RIS-Assisted Routing for Power-Constrained IoT Networks

Rawan Derbas[1], Lina Bariah[2], Sami Muhaidat[1], Lina Mohjazi[3], Osamah S. Badarneh[4], and Ernesto Damiani[1]

[1]Center for Cyber-Physical Systems, Khalifa University, Abu Dhabi 127788, United Arab Emirates
[2]Technology Innovation Institute, 9639 Masdar City, Abu Dhabi, UAE
[3]School of Engineering, University of Glasgow, Glasgow, UK
[4]Electrical Engineering Department, German-Jordanian University, Amman 11180, Jordan

***Abstract*—In this paper, we propose a novel RIS-assisted routing protocol for energy harvesting-based wireless networks, with the aim to minimize nodes' battery recharging time (BRT) while improving network performance. Furthermore, we design an optimal channel allocation scheme, considering channel fading conditions and accordingly, the route with the minimum BRT is selected. Finally, the proposed scheme is evaluated and compared with the minimum hop scheme, as a benchmark, in terms of performance using Matlab simulation.**

I. Introduction

In power-constrained wireless networks, networks' lifetime can be prolonged through leveraging energy harvesting techniques. However, designing an energy-efficient routing algorithm remains a challenge due to the instability and unpredictability of the energy harvesting process. Due to its ability to manipulate and control RF signals, reconfigurable intelligent surface (RIS) has recently gained the attention as an efficient approach that can further enhance the efficiency of energy harvesting technique.

Various routing algorithms were presented in the literature in order to optimize the consumed energy, and hence, prolong the overall network lifetime in an IoT environment [1], [2]. However, these routing frameworks, [1], [2] considered battery-free RF energy harvesting (RFEH) receivers, where there is no possibility to store energy for future transmissions. In our work, we adopt the framework presented in [3] to boost the amount of the harvested energy based on the double Beaulieu–Xie (BX) fading channel [4]. The developed framework will be then leveraged to propose an RIS-assisted energy-aware routing protocol for energy-resource constrained devices, equipped with energy harvesting capability. To the best of our knowledge, this is the first routing protocol to exploit RIS for battery recharging in IoT devices.

II. Network And Channel Model

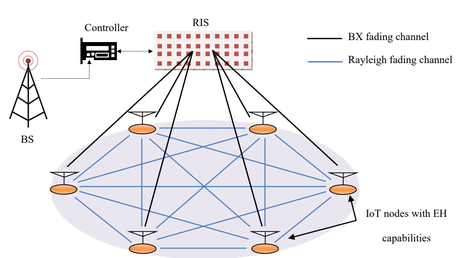

Fig. 1. Proposed system model within $A \times A\ m^2$ area.

1) Network Setting: In this work, we consider a wireless network with N_u nodes, placed randomly within an area of size A $\times$ A m^2, and a base station (BS) located at the center of the network. Also, a single RIS with M REs to assist with WPT between the BS and the N_u nodes is considered, as shown in Fig. 1. Let $\mathcal{C}$ denotes the set of all channels allocated by the BS, where each channel has a bandwidth of BW. It is also assumed that each node has only one antenna (i.e., nodes either harvest energy or transmit data at a particular time slot). The RIS reflects the signal transmitted from the BS to the nodes, which is subsequently harvested and stored in finite capacity batteries for future packet transmissions. The instantaneous received power at node u can be expressed as

$$P_{r_u} = \frac{P_t^{BS}}{(d_1 d_{2,u})^{\delta}} Q_u^2, \tag{1}$$

where $Q_u = \sum_{k=1}^{M} |h_k||g_{k,u}|$ is the end-to-end (E2E) channel gain of the node u. where P_t^{BS}, d_1 and d_{2_u} refer to the transmitted power from the BS, the distance between BS and RIS, the distance between RIS and node u, respectively. The instantaneous BRT of node u can be defined as [5]

$$\tau_r^u = \frac{\alpha}{P_r^u} \tag{2}$$

Here, $\alpha = \frac{D_d C_b V_b}{\eta}$, refers to the conversion coefficient, where V_b, D_b, C_b, and η denote the constant battery operating voltage, discharge depth, battery capacity, and RF-to-DC signal conversion coefficient, respectively.

2) Node-Node Channel Model: For each hop $\hat{h}$ in each individual route $\hat{w}$, there is a set of channels $\mathcal{C}$, which allocation is managed by the BS. $\mathcal{C}^*_{\hat{w},\hat{h}} \in \mathcal{C}$ represents the set of channels with instantaneous SNR values greater than a particular threshold (γ^*). Also, let $N_u{}^*$, where $N_u{}^* \in N_u$ refers to the nodes that have BRT less than a threshold τ_r^*. In our setup, the Rayleigh distribution is considered to model the links between different users. The instantaneous received power over channel $c \in \mathcal{C}^*_{\hat{w},\hat{h}}$ for hop $\hat{h}$ in route $\hat{w}$ can be calculated using [6, Eq. 1 and Eq. 2]. Utilizing (2) and after some mathematical manipulations, it can be rewritten as

$$P^{(c)}_{r_{\hat{h},\hat{w}}} = \frac{\alpha \epsilon^{(c)}_{\hat{h},\hat{w}}}{\tau_r^u}, \tag{3}$$

where $\epsilon^{(c)}_{\hat{h},\hat{w}} = \left(\frac{\lambda^{(c)}\sqrt{G_t^{(c)} G_r^{(c)}} B^{(c)}_{\hat{h},\hat{w}}}{4\pi d_o^{(c)}}\right)^2 \left(\frac{d}{d_o^{(c)}}\right)^{-\beta}$. where $G_t^{(u)}$, $G_r^{(u)}$, $B^{(c)}_{\hat{h},\hat{w}}$, $d_o^{(c)}$ and $\lambda^{(c)}$ represent the pathloss over channel c, the gain of the transmit antenna, the gain of the receive antenna, the channel fading coefficient between any ER pair, reference distance, and the wavelength, respectively. Also, d represents the distance between any two communicating nodes. Accordingly, the rate achieved by a particular node over the cth channel, hop $\hat{h}$, and route $\hat{p}$ can be evaluated in terms of the BRT, τ_r, as

$$R^{(c)}_{\hat{w},\hat{h}} = \text{BW} \times \log_2\left(\frac{\alpha \epsilon^{(c)}_{\hat{h},\hat{w}}}{\tau_r^u \times \text{BW} \times \mathcal{N}_o}\right). \tag{4}$$

III. RIS-assisted EAR Problem Statement and Formulation

To enhance the RFEH process, we propose a routing scheme that employs RIS to compensate the energy losses due to the transmission process. In order to formulate our problem, we first assume the following: Considering a certain SD pair (U_S and U_D), the possible routes between the given U_S-U_D pair is $\mathcal{W}$, each route $\hat{w} \in \mathcal{W}$ comprises $\mathcal{H}$ hops. Also, the group of all feasible channels is $\mathcal{C}_{\hat{w},\hat{h}} \in \mathcal{C}, \forall \hat{h} \in \mathcal{H}, \forall \hat{w} \in \mathcal{W}$. The main objective is to determine the best route $\hat{w}^*$ between U_S and U_D, such that the maximum rate is achieved, and accordingly, the BRT is minimized subject to the following constraints: (i) Each device has only one RF transceiver. (ii) The received instantaneous SNR at each device must be greater than a certain threshold, γ^*. (iii) The BRT at each node does not exceed a specific threshold, τ_r^*. (iv) Half-duplex (HD) mode is assumed.

To study the effect of employing RIS in wireless networks, we propose a routing scheme that consists of three major phases: 1) route discovery, 2) channel allocation, and 3) route selection [7].

1) Route Discovery: In this phase, the feasible routes set $\mathcal{W}$ are identified and $R^{(c)}_{\hat{w},\hat{h}}$ are computed using (4) for the scenario where channel c for hop $\hat{h}$ through each route $\hat{w} \in \mathcal{W}$ is selected.

2) Channel Allocation: Using $\mathcal{W}$ and the computed $R^{(c)}_{\hat{w},\hat{h}}$, $\forall j$, $\hat{h}$, $\hat{w}$, the channel yields the maximum rate (and hence, the minimum BRT) for each hop over each route is selected.

We can formulate the proposed channel allocation problem as follows

$$\max \sum_{\hat{h}=1}^{\mathcal{H}} \sum_{c=1}^{\mathcal{C}} R^{(c)}_{\hat{w},\hat{h}} \mathcal{Z}^{(c)}_{\hat{w},\hat{h}} \tag{5}$$

$$\text{s.t} \sum_{c=1}^{\mathcal{C}} \mathcal{Z}^{(c)}_{\hat{w},\hat{h}} \leq 1, \forall \hat{h} \in \mathcal{H}$$

$$\mathcal{Z}^{(c)}_{\hat{w},\hat{h}} + \mathcal{Z}^{(c)}_{\hat{w},\hat{h}+1} + \mathcal{Z}^{(c)}_{\hat{w},\hat{h}+2} \leq 1, \forall c \in \mathcal{C}_{\hat{w},\hat{h}},$$

$$\hat{h} \in [1, \cdots, \mathcal{C}-2]$$

$$\text{SNR}^{(c)}_{\hat{w},\hat{h}} \geq \gamma^*, \;\; \tau_r^u \leq \tau_r^*$$

where $\mathcal{Z}^{(c)}_{\hat{w},\hat{h}} \in [0,1]$ is an integer binary variable.

By examining the optimization problem in (5), it can be noticed that this problem is a unimoduler problem. Hence, it can be solved in polynomial-time (PT) utilizing linear programming (LP) [8]. Let c^* is the optimum solution of the proposed optimization problem for hop h in route $\hat{w}$. The rate over each $\hat{h} \in \mathcal{C}$ along the route $\hat{w}$ are given by

$$R_{\hat{w},\hat{h}} = R^{(c^*)}_{\hat{w},\hat{h}}, \forall \hat{h} \in T \tag{6}$$

Given $R_{\hat{w},\hat{h}}$, the rate R of route $\hat{w}$ can be computed as

$$R^{(\hat{w})} = \text{arg min}\, R_{\hat{w},\hat{h}}, \forall \hat{w} \in \mathcal{W}. \tag{7}$$

3) Route Selection: Finally, after choosing the optimal channels, our proposed algorithm picks the route, $\hat{w}^*$, with maximum rate as

$$R(\hat{w}^*) = \text{arg max}\, R^{(\hat{w})}, \, \hat{w} \in \mathcal{W} \tag{8}$$

IV. Numerical Results

In this section, we provide numerical and simulation results to demonstrate the performance of the proposed RIS-assisted routing protocol. Considering an area of $10{\times}10$ m^2, we assume that the RIS is randomly located in a 2 m of the centralized BS, and 10 nodes are arbitrarily scattered, with the assumption that all nodes are within the RIS's reflection range. We consider the 900 MHz band with 4 orthogonal channels, each with BW=5 MHz. Unless stated otherwise, the considered network parameters were mentioned in [6, Table 1]. Fig. 2 shows the impact of with/without RIS. In order to verify the superiority of the proposed algorithm, we compare its performance with the Minimum Hop (MH) algorithm. As seen, the network's overall performance in terms of throughput has improved. This is because RIS can create indirect LoS components, bridging the gab of physical distance, thereby improving overall network performance.

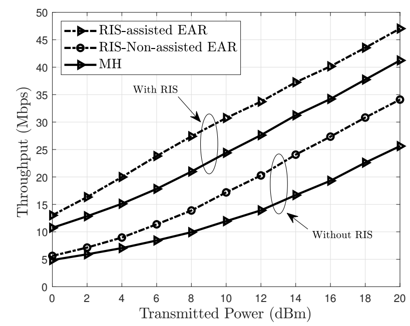

Fig. 2. The effect of presence of the RIS on the E2E network throughput vs. transmit power, Rayleigh fading model.

V. Conclusion

We proposed an RIS-assisted power-efficient routing algorithm for multi-hop wireless networks, namely RIS-assisted EAR, that considers the BRT of wireless devices in addition to fading channel conditions. The proposed RIS-assisted EAR ensures that the participating nodes have the required recharging time, thereby improving network throughput.

References

[1] F. F. Jurado-Lasso, K. Clarke, A. N. Cadavid, and A. Nirmalathas, "Energy-aware routing for software-defined multihop wireless sensor networks," *IEEE Sensors J.*, vol. 21, no. 8, pp. 10 174–10 182, Apr. 2021.

[2] Z. Sadreddini, E. Güler, M. Khalily, and H. Yanikomeroglu, "MRIRS: Mobile Ad Hoc routing assisted with intelligent reflecting surfaces," *IEEE Trans. Cogn. Commun. Netw.*, vol. 7, no. 4, pp. 1333–1346, May 2021.

[3] L. Mohjazi, S. Muhaidat, Q. H. Abbasi, M. A. Imran, O. A. Dobre, and M. Di Renzo, "Battery recharging time models for reconfigurable intelligent surfaces-assisted wireless power transfer systems," *IEEE Trans. Green Commun. Netw.*, pp. 1–1, June 2021.

[4] H. S. Silva, D. B. T. Almeida, W. J. L. Queiroz, I. E. Fonseca, A. S. R. Oliveira, and F. Madeiro, "Cascaded double beaulieu-xie fading channels," *IEEE Commun. Lett.*, vol. 24, no. 10, pp. 2133–2136, Oct. 2020.

[5] D. Altinel and G. Karabulut Kurt, "Energy harvesting from multiple RF sources in wireless fading channels," *IEEE Trans. Veh. Technol.*, vol. 65, no. 11, pp. 8854–8864, Nov. 2016.

[6] R. Derbas, L. Bariah, S. Muhaidat, P. C. Sofotasios, H. Saleh, and E. Damiani, "Battery recharging time-based routing for power constrained IoT networks," in *Proc. 4th Int. Conf. Adv. Commun. Technol. Netw. (CommNet)*, Dec. 2021, pp. 1–5.

[7] H. B. Salameh, S. Otoum, M. Aloqaily, R. Derbas, I. Al Ridhawi, and Y. Jararweh, "Intelligent jamming-aware routing in multi-hop IoT-based opportunistic cognitive radio networks," *Ad Hoc Networks*, vol. 98, p. 102035, Mar. 2020.

[8] H. B. Salameh, "Rate-maximization channel assignment scheme for cognitive radio networks," in *Proc. IEEE Global Telecommun. Conf. (GLOBECOM)*, Dec. 2010, pp. 1–5.