Reconfigurable Intelligent Surface Assisted MIMO SWIPT System

Hsuan-Fu Wang
Department of Aeronautical Engineering
National Formosa University
Yunlin, Taiwan

Fang-Biau Ueng
Department of Electrical Engineering
National Chung Hsing University
Taichung, Taiwan

Huang-Wei Shen
Department of Electrical Engineering
National Chung Hsing University
Taichung, Taiwan

***Abstract*—The large-scale Internet of Things (IoTs) of B5G networks must face the arduous challenge of bandwidth limitations. Although millimeter wave (mmWave) technology can provide greater bandwidth at the cost of complex processors in harsh environments, it can be a possible solution for building large-scale IoTs, but its cost and power requirements become obstacles to widespread adoption. In this context, Re-configurable Intelligent Surfaces (RISs) can be a key technology to meet this challenge. In this paper, we study the B5G RIS-assisted MIMO simultaneous wireless-information and power-transfer (SWIPT) mmWave large-scale IoTs, where active BS transmitted beamformer and passive RIS reflection vector are jointly optimized to maximize the minimum signal-to-interference-plus-noise-ratio (SINR) of all the information decoders (ID) and at the same time, the minimum harvested power of all the energy receivers (ER) is maintained. Some simulation examples are given to demonstrate the effectiveness of the proposed system.**

Keywords—mmWave, RIS, SWIPT

I. INTRODUCTION

Massive MIMO uses a large number of antennas to obtain large beamforming gains. In fact, under similar conditions, both massive MIMO and RIS techniques can produce similar signal-to-noise ratio (SNR) gains. However, RIS passively achieves this beamforming gain. In this paper, active beamforming through the transmitter antenna array and passive beamforming through the RIS in the channel can compensate each other and provide greater gain when both are optimized together, which is exactly what goals of this paper. Although massive MIMO technology can significantly improve the efficiency of wireless information transfer (WIT) and wireless power transfer (WPT) in emerging IoT networks by exploiting the gain of large arrays, this usually comes at a high cost [1]-[3]. As a remedy, in so-called hybrid implementations, a much smaller number of radio frequency (RF) chains than transmit/receive antennas can be used, which can also result in high hardware costs, high signal processing overhead, and high energy consumption, hindering actual implementation. As a cost-effective alternative to massive MIMO technology, RIS enables unprecedented spectral and energy efficiency, especially in complex propagation scenarios that suffer from severe signal blocking. However, because RIS is essentially a reconfigurable metal surface with a large number of passive reflective elements, it cannot perform as complex signal processing as large arrays and active MIMO repeaters, and is usually performed with lower hardware cost and low power consumption. By adjusting the phase shift and amplitude attenuation of each RIS reflective element, a good wireless propagation environment can be actively constructed for WIT and WPT [4][5]. In view of the above advantages, research on RIS-assisted communication for various wireless systems such as MISO systems [6][7], point-to-point MIMO systems [8], multi-cell multi-user MIMO systems [9], and MIMO-OFDM systems [10] [11] attracted attention. These studies usually assume perfect channel state information (CSI). In fact, traditional training-based channel estimation schemes cannot be directly applied due to the lack of fundamental frequency processing capability of RIS operating without RF chains and the need to estimate a large number of RIS-related channels. As an alternative, under the assumption of uplink-downlink channel reciprocity, for flat frequency channels and frequency selective channels, various channel estimation schemes using RIS grouping strategies have been proposed previously [10]-[13].

Nonetheless, there are new challenges to integrate RF energy harvesting and advanced WIT technologies for sustainable green IoT networks. To this end, Simultaneous Wireless Information and Power Transfer (SWIPT) has been evaluated as an attractive innovative technology [13]. Recently, there has been increasing interest in RIS-based SWIPT systems [9]. For example, [13] studied weighted harvested energy maximization in a RIS-assisted MISO SWIPT system and demonstrated that dedicated energy beamforming is practically not required. As a further development, the maximization of the minimum harvested energy among all energy receivers (ERs) in this system is studied from a fairness perspective. By deploying multiple RIS, [13] further investigated total transmit power minimization subject to separate QoS constraints at the Information Decoder (ID) and ER. [9] considered a more general RIS-assisted MIMO SWIPT system and studied the weighted sum rate maximization of all IDs while guaranteeing a certain minimum total harvested energy across all ERs. Various advanced communication technologies in IoT networks, such as NOMA, Physical Layer Security, and Mobile Edge Computing (MEC), have also been integrated with this technology together. RIS achieves better system performance, so in this paper, we consider a RIS-assisted MIMO SWIPT system consisting of a multi-antenna base station (BS), a RIS to assist communication, and multiple SWIPT-enabled systems. It consists of several IoT devices, and RIS is deployed to assist SWIPT from the BS to these IoT devices. From a fairness perspective, we further investigate the maximization of the minimum SINR among all IDs by jointly optimizing the active BS transmit beamforming vector and the passive RIS reflection coefficient, premised on the minimum total harvested energy required for all ERs.

II. SYSTEM MODEL AND PROBLEM FORMULATIoN

This section introduces the system model and problem description. We first introduce the architecture of the entire system, and then describe our goals and the problems. We consider an RIS-assisted wireless communication system, in which the RIS is deployed to assist the multi-antenna APs in the SWIPT system. It is transmitted from the AP of M antennas to two parts, including information user (IU) and energy user (EU), the number of IU is K_I, and the number of EU is K_ε. For simplicity, we consider linear transmit precoding at the AP and assume that each IU/EU is assigned a separate information/energy beam, without loss of generality. Therefore, the transmission signal from the AP can be expressed as

$$x = \sum_{i\in K_I} w_i s_i^I + \sum_{\mathrm{j}\in K_\varepsilon} v_j s_j^E \tag{1}$$

And $w_i \in C^{M\times 1}$ is the precoding vector of IU, $v_j \in C^{M\times 1}$ is the precoding vector of EU, s_i^I represents the message bearing signal, and s_j^E represents the energy signal. s_i^I are assumed to be independent and identically distributed signal with zero mean and variance one, while s_j^E carry no information, they can be any random signals. Therefore, the total transmit power required by the AP is expressed as

$$E(x^H x) = \sum_{i\in K_I} \|w_i\|^2 + \sum_{\mathrm{j}\in K_\varepsilon} \left\|v_j\right\|^2 \tag{2}$$

Next is the part of the signal received by the IU, $h_{\mathrm{d},k}^H \in C^{1\times M}$ is the channel directly transmitted by the AP to the IU, $h_{\mathrm{g},k}^H \in C^{1\times L}$ is the channel that the RIS transmits to the IU, $e_{\mathrm{d},k}^H$ is the channel that the AP transmits directly to the EU, $e_{\mathrm{g},k}^H$ is the channel that the RIS transmits to the EU, $W_g(l)$ indicates the channel transmitted from the AP to the RIS, and $\Phi_g^H(l)$ represents the reflective element channel in the RIS. Since implementing independent control of reflection amplitude and phase is expensive in reality, for simplicity, it is actually advantageous to design each element to maximize signal reflections. Therefore, we express the signal received by the IU from AP to IU and AP to RIS and then to IU as the following equations:

$$y_k^I = \left(\sum_{l=1}^{L} h_{g,k}^H(l)\Phi_g^H(l)W_g(l) + h_{\mathrm{d},k}^H\right)x + \sigma_k \tag{3}$$

Here $\sigma_k \sim CN(0,\sigma_k^2)$ is an independent and identically distributed Gaussian noise, and we simplify equation (3) and rewrite it as (4):

$$y_k^I = (h_{g,k}^H \Phi_g^H W_g + h_{\mathrm{d},k}^H)x + \sigma_k \tag{4}$$

where $h_{g,k}^H \in C^{N\times N}$, $W_g \in C^{N\times M}$ and $\Phi_g^H \in C^{N\times N}$ are represented by equations (5) and (6), respectively,

$$h_{g,k}^H = \begin{bmatrix} h_{g,k}^H(1) \\ \dots \\ h_{g,k}^H(L) \end{bmatrix}, W_g = \begin{bmatrix} W_g(1) \\ \dots \\ W_g(L) \end{bmatrix} \tag{5}$$

$$\Phi_g^H = \begin{bmatrix} \Phi_g^H(1) & 0 & 0 \\ 0 & \dots & 0 \\ 0 & 0 & \Phi_g^H(L) \end{bmatrix} \tag{6}$$

Since the energy beam carries no information but a pseudo-random signal, its waveform can be assumed to be known at the AP and each IU prior to data transmission. We hypothesize that the interference they cause can be canceled at each IU, which contributes to the fundamental performance limitations of our SWIPT system and the study of the impact of RIS on energy beamforming. Therefore, we express SINR by Equation (7):

$$\mathrm{SINR}_k = \gamma_k = \frac{\left|\sum_{\mathrm{g}=1}^{G} h_{g,k}^H \Phi_g^H W_g w_i\right|^2}{{\sum_{k=1,k\neq i}^{K} \left|\sum_{\mathrm{g}=1}^{G} h_{g,k}^H \Phi_g^H W_g w_k\right|^2 + \sigma_i^2}^{2}} \tag{7}$$

On the other hand, it is the part of the energy received by the EU. We express the energy received by the EU with Equation (8):

$$Q_j = \sum_{i\epsilon K_i} \left|(e_{g,j}^H \Phi_g^H W_g + e_{\mathrm{d},j}^H)w_i\right|^2 + \sum_{i\epsilon K_\varepsilon} \left|(e_{g,j}^H \Phi_g^H W_g + e_{\mathrm{d},j}^H)v_m\right|^2 \tag{8}$$

Then comes the problem description part, our goal is to maximize the transmission rate of the entire system through optimization subject to the constraints of the transmission power and the energy harvesting at the EU, we formulate the problem description as Eq. (9):

$$\underset{P,\Phi_g}{\text{maximize}}\, f_1(P,\Phi_g) = \sum_{k=1}^{K} z_k \log_2(1+\gamma_k) \tag{9}$$

$$\text{subject to } \sum_{i\in K_I} \|w_i\|^2 + \sum_{\mathrm{j}\in K_\varepsilon} \left\|v_j\right\|^2 \le P, \tag{10}$$

$$\sum_{i\epsilon K_i} \left|(e_{g,j}^H \Phi_g^H W_g + e_{\mathrm{d},j}^H)w_i\right|^2 + \sum_{i\epsilon K_\varepsilon} \left|(e_{g,j}^H \Phi_g^H W_g + e_{\mathrm{d},j}^H)v_m\right|^2 \ge E_j \tag{11}$$

$$0 < \theta_n \le 2\pi, \forall n \in N. \tag{12}$$

Where z_k is the data weight assigned to the kth IU, P represents the maximum transmission power, $E_j > 0$ is the least energy received by each energy user, and θ_n represents the phase of the RIS.

III. THE PROPOSED METHODS AND ALGORITHM

First, we change the formula of power limit into the form of rank, such as (13):

$$\begin{gathered} \underset{P,\Phi_g}{\text{maximize}}\, f_1(P,\Phi_g) = \sum_{k=1}^{K} z_k\, log_2(1+\gamma_k) \\ \text{subject to } \sum_{k\in K} Tr(W_k) + Tr(V_l) \le P, \\ \sum_{i\epsilon K_i} \left|(e_{g,j}^H \Phi_g^H W_g + e_{\mathrm{d},j}^H)w_i\right|^2 + \\ \sum_{i\epsilon K_\varepsilon} \left|(e_{g,j}^H \Phi_g^H W_g + e_{\mathrm{d},j}^H)v_m\right|^2 \ge E_j, \\ 0 < \theta_n \le 2\pi, \forall n \in N. \end{gathered} \tag{13}$$

Next, we use the Lagrangian dual transformation [3] that the term $\sum_{k=1}^{K} z_k\, log_2(1+\gamma_k)$ can be converted into $\sum_{k=1}^{K} z_k\, ln(1+\alpha_k) - z_k\alpha_k + \frac{z_k(1+\alpha_k)\gamma_k}{1+\gamma_k}$. Therefore, we transform f_1 into problem f_2, which is represented by equation (14):

$$\underset{P,\Phi_g,\alpha}{\text{maximize}}\, f_2\left(P,\Phi_g,\alpha\right) = \sum_{k=1}^{K} z_k\, ln(1+\alpha_k) - z_k\alpha_k + \frac{z_k(1+\alpha_k)\gamma_k}{1+\gamma_k} \tag{14}$$

$$\text{subject to} \quad tr(PP^H) \le P, \tag{15}$$

$$\sum\nolimits_{i\epsilon K_i} \left|e_j^H w_i\right|^2 + \sum\nolimits_{i\epsilon K_\varepsilon} \left|e_j^H v_m\right|^2 \geq E_j, \quad (16)$$

$$\theta_{g,m} \in F_c, \forall g, \forall m. \quad (17)$$

f_1 and f_2 are equivalent, so solving f_1 is equivalent to solving f_2, where $\alpha = [\alpha_1, \cdots, \alpha_k]^T$ is the additional vector generated after conversion. In addition, the formula of the transmission power is simplified again, and the mathematical symbol e_j^H is used to represent $e_j^H = e_{g,j}^H \Phi_g^H W_g + e_{\mathrm{d},j}^H$. After the conversion, we give α_k, optimize P and Φ_g, and rewrite the problem f_2 into the problem f_3 as follows,

$$\underset{P,\Phi_g}{\text{maximize}}\, f_3\left(P, \Phi_g\right) = \sum\nolimits_{k=1}^{K} \frac{z_k(1+\alpha_k)\gamma_k}{1+\gamma_k} \quad (18)$$

subject to (15), (16), (17).

Given the set $\{\Phi_1, \cdots, \Phi_g\}$, for convenience, we use the mathematical notation $\tilde{h}_k^H$ to represent (19):

$$\tilde{h}_k^H = \sum\nolimits_{\mathrm{g}=1}^{G} h_{g,k}^H \Phi_g^H W_g \quad (19)$$

Substitute formula (19) into the above SINR formula, that is, formula (7), and rearrange f_3 to generate f_4, such as formula (20):

$$\underset{P}{\text{maximize}}\, f_4\,(P) = \sum_{k=1}^{K} \frac{\bar{\alpha}_k |\tilde{h}_k^H p_k|^2}{\sum_{j=1}^{K} \left|\tilde{h}_k^H p_j\right|^2 + \sigma_u^2} \quad (20)$$

subject to (15).

where the symbol $\bar{\alpha}_k = z_k(1+\alpha_k)$, and we can see that f_4 is a multi-score programming problem, so we can use Quadratic Transform (QT) [3][4] to convert f_4 to f_5, such as formula (21):

$$\underset{P,\beta}{\text{maximize}}\, f_5\,(P, \beta) = \sum_{k=1}^{K} 2\sqrt{\bar{\alpha}_k}\,\mathfrak{R}\{\beta_k^* \tilde{h}_k^H p_k\} - |\beta_k|^2 (\sum\nolimits_{\mathrm{j}=1}^{K} \left|\tilde{h}_k^H p_j\right|^2 + \sigma_u^2) \quad (21)$$

And $\beta = [\beta_1, \cdots, \beta_k]^T$ is the additional vector generated after the QT conversion. Using $\frac{\partial f_5}{\partial \beta_k} = 0$, such as equations (22) and (23), and given P, the optimal solution of β_k can be described as follows:

$$\frac{\partial f_5}{\partial \beta_k} = 2\sqrt{\bar{\alpha}_k} \tilde{h}_k^H p_k - 2\beta_k \left(\sum\nolimits_{\mathrm{j}=1}^{K} \left|\tilde{h}_k^H p_j\right|^2 + \sigma_u^2\right) = 0 \quad (22)$$

$$\beta_k \left(\sum\nolimits_{\mathrm{j}=1}^{K} \left|\tilde{h}_k^H p_j\right|^2 + \sigma_u^2\right) = \sqrt{\bar{\alpha}_k} \tilde{h}_k^H p_k \quad (23)$$

$$\hat{\beta}_k = \frac{\sqrt{\bar{\alpha}_k} \tilde{h}_k^H p_k}{\sum_{j=1}^{K} \left|\tilde{h}_k^H p_j\right|^2 + \sigma_u^2} \quad (24)$$

Since the problem f_5 is a convex problem about p_{k}, using the Lagrange multiplier method, given β, the optimal solution of p_k can be described as equation (25):

$$\hat{p}_k = \sqrt{\bar{\alpha}_k}\, \beta_k \left(\mu I_N + \sum\nolimits_{i=1}^{k} |\beta_i|^2 \tilde{h}_i \tilde{h}_i^H\right)^{-1} \tilde{h}_k \quad (25)$$

Next, we simplify the mathematical formula to facilitate the operation and derivation, $\tilde{h}_k^H p_j$ can be expressed as formula (26):

$$\tilde{h}_k^H p_j = \sum\nolimits_{g=1}^{G} \theta_g^H \operatorname{diag}(h_{g,k}^H) W_g p_j \quad (26)$$

Where $\boldsymbol{\theta}_g$ is defined as $\boldsymbol{\theta}_g = \left[\theta_{g,1}, \cdots, \theta_{g,M}\right]^T$ and $v_{g,k,j}$ is defined as $v_{g,k,j} = \operatorname{diag}(h_{g,k}^H) W_g p_j$. Given α and P, we rewrite the problem f_4 into the problem f_6, as shown in equation (27):

$$\underset{\theta_g}{\text{maximize}}\, f_6\left(\theta_g\right) = \sum_{k=1}^{K} \frac{\bar{\alpha}_k \left|\sum_{g=1}^{G} \theta_g^H v_{g,k,k}\right|^2}{\sum_{j=1}^{K} \left|\sum_{g=1}^{G} \theta_g^H v_{g,k,j}\right|^2 + \sigma_u^2} \quad (27)$$

subject to $\left|\theta_{g,m}\right|^2 = 1,\ \forall g,\ \forall m.$

In order to facilitate the subsequent derivation, we first construct several symbols to represent the following equations, as shown in equations (28) and (29):

$$\boldsymbol{\Theta} = [\theta_1, \theta_2, \cdots, \theta_G] \quad (28)$$

$$V_{k,j} = \left[v_{1,\mathrm{k},j}, v_{2,k,j}, \cdots, v_{G,k,j}\right] \quad (29)$$

After the construction is completed, we can rewrite the problem f_6 into the problem f_7, as shown in equation (30):

$$\underset{\tilde{\theta}}{\text{maximize}}\, f_7\left(\tilde{\theta}\right) = \sum_{k=1}^{K} \frac{\bar{\alpha}_k \left|tr\left(\Theta^H V_{k,k}\right)\right|^2}{\sum_{j=1}^{K} \left|tr\left(\Theta^H V_{k,j}\right)\right|^2 + \sigma_u^2} \quad (30)$$

$$= \sum_{k=1}^{K} \frac{\bar{\alpha}_k \left|\tilde{\theta}^H \tilde{v}_{k,k}\right|^2}{\sum_{j=1}^{K} \left|\tilde{\theta}^H \tilde{v}_{k,j}\right|^2 + \sigma_u^2} \quad (31)$$

subject to $\left|\theta_{g,m}\right|^2 = 1,\ \forall g,\ \forall m.$

where $\tilde{\theta}$ is expressed as $\tilde{\theta} = \operatorname{vec}(\Theta)$, and $\tilde{v}_{k,j}$ is expressed as $\tilde{v}_{k,j} = \operatorname{vec}(V_{k,j})$. Next, we transform problem f_7 into problem f_8 using quadratic transformation (QT) [3], as shown in Eq. (32):

$$\underset{\tilde{\theta},\rho}{\text{maximize}}\, f_8\left(\tilde{\theta}, \rho\right) = \sum_{k=1}^{K} 2\sqrt{\bar{\alpha}_k}\,\mathfrak{R}\{\rho_k^* \tilde{\theta}^H \tilde{v}_{k,k}\} - |\rho_k|^2 (\sum\nolimits_{\mathrm{j}=1}^{K} \left|\tilde{\theta}^H \tilde{v}_{k,j}\right|^2 + \sigma_u^2) \quad (32)$$

subject to $\left|\theta_{g,m}\right|^2 = 1,\ \forall g,\ \forall m.$

After conversion, $\rho = [\rho_1, \cdots, \rho_k]^T$ is the additional vector generated by the secondary conversion. Using the Lagrange multiplier method [3], the optimal solution of ρ_k is shown in formula (33):

$$2\sqrt{\bar{\alpha}_k} \tilde{\theta}^H \tilde{v}_{k,k} - 2\rho_k \left(\sum\nolimits_{\mathrm{j}=1}^{K} \left|\tilde{\theta}^H \tilde{v}_{k,j}\right|^2 + \sigma_u^2\right) = 0 \quad (33)$$

$$\rho_k \left(\sum\nolimits_{\mathrm{j}=1}^{K} \left|\tilde{\theta}^H \tilde{v}_{k,j}\right|^2 + \sigma_u^2\right) = \sqrt{\bar{\alpha}_k} \tilde{\theta}^H \tilde{v}_{k,k} \quad (34)$$

$$\hat{\rho}_k = \frac{\sqrt{\bar{\alpha}_k} \tilde{\theta}^H \tilde{v}_{k,k}}{\sum_{j=1}^{K} \left|\tilde{\theta}^H \tilde{v}_{k,j}\right|^2 + \sigma_u^2} \quad (35)$$

IV. SIMULATION RESULTS

In this section, we use MATLAB software to perform simulations to compare the performance of the entire SWIPT system with and without RIS. The simulation parameters include: the number of users (*K*), the number of antennas (*N*), the number of reflective elements (*M*), and the transmission power (*P*). For the channel part, we use the Rayleigh channel. Figure 1 is the schematic diagram of the simulation environment.

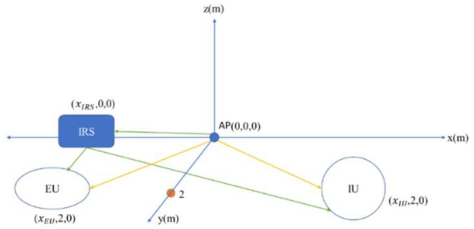

Fig. 1. Simulation Schematic

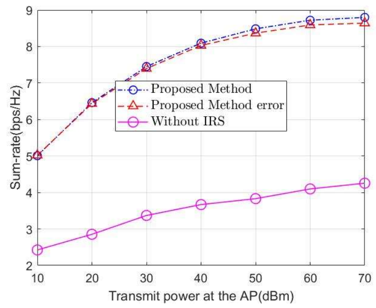

Fig. 2. Comparison of transmission sum rates when the number of users (information receiving end and energy receiving end) is 2, the number of antennas is 16, and the number of reflective elements is 20.

Figure 2 shows the performance comparisons employing 2 users (information receiving end and energy receiving end), 16 antennas and 20 reflective elements with and without RIS. The error part is the 10% parameter error of our proposed method. In addition, whether it is a system with RIS or a system without RIS, the two transmission powers are fixed. It can be seen from the figure that with RIS, the total rate is faster than that without RIS, from 10-dBm faster by 2 (bps/Hz) to 70-dBm by nearly 4 (bps/Hz).

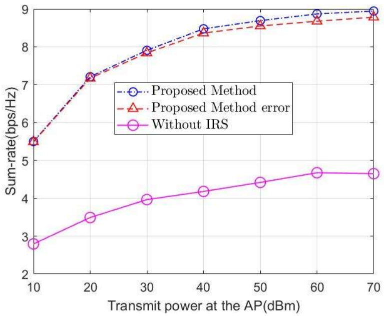

Fig. 3. Comparison of transmission sum rates when the number of users (information receiving end and energy receiving end) is 3, the number of antennas is 16, and the number of reflective elements is 20.

Figure 3 shows the performance comparisons employing 3 users (information receiving end and energy receiving end), 16 antennas and 20 reflective elements with and without RIS. The error part is the 10% parameter error of our proposed method. In addition, whether it is a system with RIS or a system without RIS, the two transmission powers are fixed. It can be seen from the figure that with RIS, the overall rate is faster than that without RIS, from 10-dBm faster than 2 (bps/Hz) to 70-dBm faster than 4 (bps/Hz).

V. CONCLUSION

In this paper, we study an RIS-assisted SWIPT communication system. Specifically, we want to maximize the transmission sum rate of the system, subject to power constraints and energy harvesting constraints. The transmission sum rate of the system is significantly faster than that of the system without RIS. Some simulation examples are given to demonstrate the effectiveness of the proposed system.

REFERENCES

[1] L. Lu, G. Y. Li, A. L. Swindlehurst, A. Ashikhmin, and R. Zhang, "An overview of massive MIMO: Benefits and challenges," IEEE J. Sel. Top. Sign. Proces., vol. 8, no. 5, pp. 742 – 758, 2014.

[2] H. Liu, F. Hu, S. Qu et al., "Multipoint wireless information and power transfer to maximize sum-throughput in WBAN with energy harvesting," IEEE Internet Things J., vol. 6, no. 4, pp. 7069 – 7078, 2019.

[3] L. O. Varga, G. Romaniello, Vu ˇ cini´c et al., "Greennet: An energyharvesting IP-enabled wireless sensor network," IEEE Internet Things J., vol. 2, no. 5, pp. 412 – 426, 2015.

[4] G. Yu, X. Chen, C. Zhong et al., "Design, analysis and optimization of a large intelligent reflecting surface aided B5G cellular Internet of Things," IEEE Internet Things J., 2020.

[5] Q. Wu and R. Zhang, "Towards smart and reconfigurable environment: Intelligent reflecting surface aided wireless network," IEEE Commun. Mag., 2019.

[6] ——, "Intelligent reflecting surface enhanced wireless network via joint active and passive beamforming," IEEE Trans. Wireless Commun., vol. 18, no. 11, pp. 5394 – 5409, 2019.

[7] S. Gong, Z. Yang, C. Xing, J. An and L. Hanzo, "Beamforming Optimization for Intelligent Reflecting Surface Aided SWIPT IoT Networks Relying on Discrete Phase Shifts," in IEEE Internet of Things Journal, doi: 10.1109/JIOT.2020.3046929.

[8] S. Zhang and R. Zhang, "Capacity characterization for intelligent reflecting surface aided MIMO communication," IEEE J. Sel. Areas in Commun., 2020.

[9] C. Pan, H. Ren, K. Wang, W. Xu, M. Elkashlan, A. Nallanathan, and L. Hanzo, "Intelligent reflecting surface for multicell MIMO communications," arXiv preprint arXiv:1907.10864, 2019.

[10] Y. Yang, B. Zheng, S. Zhang, and R. Zhang, "Intelligent reflecting surface meets OFDM: Protocol design and rate maximization," IEEE Trans. Commun., 2020.

[11] B. Zheng and R. Zhang, "Intelligent reflecting surface-enhanced OFDM: Channel estimation and reflection optimization," IEEE Wireless Commun. Lett., 2019.

[12] Z. Q. He and X. Yuan, "Cascaded channel estimation for large intelligent metasurface assisted massive MIMO," IEEE Wireless Commun. Lett., 2019.

[13] C. You, B. Zheng, and R. Zhang, "Progressive channel estimation and passive beamforming for intelligent reflecting surface with discrete phase shifts," arXiv preprint arXiv:1912.10646, 2019.

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