Optimization of IRS-assisted OFDMA SWIPT Systems with Dynamic Subcarrier Allocation and AC Computing

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***Abstract*—This study aims to explore the potential of an intelligent reflecting surface (IRS) in facilitating simultaneous wireless information and power transfer (SWIPT) in an orthogonal frequency division multiple access (OFDMA) system. A power-splitting (PS) protocol is employed to enable both energy harvesting (EH) and information decoding (ID). Moreover, an alternating current computing (ACC) is integrated into the EH receivers to directly utilize the harvested AC power, unlike the conventional direct current computing (DCC) approach. Specifically, we consider joint optimization of beamforming, dynamic subcarrier allocation (SA), IRS phase shift, PS coefficient, and ACC coefficient for the IRS-assisted OFDMA-SWIFT system, with the objective of maximizing the overall sum rate. To solve the optimization problem, we propose an alternating optimization (AO) framework combined with inner approximation (IA) methods. Numerical results demonstrate the effectiveness of the proposed system, as compared to alternative approaches.**

Keywords*—*alternating current computing (ACC), subcarrier allocation (SA), intelligent reflecting surface (IRS), energy harvesting (EH), alternating optimization (AO).

I. INTRODUCTION

Recently, intelligent reflecting surfaces (IRS) have gained considerable attention as a potential solution to meet the increasing demands for spectral and energy efficiency in next-generation wireless networks [1]. Through the precise manipulation of reflection phase and amplitude of numerous passive elements, an IRS can reshape the wireless propagation environment. This dynamic reshaping enables the establishment of optimal signal paths between transceivers, leading to substantial improvements in communication performance. One notable advantage of IRS is its ability to achieve intelligent control over signal propagation without relying on complex signal processing, decoding, or amplification. Unlike traditional methods such as active beamforming and relaying, IRS leverages the inherent properties of passive reflecting elements to effectively enhance wireless communications.

The potential benefits of IRS have sparked significant interest in various research areas, including non-orthogonal multiple access (NOMA), orthogonal frequency division multiple access (OFDMA), simultaneous wireless information and power transfer (SWIPT), and full-duplex radio [2], [3]. Among these techniques, the implementation of OFDMA-SWIPT systems has recently gained substantial attention due to their versatile capabilities. These systems can utilize a PS protocol to enable both energy harvesting (EH) and information decoding (ID). However, previous works in

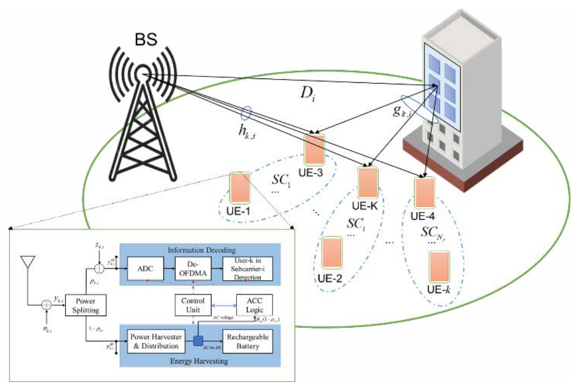

Fig. 1. An IRS-assisted OFDMA-SWIPT system using ACC.

this field have overlooked the power consumption associated with activating the computational blocks, particularly in the case of OFDMA systems where additional computational complexity is introduced in inverse fast Fourier transform (IFFT) blocks. On the other hand, conventional methods that rely on DCC in EH receivers can lead to significant system performance degradation due to low conversion efficiency of current rectifiers. To address this challenge, recent breakthrough discoveries reported in [4], [5] demonstrate that wirelessly harvested AC power can be directly utilized to power the computational blocks, as confirmed by practical experiments. This approach achieves a remarkable improvement in energy efficiency by leveraging the low-power consumption of ACC and eliminating the absence of conversion losses.

Motivated by the aforementioned considerations, we investigate an IRS-assisted OFDMA-SWIFT system integrated with ACC logic at the receivers. Our primary objective is to maximum the sum rate by optimizing dynamic SA and beamforming in the OFDMA-SWIFT system, while satisfying quality of service (QoS) requirements, harvested DC power limitations, ACC power consumption, and the power budget at the BS. To efficiently tackle the problem, we propose a highly efficient algorithm that leverages an AO framework combined with IA techniques.

The remainder of this paper is organized as follows. In Section II, we describe an IRS-assisted OFDMA-SWIFT system using ACC. Section III presents the formulation of the optimization problem for the proposed system. In Section IV, we present simulation results and compare the performance of our proposed system with those of a few alternative schemes. Finally, in Section V, we conclude the paper and discuss potential directions for future research.

II. SYSTEM MODEL

Fig. 1 depicts an IRS-assisted OFDMA-SWIPT system with ACC, where the BS, equipped with N antennas, serves K users in a single cell. The system includes an IRS with M elements connected to a controller that adjusts the reflection coefficients. This configuration gives rise to three distinct links: the BS-user direct link, the BS-IRS reflection link, and the IRS-user link. In the context of OFDMA operation, the K users are allocated to N_c subcarriers. To optimize the performance, we propose a novel dynamic SA scheme for the IRS-assisted OFDMA-SWIFT system. The users will be allocated to subcarriers based on the optimization variables, referred to as subcarrier selection coefficients, denoted as $\alpha_{k,i}$, $k = 1, 2, \dots, K$, $i = 1, 2, \dots, N_c$. Specifically, when $\alpha_{k,i} = 1$, the k-th user is assigned to the i-th subcarrier; otherwise, when $\alpha_{k,i} = 0$, the user is not allocated to that subcarrier. Prior to IFFT, the transmit signal for the i-th subcarrier is given as

$$x_i = \sum_{k=1}^{K} w_{k,i}\sqrt{\alpha_{k,i}}s_k, \quad i = 1,2,\dots,N_c, \tag{1}$$

where s_k is the transmitted data for user k with $E\{s_k s_k^H\} = 1$ and $w_{k,i}$ is the corresponding beamforming vector. The transmit signal is then appended with a cyclic prefix (CP).

After removing the CP, the received signal at each user undergoes FFT processing. Consequently, the received signal at the k-th user, considering both the BS-user and BS-IRS-user channels, can be expressed as

$$\begin{aligned} y_{k,i} &= \left(\boldsymbol{h}_{k,i}^H + \boldsymbol{g}_{k,i}^H \boldsymbol{\Phi} \boldsymbol{d}_i\right) \boldsymbol{w}_{k,i}\sqrt{\alpha_{k,i}}s_k \\ &+ \left(\boldsymbol{h}_{k,i}^H + \boldsymbol{g}_{k,i}^H \boldsymbol{\Phi} \boldsymbol{d}_i\right) \sum_{j=1, j\neq k}^{K} \boldsymbol{w}_{j,i}\sqrt{\alpha_{j,i}}s_j + n_{k,i}, \\ & k = 1,2,\dots,K, \; i = 1,2,\dots,N_c, \end{aligned} \tag{2}$$

where $\boldsymbol{h}_{k,i}$, $\boldsymbol{d}_i$, and $\boldsymbol{g}_{k,i}$ represent the baseband equivalent channels from the BS to user k, from the BS to the IRS, and from the IRS to user k, respectively. $n_{k,i} \sim CN(0, \sigma_{k,i}^2)$ denotes the additive white Gaussian noise at the receiver of the k-th user. A diagonal matrix $\boldsymbol{\Phi} = \mathrm{diag}(\phi_1, \dots, \phi_M)$ represents the reflection coefficients of the IRS. Each component $\phi_m = \kappa_m e^{j\theta_m}$ ($\theta_m \in [0, 2\pi)$, $\kappa_m \in [0,1]$, $m = 1, 2, \dots, M$) corresponds to the phase shift and amplitude reflection coefficient of the m-th element of the IRS.

For SWIPT operation in the OFDMA system, we employ the PS scheme to separate the received signal into two parts: ID and EH. For the k-th user, a portion of the receive signal power, denoted as $\rho_{k,i}$ ($0 < \rho_{k,i} < 1$), is allocated to the ID block, while the remaining 1-$\rho_{k,i}$ portion of power is allocated to the EH block. Consequently, the signal split for the ID block at the k-th user can be expressed as

$$\begin{aligned} y_{k,i}^{ID} &= \sqrt{\rho_{k,i}}\left(\sum_{j=1, j\neq k}^{K}\left(\boldsymbol{h}_{k,i}^H + \boldsymbol{g}_{k,i}^H \boldsymbol{\Phi} \boldsymbol{d}_i\right) \boldsymbol{w}_{j,i}\sqrt{\alpha_{j,i}}s_j + n_{k,i}\right) + z_{k,i}, \\ & k = 1,2,\dots,K, \; i = 1,2,\dots,N_c, \end{aligned} \tag{3}$$

where $z_{k,i} \sim CN(0, \delta_{k,i}^2)$ represents the additional noise introduced by the ID block for the k-th user and i-th subcarrier. Similarly, the signal split for the EH block is given as

$$\begin{aligned} y_{k,i}^{EH} &= \sqrt{1-\rho_{k,i}}\left(\sum_{j=1, j\neq k}^{K}\left(\boldsymbol{h}_{k,i}^H + \boldsymbol{g}_{k,i}^H \boldsymbol{\Phi} \boldsymbol{d}_i\right) \boldsymbol{w}_{j,i}\sqrt{\alpha_{j,i}}s_j + n_{k,i}\right) + z_{k,i}, \\ & k = 1,2,\dots,K, \; i = 1,2,\dots,N_c. \end{aligned} \tag{4}$$

III. PROBLEM FORMULATTION

A. Achivevable Rate

In our system, we consider assigning only two users to each subcarrier. Based on (3), the signal- to-interference plus-noise ratio (SINR) on the i-th subcarrier for user k can be computed as

$$\gamma_{k,i}^{ID}(\mathbf{w}, \boldsymbol{\alpha}, \boldsymbol{\Phi}, \boldsymbol{\rho}) \triangleq \frac{\left|[\boldsymbol{h}_{k,i}^H + \boldsymbol{g}_{k,i}^H \boldsymbol{\Phi} \boldsymbol{d}_i]\mathbf{w}_{k,i}\right|^2 \alpha_{k,i}\rho_{k,i}}{\rho_{k,i}\left(\sum_{j\neq k}^{2}\left|[\boldsymbol{h}_{k,i}^H + \boldsymbol{g}_{k,i}^H \boldsymbol{\Phi} \boldsymbol{d}_i]\mathbf{w}_{j,i}\right|^2 \alpha_{j,i} + \sigma_{k,i}^2\right) + \delta_{k,i}^2}, \tag{5}$$

where $\mathbf{w} \triangleq [\mathbf{w}_1, \mathbf{w}_i, \dots, \mathbf{w}_{N_c}]$ and $\mathbf{w}_i \triangleq \{\mathbf{w}_{k,i}\}^{KxN}$ represents the beamforming matrix for the i-th subcarrier. $\boldsymbol{\alpha} \triangleq \{\alpha_{k,i}\}^{KxN_c}$ and $\boldsymbol{\rho} \triangleq \{\rho_{k,i}\}^{KxN_c}$ denote the subcarrier allocation matrix and the power splitting matrix, respectively. From (5), the achievable rate of the proposed system can be expressed as

$$\mathbf{R}(\mathbf{w}, \boldsymbol{\alpha}, \boldsymbol{\Phi}, \boldsymbol{\rho}) = \sum_{k=1}^{K}\sum_{i=1}^{N_c}\frac{1}{N_c}\log_2\left(1 + \gamma_{k,i}^{ID}\right). \tag{6}$$

In addition to considering the sum rate for the entire system, we also account for the QoS guarantee for user rates and the threshold of the ACC. These aspects will be elaborated on in the following subsection.

B. Optimization Problem

After harvesting the RF AC power from the EH block in Fig. 1, the power current will continue to divide into two currents: the first current is utilized to convert the AC power to DC power and store it in the battery for future use, while the second current is immediately consumed by the ACC logic. Let $\beta_{k,i}$ represent the fraction of the harvested AC power consumed by the ACC logic. Consequently, the AC power consumed by the ACC logic can be expressed as

$$p_{k,i}^{ACC} = \beta_{k,i}(1-\rho_{k,i})\left(\sum_{j=1}^{K}\left|[\boldsymbol{h}_{k,i}^H + \boldsymbol{g}_{k,i}^H \boldsymbol{\Phi} \boldsymbol{d}_i]\mathbf{w}_{j,i}\right|^2 \alpha_{j,i}\right). \tag{7}$$

The remaining harvested AC power is given as

$$p_{k,i} = (1-\beta_{k,i})(1-\rho_{k,i})\left(\sum_{j=1}^{K}\left|[\boldsymbol{h}_{k,i}^H + \boldsymbol{g}_{k,i}^H \boldsymbol{\Phi} \boldsymbol{d}_i]\mathbf{w}_{j,i}\right|^2 \alpha_{j,i}\right), \tag{8}$$

In our system, we consider a non-linear EH model with a realistic RF-DC power rectifier. The harvested DC power is calculated as

$$p_{k,i}^{DC} = \frac{P'^{EH}_{k,i}}{1-\Omega_{k,i}} \times \left(\frac{1}{1+exp(-a_{k,i}(p_{k,i}-b_{k,i}))} - \Omega_{k,i}\right), \tag{9}$$

$$\Omega_{k,i} = 1/(1+exp(a_{k,i}b_{k,i})), \tag{10}$$

where $P'^{EH}_{k,i}$ represents the maximum power that can be harvested, and $a_{k,i}$ and $b_{k,i}$ are constants defined based on the circuit specifications.

Our objective is to maximize the overall sum rate for all users while satisfying the rate requirement of each user, harvested DC power limits, ACC power consumption, and power budget at the BS. As a result, the optimization problem for the proposed system can be formulated as

$$\max_{\mathbf{w}, \boldsymbol{\alpha}, \boldsymbol{\Phi}, \boldsymbol{\rho}, \boldsymbol{\beta}} \quad \sum_{k=1}^{K}\sum_{i=1}^{N_c}\frac{1}{N_c}\log_2\left(1 + \gamma_{k,i}^{ID}\right), \tag{11}$$

$$s.t. \quad \alpha_{k,i} \in \{0,1\},\ k = 1, \dots, K, i = 1, \dots, N_c, \tag{11a}$$

$$\sum_{i=1}^{N_c}\log_2\left(1 + \gamma_{k,i}^{ID}\right) \geq R_{QoS}, \tag{11b}$$

$$p_{k,i}^{ACC} \geq \bar{P}_{k,i}^{ACC}, \tag{11c}$$

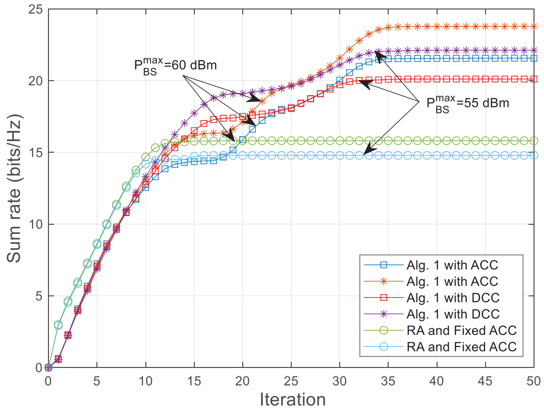

Fig. 2. Convergence behavior of the proposed algorithm with ACC compared to other systems with $N = 2$.

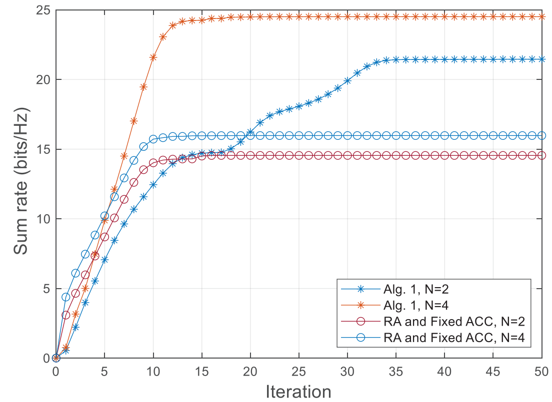

Fig. 3. Convergence behavior of the proposed algorithm with ACC versus the number of antennas.

$$p_{k,i}^{DC} \geq \bar{P}_{k,i}^{DC}, \tag{11d}$$

$$\sum_{k=1}^{K} \sum_{i=1}^{N_c} \|\mathbf{w}_{k,i}\|^2 \leq P_{\mathrm{BS}}^{\max}, \tag{11e}$$

$$|\phi_m| \leq 1;\ \mathrm{m} = 1, \dots, \mathrm{M}, \tag{11f}$$

$$0 < \sum_{k=1}^{K} \alpha_{k,i} \leq 2, \tag{11g}$$

$$\sum_{i=1}^{N_c} \alpha_{k,i} \leq 1, \tag{11h}$$

$$0 < \rho_{k,i} \leq 1, \tag{11i}$$

where R_{Qos} represents the rate requirement, and $\bar{P}_{k,i}^{ACC}$ *and* $\bar{P}_{k,i}^{DC}$ denote the thresholds for ACC power consumption and harvested DC power, respectively.

IV. Numerical Results

In this section, we demonstrate the effectiveness of the IRS-assisted OFDMA-SWIFT system with ACC. While we do not provide the detailed methodology in this paper, we employed an AO framework in conjunction with IA techniques was used to solve the optimization problem. Numerical results indicate that dynamic SA and PS scheme using ACC logic outperform the random SA and fixed PS approaches, while satisfying constraints on ACC consumption and PS threshold.

Fig. 2 illustrates the convergence behavior of the proposed algorithm with ACC compared to the algorithm involving DCC, random SA, and fixed ACC for a scemarop with two antennas ($N = 2$). It is evident that utilizing ACC logic significantly improves performance compared to the other two algorithms, under both power budgets of 55 dBm and 60 dBm. In contrast, the RA and fixed ACC systems exhibit the worst performance acrosss all strategies, as they do not leverage optimization for SA and ACC. These finding further emphasize the effectiveness of using ACC in the proposed system.

Furthermore, Fig. 3 depects the sum rate versus the number of antennas equipped at the BS, with a maximum BS power of 55 dBm ($P_{\mathrm{BS}}^{\max} = 55$ dBm). It is evident the sum rate experiences a substantial increase as the number of antennas increases for all solutions. Once again, the proposed algorithm utilizing ACC logic provides a significant performance gain compared to the other baseline schemes regardless the number of atnennas (i.e., $N = 2$, $N = 4$).

V. Conclusion

In this paper, we present a sum rate maximization problem for an IRS-assisted OFDMA-SWIPT system. To address the challenging task, we used an AO combined with IA algorithm. As part of our future work, we aim to extend the application of OFDMA-SWIFT systems to multi-cell scenarios and investigate their suitability for communication environments involving unmanned aerial vehicle.

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