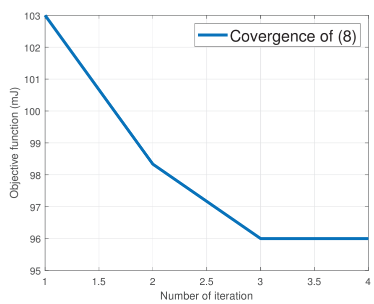

Fig. 5: Convergence performance

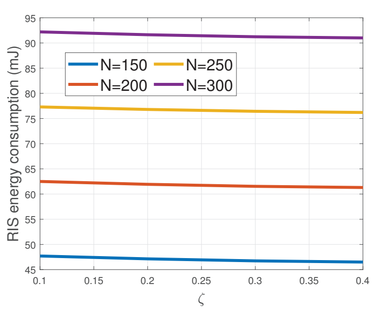

Fig. 6: RIS elements energy consumption at both time slots

Finally, the RIS panel energy consumption due to active and passive elements at both time slots vs. various efficiency factors is shown in Fig. 6. We also show the RIS panel energy consumption for the various number of RIS elements. Intuitively, more RIS elements contribute to the network means the RIS panel consumes higher energy. This scenario is reflected in Fig. 6. A lower power efficiency factor means higher RIS energy consumption. The energy consumption is lower for smaller active and passive elements.

VI. Conclusion

This paper develops a framework to minimize the RIS panel energy consumption due to active and passive elements for IoT systems when IoT devices require energy from BS RF signals to operate. We consider that the transmitting nodes communicate with the receiving nodes with the help of RIS. RIS panel is powered by the harvested energy from BS RF signals. Active elements of RIS panel consume energy due to signal reflection and amplification properties. Passive elements of RIS panel consume energy due to its signal reflection property. We divide the fixed time frame into two optimal slots. IoT device harvests energy from BS RF signals to operate in the first time slot. IoT device transmits bits to the BS using the harvested RF signals in the second time slot. We, therefore, minimize the overall RIS energy consumption at optimal time slots, subject to energy harvesting from BS RF signals, bits transmission, and transmit power. We formulate a non-convex MINLP problem and propose an iterative algorithm to solve it. Finally, we present results to prove the efficacy of our model.

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References

[1] E. Basar, "Reconfigurable intelligent surface-based index modulation: A new beyond MIMO paradigm for 6G," *IEEE Trans. Commun.*, vol. 68, no. 5, pp. 3187-3196, May 2020

[2] E. Basar, M. Di Renzo, J. De Rosny, M. Debbah, M. -S. Alouini and R. Zhang, "Wireless communications through reconfigurable intelligent surfaces," *IEEE Access.*, vol. 7, pp. 116753-116773, 2019.

[3] H. Elahi, K. Munir, M. Eugeni, S. Atek, and P. Gaudenzi, "Energy harvesting towards self-powered IoT devices," *Energ.* 13, 5528, 2020.

[4] Liu, Yuanwei, Xiao Liu, Xidong Mu, Tianwei Hou, Jiaqi Xu, Marco Di Renzo, and Naofal Al-Dhahir. "Reconfigurable intelligent surfaces: Principles and opportunities," *IEEE Commun. Surv. & Tuto.* (2021).

[5] R. Long, Y. Liang, Y. Pei, and E. G. Larsson, "Active reconfigurable intelligent surface aided wireless communications," *IEEE Trans. Wirel. Commu.*, 2021.

[6] A. Taha, M. Alrabeiah and A. Alkhateeb, "Deep learning for large intelligent surfaces in millimeter wave and massive MIMO systems," *2019 IEEE Global Communications Conference (GLOBECOM)*, 2019.

[7] Q. Nadeem, A. Kammoun, A. Chaaban, M. Debbah, and M. Alouini, "Asymptotic max-min SINR analysis of reconfigurable intelligent surface assisted MISO systems," *IEEE Trans. Wirel. Commu.*, vol. 19, no. 12, pp. 7748-7764, Dec. 2020.

[8] Q. Wu and R. Zhang,"Intelligent reflecting surface enhanced wireless network via joint active and passive beamforming," *IEEE Trans. Wirel. Commun.*, vol. 18, no. 11, pp. 5394-5409, Nov. 2019

[9] N. Nguyen, Q. Vu, K. Lee, and M. Juntti, "Hybrid relay-reflecting intelligent surface-assisted wireless communication," *arXiv:2103.03900*, 2021.

[10] N. M. Estakhri and A. Alú, "Wave-front transformation with gradient metasurfaces," *Phys. Rev. X*, vol. 6, no. 4, Art. no. 041008, 2016.

[11] E. Björnson, Ö. Özdogan and E. G. Larsson, "Intelligent reflecting surface versus decode-and-forward: how large surfaces are needed to beat relaying?," *IEEE Wirel. Commu. Lett.*, vol. 9, no. 2, pp. 244-248, Feb. 2020

[12] W. Dinkelbach, "On nonlinear fractional programming," *Manag. Scien.*, vol. 13, no. 7, pp. 492-498, Mar. 1967.

[13] https://www.gams.com/