

RSMA-Enabled SWIPT Systems for RIS-Assisted Full-Duplex MIMO Networks

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Abstract—This paper examines a rate-splitting multiple access (RSMA)-enabled integrated power transfer and communication (IPAC) framework, termed RSIPAC, for full-duplex (FD) multi-user reconfigurable intelligent surface (RIS)-assisted simultaneous wireless information and power transfer (SWIPT) networks with dedicated energy beamforming. In the proposed framework, the FD access point (FD-AP) simultaneously transmits downlink (DL) RSMA common and private streams with a superimposed dedicated energy stream, while battery-limited FD mobile users (MUs) harvest energy through power splitting and utilize the harvested energy for RSMA-based uplink (UL) transmission. To enhance the system spectral efficiency (SE), the DL and UL power allocation variables are jointly optimized. The proposed RSIPAC FD RIS-assisted SWIPT framework is evaluated against non-orthogonal multiple access (NOMA) and space-division multiple access (SDMA) benchmarks. In addition, two benchmark variants are considered: 1) an FD-half-duplex (HD) RSIPAC RIS-assisted SWIPT system with an FD-AP and HD-MUs, and 2) an HD-HD RSIPAC RIS-assisted SWIPT system with an HD-AP and HD-MUs. Assuming perfect channel state information and successive interference cancellation, simulation results demonstrate that the proposed FD RSIPAC RIS-assisted system achieves superior sum-rate performance compared with conventional NOMA and SDMA-based counterparts.

Index Terms—Integrated power and communication (IPAC), rate-splitting multiple access (RSMA), Full duplex (FD), reconfigurable intelligent surface (RIS), energy harvesting (EH).

I. INTRODUCTION

Recently, to address the growing challenges of beyond-sixth-generation (6G) wireless networks, such as increasing device connectivity, spectrum scarcity and energy-constrained operation, rate-splitting multiple access (RSMA) has emerged as a promising interference-management and multiple-access strategy for enhancing spectral efficiency (SE) and energy efficiency (EE) [1], [2]. In DL RSMA, each mobile user (MU) message is split into common and private parts, which are encoded into common and private streams, respectively

[1], [3]. Each MU first decodes and removes the common stream via successive interference cancellation (SuIC) before decoding its intended private stream, while treating the remaining interference as noise. In UL RSMA, each MU message is divided into multiple sub-messages based on predefined power-splitting proportions [3], [4]. The AP then decodes these sub-messages using SuIC according to a specified decoding order. By utilizing RSMA, the available resources can be flexibly allocated among MUs, thereby improving interference-management and enhancing system throughput.

Alongside throughput enhancement, simultaneous wireless information and power transfer (SWIPT) is an efficient technology to address the problem of limited-battery life of energy-constrained devices [5], [6]. SWIPT allows wireless devices to divide the received signal power between information decoding (ID) and energy harvesting (EH) via power splitting (PS) [5]–[7]. However, it faces challenges such as limited near-field coverage, which significantly degrades the data rate and EH performance. To partially address this issue, an unconventional approach termed integrated power transfer and communication (IPAC) is considered, in which dedicated energy beamforming is integrated with SWIPT to enhance EH and improve system throughput. Additionally, to improve information transfer and EH coverage in IPAC-SWIPT systems, reconfigurable intelligent surfaces (RISs) can be deployed to enhance spatial diversity [8]. Furthermore, full-duplex (FD) transmission can significantly improve the SE of RIS-assisted IPAC-SWIPT systems by enabling simultaneous DL and UL operation over the same time-frequency resource, compared with half-duplex (HD) transmission [8], [9].

Despite the potential benefits of jointly exploiting FD transmission, RSMA, RIS, and SWIPT, their combined use has not been extensively studied, as most existing works, such as those in [2], [3], [5]–[8], have investigated these technologies separately or in partial combinations. For instance, the works in [2], [7] investigated transmit power minimization and sum-rate maximization for RSMA-enabled systems. In addition, the studies in [4]–[6] considered sum-rate maximization for RSMA-based RIS-assisted SWIPT systems. The work in [8] also investigated sum-rate maximization for an FD-FD RIS-assisted wireless-powered communication network by jointly optimizing the power resource allocation and compared the re-

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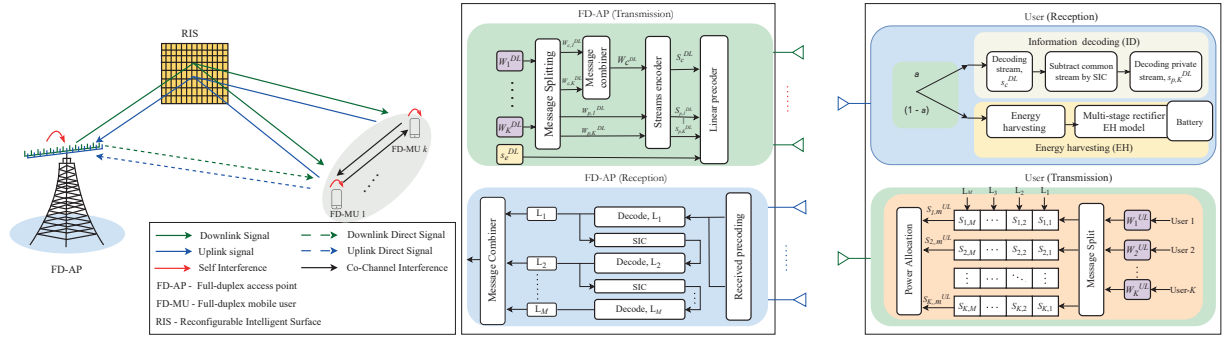


Fig. 1. FD-RSMA RIS-assisted SWIPT system model

sults with FD-AP/HD-MU and HD-AP/HD-MU benchmarks. To address this unexplored research gap, this paper focuses on performing a system analysis and evaluation of an FD RSMA-enabled IPAC (RSIPAC) RIS-assisted SWIPT network. Here, the FD-AP and MUs (FD-MUs) operate in FD mode. The FD-AP is equipped with separate multi-antenna sets for DL transmission and UL reception, while each FD-MU employs two single antennas—one for ID and EH, and the other for UL transmission. The FD-AP transmits IPAC signals by superimposing one-layer DL RSMA common and private streams with a dedicated energy stream, while each FD-MU transmit UL data to the FD-AP via RSMA-based sub-messages. Although this work adopts the benchmark architectures in [8], it extends them to RIS-assisted SWIPT networks by integrating DL RSMA-enabled IPAC with dedicated energy beamforming, UL RSMA-based transmission, and a realistic multi-stage rectifier EH model. Assuming perfect channel state information (CSI) and SuIC, the proposed framework is evaluated in terms of SE and benchmarked against non-orthogonal multiple access (NOMA) and space-division multiple access (SDMA) based schemes under different FD and HD configurations.

II. SYSTEM MODEL AND RATES FORMULATION

As illustrated in Fig. 1, the considered FD RSIPAC RIS-assisted SWIPT network consists of an FD-AP, an RIS with N reflecting elements, and K power-limited FD-MUs, each implementing a PS structure. The FD-AP employs two separate antenna sets (N_t, N_r) for DL transmission and UL reception, while each FD-MU uses two single antennas sets i.e., one for DL ID and EH, and the other for UL data transmission. The phase shift matrix of the RIS is described as $\Phi = \text{diag}[\theta_1, \theta_2, \dots, \theta_N] \in \mathbb{C}^{N \times N}$, where each $\theta_n = e^{j\phi_n}$, with $\phi_n \in [0, 2\pi)$, $n \in [1, 2, \dots, N]$. In this system, all FD-MUs are assumed to belong to a single communication group. Also, Perfect CSI and SuIC are assumed throughout this work.

The DL channels between; the FD-AP and FD-MU k (i.e., $k \in \mathcal{K}$, $k = 1, \dots, K$) (direct link), the FD-AP and the RIS, the RIS and the FD-MU k are denoted by $\mathbf{g}_{D,k} \in \mathbb{C}^{1 \times N_t}$, $\mathbf{G}_D \in \mathbb{C}^{N_r \times N_t}$ and $\mathbf{g}_{R,k} \in \mathbb{C}^{1 \times N}$, respectively. The UL channels between; the FD-MU k and the FD-AP, the FD-MU k and RIS, and RIS and the FD-AP are defined as $\mathbf{h}_{D,k} \in \mathbb{C}^{N_r \times 1} = [\mathbf{g}_{D,k}^*]$, $\mathbf{h}_{k,R} \in \mathbb{C}^{N \times 1} = [\mathbf{g}_{R,k}^*]$ and $\mathbf{H}_U \in \mathbb{C}^{N_r \times N} = [\mathbf{H}_D^*]$, respectively. The DL and UL aggregated channels for FD-MU k are defined as $\mathbf{g}_{e,k} = \mathbf{g}_{D,k} +$

$\mathbf{g}_{R,k} \Phi \mathbf{G}_D \in \mathbb{C}^{1 \times N_t}$, and $\mathbf{h}_{e,k} = \mathbf{h}_{D,k} + \mathbf{H}_U \Phi \mathbf{h}_{k,R} \in \mathbb{C}^{N_r \times 1}$, respectively. Both the FD-AP and the FD-MUs experience self interference (SI), and their channel (direct + cascaded) denoted by, $\hat{\mathbf{H}}_{AP} = (\mathbf{H}_D^S + \mathbf{H}_U \Phi \mathbf{G}_D) \in \mathbb{C}^{N_r \times N_t}$, and $f_k \in \mathbb{C}^{1 \times 1}$, respectively¹. Finally, co-channel interference (CoI) occur between FD-MUs k and FD-MU j ($j \in \mathcal{K}$, $j \in \{1, \dots, K\}$, $j \neq k$), and given as $f_{j,k} \in \mathbb{C}^{1 \times 1}$. The channels small-scale fading components are modeled as $\sqrt{\varepsilon_{DL}}(\sqrt{\Theta_{DL}}/(\sqrt{\Theta_{DL}} + 1))\tilde{\mathbf{G}}_D + \sqrt{1}/(\sqrt{\Theta_{DL}} + 1)\tilde{\mathbf{G}}_D$ or $\sqrt{\varepsilon_{DL,k}}(\sqrt{\Theta_{DL,k}}/(\sqrt{\Theta_{DL,k}} + 1))\tilde{\mathbf{g}}_{R,k} + \sqrt{1}/(\sqrt{\Theta_{DL,k}} + 1)\tilde{\mathbf{g}}_{D,k}$, where, $\{\Theta_{DL}, \Theta_{DL,k}\}$ and $\{\varepsilon_{DL}, \varepsilon_{DL,k}\}$ are the Rician K factors and distance dependent path-loss, respectively [8].

A. FD-FD System Signal Flow and Rate Formulation

In the considered FD-FD RSIPAC RIS-assisted SWIPT system, the FD-AP adopts one-layer DL RSMA to transmit DL RSMA-based IPAC signal. Let $\mathcal{M}^{DL} \triangleq \{M_1^{DL}, \dots, M_K^{DL}\}$ denote the set of DL messages intended for the FD-MUs. The message M_k^{DL} of the k -th DL FD-MU is split into a common message $M_{k,c}^{DL} \in \mathbb{C}$ and a private message $M_{k,p}^{DL} \in \mathbb{C}$, and ensuring that, $\mathbb{E}[M_{k,c}^{DL}(M_{k,c}^{DL})^H] = 1$ and $\mathbb{E}[M_{k,p}^{DL}(M_{k,p}^{DL})^H] = 1$, $\forall k \in \mathcal{K}$. Specifically, the common message of all FD-MU are jointly encoded into a common stream, s_c^{DL} while each private message is independently encoded into a private stream, $s_{k,p}^{DL}$, $\forall k$. In addition, dedicated energy stream, s_e^{DL} is superimposed with the information streams to enable DL energy transfer, and $\mathbb{E}[|s_c^{DL}|^2] = \mathbb{E}[|s_{k,p}^{DL}|^2] = \mathbb{E}[|s_e^{DL}|^2] = 1$. Consequently, the superimposed DL transmit signal at the FD-AP is given by, $\mathbf{x}^{DL} = \sqrt{p_c^{DL}}\mathbf{p}_c s_c^{DL} + \sqrt{p_p^{DL}} \sum_{k \in \mathcal{K}} \mathbf{p}_k s_{k,p}^{DL} + \sqrt{p_e^{DL}}\mathbf{p}_e s_e^{DL}$, where $\mathbf{p}_c \in \mathbb{C}^{N_t \times 1}$, $\mathbf{p}_k \in \mathbb{C}^{N_t \times 1}$, and $\mathbf{p}_e \in \mathbb{C}^{N_t \times 1}$, $\forall k \in \mathcal{K}$ are the transmit beamformers for the common stream, private stream and energy stream of DL FD-MU k , respectively. The power allocated to the common, private and energy stream are defined, respectively as, $p_c^{DL} = (1 - \mu)(1 - \zeta)P_{\max}^{DL}$, $p_{p,k}^{DL} = (1 - \mu)\zeta P_{\max}^{DL}/K$, $\forall k$, and $p_e^{DL} = \mu P_{\max}^{DL}$, $0 < \mu < 1$ and $0 < \zeta < 1$, and $P_{\max}^{DL}$ is the total FD-AP transmit power. Maximum ratio transmission scheme is adopted for the common, private, and energy streams, respectively, with the corresponding beamforming vectors are expressed as, $\mathbf{p}_c = \sum_{k \in \mathcal{K}} \mathbf{g}_{e,k}^H / \|\sum_{k \in \mathcal{K}} \mathbf{g}_{e,k}^H\|$, $\mathbf{p}_k = \mathbf{g}_{e,k}^H / \|\mathbf{g}_{e,k}^H\|$ and $\mathbf{p}_e = \sum_{k \in \mathcal{K}} \mathbf{g}_{e,k}^H / \|\sum_{k \in \mathcal{K}} \mathbf{g}_{e,k}^H\|$.

¹Note, the loop-back SI at the FD-MUs act as an extra source of harvested energy and contributes to total power harvested

$$y_k^{\text{DL}} = \underbrace{(\mathbf{g}_{e,k})\mathbf{p}_c s_c^{\text{DL}}}_{\text{Common stream}} + \underbrace{(\mathbf{g}_{e,k}) \sum_{k \in \mathcal{K}} \mathbf{p}_k s_{k,p}^{\text{DL}}}_{\text{Private stream}} + \underbrace{(\mathbf{g}_{e,k})\mathbf{p}_e s_e^{\text{DL}}}_{\text{Energy stream}} + \underbrace{\sum_{j \in \mathcal{K}} \sum_{m \in \mathcal{M}} (\mathbf{h}_{j,R} \Phi \mathbf{g}_{R,k} + f_{j,k}) \sqrt{p_{j,m}^{\text{UL}} s_{j,m}^{\text{UL}}}}_{\text{FD-MU } k \text{ Loop back SI + other FD-MUs Co-channel Interference}} + \underbrace{n_k^{\text{DL}}}_{\text{Noise}} \quad (1)$$

$$\bar{p}_k^{\text{EH}} = \frac{\beta_k^2 R_{At,k}^2 f_{LPF}(\Omega_k)^2}{4 R_{Ld,k} \eta_k^2 V_{T,k}^2} + \frac{\beta_k^2 R_{At,k}^3 f_{LPF}(\Omega_k)^3}{32 R_{Ld,k} \eta_k^4 V_{T,k}^4} + \frac{\beta_k^2 R_{At,k}^4 f_{LPF}(\Omega_k)^4}{1024 R_{Ld,k} \eta_k^6 V_{T,k}^6} \quad (2)$$

$$\mathbf{y}_{\text{AP}}^{\text{UL}} = \underbrace{\sum_{k=1}^K (\mathbf{H}_U \Phi \mathbf{h}_{k,R} + \mathbf{h}_{D,k}) \sum_{m \in \mathcal{M}} \sqrt{p_{k,m}^{\text{UL}} s_{k,m}^{\text{UL}}}}_{\text{RSMA Signal from the FD-MUs}} + \underbrace{\hat{\mathbf{H}}_{\text{AP}} (\mathbf{p}_c s_c^{\text{DL}} + \sum_{j=1}^K \mathbf{p}_j s_{j,p}^{\text{DL}} + \mathbf{p}_e s_e^{\text{DL}})}_{\text{Residual SI}} + \underbrace{\mathbf{n}_{\text{AP}}^{\text{UL}}}_{\text{Noise}} \quad (3)$$

$$\mathbf{r}_{\text{AP}}^{\text{UL}} = \sum_{k=1}^K \mathbf{u}_k^H (\mathbf{h}_{e,k}) \sum_{m \in \mathcal{M}} \sqrt{P_{k,m}^{\text{UL}} s_{k,m}^{\text{UL}}} + \mathbf{u}_k^H \hat{\mathbf{H}}_{\text{AP}} (\mathbf{p}_c s_c^{\text{DL}} + \sum_{j=1}^K \mathbf{p}_j s_{j,p}^{\text{DL}} + \mathbf{p}_e s_e^{\text{DL}}) + \mathbf{u}_k^H \mathbf{n}_{\text{AP}}^{\text{UL}}. \quad (4)$$

Additionally, each FD-MU splits its UL message, W_k^{UL} into two sub-messages, denoted by $W_{k,1}^{\text{UL}}$ and $W_{k,2}^{\text{UL}}$, such that $\mathbb{E}[W_{k,m}^{\text{UL}}(W_{k,m}^{\text{UL}})^H] = 1, \forall m \in \mathcal{M} \triangleq \{1 \dots M\}, \forall k \in \mathcal{K}$. The sub-messages are then encoded into distinct streams, $s_{k,m}^{\text{UL}}, \forall k, \forall m$, and then transmitted to the FD-AP from all UL FD-MUs. Thus, the signal transmitted by each FD-MU k is expressed as $x_k^{\text{UL}} = \sum_{m \in \mathcal{M}} \sqrt{p_{k,m}^{\text{UL}} s_{k,m}^{\text{UL}}}$, where $p_{k,m}^{\text{UL}}$ is the transmit power of the m -th sub-message of UL FD-MU k . The power is split between the two sub-messages according to $p_{k,1}^{\text{UL}} = \rho P_k^{\text{UL}}$ and $p_{k,2}^{\text{UL}} = (1 - \rho) P_k^{\text{UL}}, (0 < \rho < 1)$ and P_k^{UL} is the total UL power budget of FD-MU k . Note that, the UL transmit power of FD-MU k is constrained by its available battery and harvested power as $P_k^{\text{UL}} = \sum_{m \in \mathcal{M}} p_{k,m}^{\text{UL}} \leq \bar{p}_k^{\text{CB}} + \bar{p}_k^{\text{EH}}$, where, $\bar{p}_k^{\text{CB}}$ and $\bar{p}_k^{\text{EH}}$ are the current battery power and harvested power, respectively. Therefore, the signal received by each DL FD-MU k is expressed in (1), where $n_k^{\text{DL}} \sim \mathcal{CN}(0, (\sigma_k^{\text{DL}})^2)$ denotes noise at FD-MU k , with $(\sigma_k^{\text{DL}})^2$ as the noise variance.

Moreover, each FD-MU k employs a PS receiver, where the received DL signal is divided between the ID and EH units. Specifically, let, $\sqrt{\alpha_k} \in (0 \leq \alpha_k \leq 1)$ be the PS factor at the k -th FD-MU, where $\sqrt{\alpha_k}$ of the received DL signal power is allocated to the ID unit and $\sqrt{1 - \alpha_k}$ is allocated to the EH unit. Accordingly, the signals at the ID and EH units are given by $y_{k,\text{ID}}^{\text{DL}} = \sqrt{\alpha_k}(y_k^{\text{DL}}) + n_{k,\text{ID}}^{\text{DL}}$ and $y_{k,\text{EH}}^{\text{DL}} = \sqrt{1 - \alpha_k}(y_k^{\text{DL}})$, where, $n_{k,\text{ID}}^{\text{DL}} \sim \mathcal{CN}(0, (\sigma_{k,\text{ID}}^{\text{DL}})^2)$ denotes the additional noise introduced by the ID circuit. The multi-stage rectifier EH model in [8], [9] is adopted for practical EH modeling at each FD-MU. Therefore, the harvested power at FD-MU k is presented in (2), where $\Omega_k = (1 - \alpha_k)|\mathbf{g}_{e,k}\mathbf{p}_c|^2 + ((1 - \alpha_k) \sum_{k \in \mathcal{K}} |\mathbf{g}_{e,k}\mathbf{p}_k|^2) + (1 - \alpha_k)|\mathbf{g}_{e,k}\mathbf{p}_e|^2 + \sum_{m \in \mathcal{M}} p_{k,m}^{\text{UL}} |\mathbf{h}_{k,\text{ER}}|^2$. Note that, $\mathbf{h}_{k,\text{ER}}$ is the effective channel vector of FD-MU k SI, hence, termed *energy recycling*. $R_{Ld,k}, R_{At,k}, \beta_k, \eta_k$, and $V_{T,k}$ denotes the system load, antenna impedance load, number of voltage rectifier stages, ideality factor and diode thermal voltage, respectively. Detailed derivations and circuit parameters used can be found in [8], [9]. Thus, the received and decoded UL signals are given in (3) and (4), respectively, where, $\mathbf{u}_k^H = \mathbf{h}_{e,k}^H / \|\mathbf{h}_{e,k}\|$ denotes the maximum ratio combining receive filter.

DL/UL Achievable Rates: For a unified rate formulation, the signal-to-interference-plus-noise ratio (SINR) of each decoded

stream is expressed in a general form. Let $z \in \{q, t, v\}$, where q, t , and v represent the DL common and private streams, and UL sub-message, respectively. The corresponding SINR for the DL/UL is expressed as

$$\gamma_k^z = \frac{S_k^z}{\mathcal{I}_k^z + \mathcal{J}_k^z + \mathcal{Q}_k^z}, \quad z \in \{q, t, v\}. \quad (5)$$

During DL decoding, FD-MU k first decodes the common stream using SuIC while treating all other signals as interference. Although, the energy stream enhances the power harvested, it acts as interference during ID. Therefore, SINR for decoding the common stream at FD-MU k is expressed in (5), where, $S_k^q \triangleq \alpha_k(1 - \mu)(1 - \zeta)P_{\text{max}}^{\text{DL}} \varrho_{k,k,1} |\mathbf{g}_{e,k}\mathbf{p}_c|^2$, $\mathcal{I}_k^q \triangleq \alpha_k \sum_{j \in \mathcal{K}} (1 - \mu) \zeta P_{\text{max}}^{\text{DL}} / K \varrho_{k,j,1} |\mathbf{g}_{e,k}\mathbf{p}_j|^2 + \alpha_k \mu P_{\text{max}}^{\text{DL}} |\mathbf{g}_{e,k}\mathbf{p}_e|^2$, $\mathcal{J}_k^q \triangleq \sum_{j \in \mathcal{K}} \sum_{m \in \mathcal{M}} \alpha_k \varrho_{k,j,m} p_{j,m}^{\text{UL}} |\mathbf{h}_{j,R} \Phi \mathbf{g}_{R,k} + f_{j,k}|^2$, and $\mathcal{Q}_k^q \triangleq \alpha_k \|n_k^{\text{DL}}\|^2 + \|n_{k,\text{ID}}^{\text{DL}}\|^2$, are the power of the desired common stream, private stream interference, CoI plus FD-MU k SI and noise, respectively. Here, $\varrho_{k,j,m}$ denotes the residual interference factor at FD-MU k after SuIC when canceling the m -th UL sub-message of FD-MU j , i.e., $\varrho_{k,j,m} = 0$ (perfect SuIC), $0 < \varrho_{k,j,m} < 1$ (imperfect SuIC) and $\varrho_{k,j,m} = 1$ (no SuIC). Thus, the common rate is given as, $R_{c,k}^{\text{DL}} = \log_2(1 + \gamma_{c,k}^{\text{DL}}) \forall k \in \mathcal{K}$, and satisfies $R_c^{\text{DL}} = \min\{R_{c,1}^{\text{DL}} \dots R_{c,K}^{\text{DL}}\}$ to guarantee successful decoding of the common stream by all FD-MU. The corresponding FD-MU k private stream SINR is, $S_k^t \triangleq \alpha_k(1 - \mu) \zeta P_{\text{max}}^{\text{DL}} / K \varrho_{k,k,1} |\mathbf{g}_{e,k}\mathbf{p}_k|^2$, $\mathcal{I}_k^t \triangleq \alpha_k \sum_{j \in \mathcal{K}, j \neq k} (1 - \mu) \zeta P_{\text{max}}^{\text{DL}} / K \varrho_{k,j,1} |\mathbf{g}_{e,k}\mathbf{p}_j|^2$, $\mathcal{J}_k^t \triangleq \mathcal{J}_k^q$, and $\mathcal{Q}_k^t = \mathcal{Q}_k^q$. FD-MU k private rate is expressed as, $R_{k,p}^{\text{DL}} = \log_2(1 + \gamma_{k,p}^{\text{DL}})$. Therefore, the rate at FD-MU k is written as, $R_{k,\text{tot}}^{\text{DL}} = C_k^{\text{DL}} + R_{k,p}^{\text{DL}}, \forall k \in \mathcal{K}$, where C_k^{DL} is FD-MU k portion of the common stream, satisfying $\sum_k C_k^{\text{DL}} = R_c^{\text{DL}}$.

In UL decoding, the FD-AP employs SuIC to decode all received sub-messages. To maximize user fairness, the decoding order Π in [3] is adopted, such that,

$$\Pi^{\text{AP}} = \{ (s_{k',m}^{\text{UL}} \rightarrow s_{k',m'}^{\text{UL}} \rightarrow s_{k,m}^{\text{UL}} \rightarrow s_{k,m'}^{\text{UL}}) : \|\mathbf{h}_{e,k}\| \geq \|\mathbf{h}_{e,k'}\|, k \neq k', k, k' \in \mathcal{K}, m, m' \in \mathcal{M} \}. \quad (6)$$

Therefore, the SINR for decoding the m -th UL sub-message of FD-MU k is obtained from (5) as, $S_{k,m}^v \triangleq p_{k,m}^{\text{UL}} \varrho_{k,m}^{\text{AP}} |\mathbf{u}_k^H \mathbf{h}_{e,k}|^2$, $\mathcal{I}_{k,m}^v \triangleq \sum_{j \in \mathcal{K}} \sum_{n \in \mathcal{M}} p_{j,n}^{\text{UL}} \varrho_{j,n}^{\text{AP}} |\mathbf{u}_k^H \mathbf{h}_{e,j}|^2$, $\mathcal{J}_{k,m}^v \triangleq \varrho_{c,1}^{\text{AP}} |\mathbf{u}_k^H \hat{\mathbf{H}}_{\text{AP}} \mathbf{p}_c|^2 + \sum_{j=1}^K \varrho_{j,1}^{\text{AP}} |\mathbf{u}_k^H \hat{\mathbf{H}}_{\text{AP}} \mathbf{p}_j|^2$, and

$\mathcal{Q}_{k,m}^v = \varrho_e^{\text{AP}} |\mathbf{u}_k^H \hat{\mathbf{H}}_{\text{AP}} \mathbf{p}_e|^2 + \sigma_{\text{AP}}^2 \|\mathbf{u}_k^H\|^2$, denoting FD-MU k UL desired sub-message power, interference power of other sub-messages with higher decoding order, and the interference from DL energy stream plus FD-AP noise, respectively. Therefore, the UL overall rate of FD-MU k is given as, $R_k^{\text{UL}} = \sum_{m \in \mathcal{M}} R_{k,m}^{\text{UL}} = \sum_{m \in \mathcal{M}} \log_2(1 + \gamma_{k,m}^{\text{UL}})$, $\forall k \in \mathcal{K}$, and the total SE of the system is $R_{\text{sum}} = \sum_{k \in \mathcal{K}} (C_k^{\text{DL}} + R_{k,p}^{\text{DL}}) + \sum_{k \in \mathcal{K}} R_k^{\text{UL}}$.

B. Special Cases of FD-FD RSIPAC RIS-SWIPT System

For comparison, two special cases of the FD-FD system are considered as follows.

1) **FD-HD RSIPAC System:** In the FD-HD benchmark, the K RSIPAC SWIPT devices operate in HD mode and are divided into two transmission groups, $\mathcal{S}_1$ and $\mathcal{S}_2$, with $K_1 + K_2 = K$. During time-slot τ_1 , devices in $\mathcal{S}_1$ perform DL ID and EH, while devices in $\mathcal{S}_2$ perform UL transmission. During time-slot τ_2 , the transmission roles of the two groups are reversed. The DL and UL achievable rates, and harvested power can be directly obtained from the FD-FD formulation in (1), (4) and (2), respectively, where the DL and UL rates are given as, $R_{k,l,\text{tot}}^{\text{DL}} = \sum_{l=1}^2 \varsigma_{k,l} \tau_l (C_{k,l}^{\text{DL}} + R_{k,p,l}^{\text{DL}})$, $R_{k,l}^{\text{DL}} = \log_2(1 + \gamma_{k,p,l}^{\text{DL}})$, $R_{k,l}^{\text{UL}} = \sum_{l=1}^2 \sum_{m \in \mathcal{M}} \varsigma_{k,l} \tau_l \log_2(1 + \gamma_{k,m,l}^{\text{UL}})$, where, $\hat{l} = 3 - l$, $l = \{1, 2\}$ and $\varsigma_{k,l} \in \{0, 1\}$ is the group switching factor. $\bar{p}_{k,l}^{\text{EH}}$ (harvested power), with $\Omega_{k,l} = (1 - \alpha_k) |\mathbf{g}_{e,k} \mathbf{p}_c|^2 + (1 - \alpha_k) \sum_{j \in \mathcal{S}_l} |\mathbf{g}_{e,k} \mathbf{p}_j|^2 + (1 - \alpha_k) |\mathbf{g}_{e,k} \mathbf{p}_e|^2$.

2) **HD-HD RSIPAC System:** In the HD-HD case, both operate in HD mode. The DL and UL rates are, $R_{k,\text{tot}}^{\text{DL}} = \tau_1 (C_k^{\text{DL}} + \log_2(1 + \gamma_k^{\text{DL}}))$ and $R_k^{\text{UL}} = \tau_2 \sum_{m \in \mathcal{M}} \log_2(1 + \gamma_{k,m}^{\text{UL}})$.

C. Signal Derivations for SDMA and NOMA Benchmarks

The DL and UL SINRs for NOMA and SDMA follow from the generalized expression in (5) by setting the power allocation $\{\mu, \zeta, \rho\}$ and SuIC $\{\varrho_{j,n}^{\text{AP}}, \varrho_{c,1}^{\text{AP}}, \varrho_{j,1}^{\text{AP}}, \varrho_e^{\text{AP}}\}$ variables.

1) **NOMA Scheme:** For NOMA scheme, the DL power allocation variables are set as, $0 < \mu < 1$ and $\zeta = 1$ ($p_c^{\text{DL}} = 0$, implying no common stream is transmitted), and UL variable, $\rho = 1$ (implying no message splitting). The SuIC variables are set as, $0 \leq \{\varrho_{\hat{z},1}^{\text{AP}}, \hat{z} \in \{j, e\}\} \leq 0$.

2) **SDMA Scheme:** Similarly, for SDMA, $0 < \mu < 1$, $\zeta = 1$ ($p_c^{\text{DL}} = 0$), and $\rho = 1$. Here, SDMA does not use SuIC, hence, $\varrho_{j,\hat{s},1}^{\text{AP}}, \hat{s} \in \{n, e\} = 1$ (implying no SuIC).

D. System Optimization Problem

The system optimization problem for maximizing SE is formulated as

$$\max_{\zeta, \mu, \rho} R_{\text{sum}} \text{ s.t. } p_c^{\text{DL}} + \sum_{k \in \mathcal{K}} p_{k,p}^{\text{DL}} + p_e^{\text{DL}} \leq P_{\text{max}}^{\text{DL}}, \quad (7a)$$

$$\sum_{m \in \mathcal{M}} p_{k,m}^{\text{UL}} \leq P_k^{\text{UL}} \leq \bar{p}_k^{\text{CB}} + \bar{p}_k^{\text{EH}} \quad (7b)$$

$$0 \leq \mu \leq 1, 0 \leq \zeta \leq 1, 0 \leq \rho \leq 1. \quad (7c)$$

To obtain the optimal power allocation factors, an exhaustive search (EH) is performed over μ, ζ , and ρ with step size Δ . For each variable set (μ, ζ, ρ) , the total sum-rate is calculated, and the variable set that maximizes the achievable sum-rate is selected. The selected variables allocate power to the common

TABLE I
SYSTEM SCENARIOS AND CASE DEFINITIONS.

	FD-FD	FD-HD	HD-HD
RSMA	RS FF	RS FH	RS HH
NOMA	NO FF	NO FH	NO HH
SDMA	SD FF	SD FH	SD HH

stream, private streams, dedicated energy stream, and UL sub-messages. The procedure is summarized in Algorithm 1.

Algorithm 1 Joint Power Allocation Algorithm

Initialize $(\mu, \zeta, \rho) = 0$, $(\Delta_\mu, \Delta_\zeta, \Delta_\rho) = 0.01$, P_k^{UL} , $R_{\text{sum}}^* = 0$
repeat
 Line Search μ^* and ζ^* with $R_{k,\text{tot}}^{\text{DL}}$
 Set $p_e^{\text{DL}} = \mu P_{\text{max}}^{\text{DL}}$, $p_c^{\text{DL}} = (1 - \mu)(1 - \zeta) P_{\text{max}}^{\text{DL}}$ and $P_k^{\text{DL}} = (1 - \mu) \zeta P_{\text{max}}^{\text{DL}} / K$
 Line Search ρ^* with R_k^{UL}
 Set $p_{k,1}^{\text{UL}} = \rho P_k^{\text{UL}}$ and $p_{k,2}^{\text{UL}} = (1 - \rho) P_k^{\text{UL}}$
 Calculate Total SE using R_{sum}
 Update $R_{\text{sum}}^* \leftarrow \max(R_{\text{sum}}, R_{\text{sum}}^*)$
until $|R_{\text{sum}}^* - R_{\text{sum}}| < \eta$

III. NUMERICAL RESULTS AND DISCUSSION

This section presents simulation results for the considered FD RSIPAC RIS-assisted SWIPT system. The following simulation parameters are considered; $\{N_t, N_r\} = 10$, $M = 50$, $K = 6$, $\{\Theta_{\text{DL}}, \Theta_{\text{DL},k}\} = 10$ dB, $\{\tau_1, \tau_2\} = 0.5$, and $\{(\sigma_k^{si})^2, (\sigma_{\text{AP}}^{si})^2\} = -96$ dBm. The FD-AP and RIS are located at $(0, 0, 25)$ m and $(60, 60, 22.5)$ m, respectively. The FD-MUs are randomly distributed within a circular area of radius 5m centered at $(80, 0)$ m, with user height fixed at 1.5m. The large-scale fading coefficient is modeled as $\sqrt{A_0(d/d_0)^{-\kappa}}$, where $A_0 = -10$ dB, denotes the path-loss at the reference distance $d_0 = 1$ m, d is the link distance and $\kappa = 2.5$ is the path-loss exponent. Table I summarizes the system scenarios and combinations.

Fig. 2 shows the impact of $P_{\text{max}}^{\text{DL}}$, on the system sum-rate's and total harvested power for the RIS-assisted (with-RIS) and non-RIS (without-RIS) cases. As shown in Fig. 2(a) and Fig. 2(b) for all the system scenarios, i.e., FF, FH and HH, the total system sum-rate of RSMA and NOMA increases with $P_{\text{max}}^{\text{DL}}$, in both RIS and non-RIS cases, while the SDMA scheme exhibits saturation in the high-power regime. The saturation in the SDMA scheme is due to the increased MU interference with $P_{\text{max}}^{\text{DL}}$ being treated as noise, unlike RSMA and NOMA which mitigate such interference through SuIC-based decoding. Moreover, RSMA scheme achieves a higher sum-rate than NOMA in the FF, FH, and HH scenarios due to its more flexible interference-management capability, enabling partial interference decoding, and partial treating of interference as noise. For instance, at $P_{\text{max}}^{\text{DL}} = 20$ dB, RS-FF scheme outperforms NO-FF scheme by approximately 40%, corresponding to about 16 bps/Hz gain, while the RS-FH and RS-MA-HH schemes outperform their NOMA counterparts by approximately 23% (about 8 bps/Hz) and 35% (about 9 bps/Hz), respectively. It can be observed that, across all system

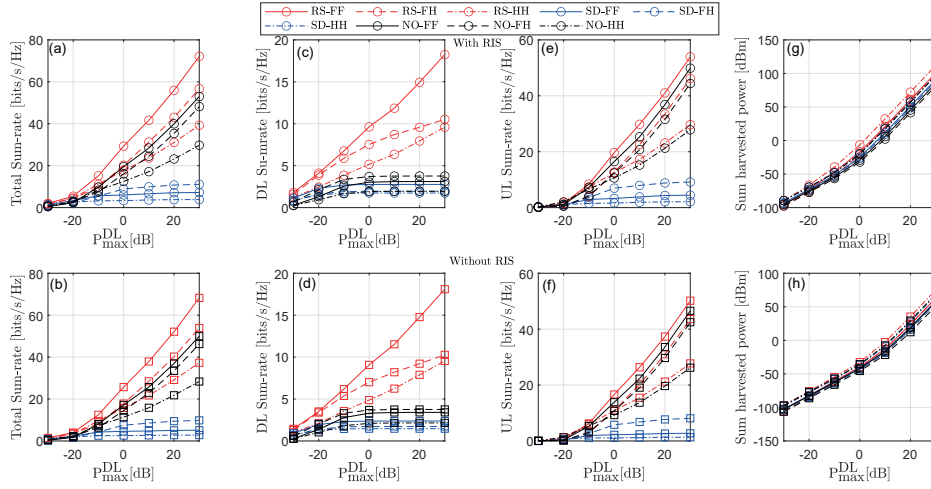


Fig. 2. Performance comparison vs $P_{\max}^{\text{DL}}$: (a), (b) Total sum-rate; (c), (d) DL sum-rate; (e), (f) UL sum-rate; and (g), (h) harvested power for RIS and non-RIS.

scenarios and schemes, the RIS cases achieves approximately 0.2 ~ 0.35 bps/Hz higher sum-rate gain than the non-RIS cases due to the increased RIS spatial diversity.

For the DL sum-rate, as shown in Fig. 2(c) and Fig. 2(d), only the RSMA schemes maintain an increasing trend with $P_{\max}^{\text{DL}}$ in both the RIS and non-RIS cases. This is because increasing $P_{\max}^{\text{DL}}$ enhances the received common and private streams. In addition, the common stream enables partial MU interference cancellation before decoding the private-stream, thereby reducing interference in the high-power regime. Comparing the RSMA schemes at $P_{\max}^{\text{DL}} = 20$ dB, RS-FF outperforms RSMA FH and RS-HH by approximately, 5.2 bps/Hz and 7 bps/Hz, respectively. However, it can be observed that, the NOMA schemes saturates as $P_{\max}^{\text{DL}}$ increases. This is because the DL SINR is limited by both MU interference and the dedicated energy stream, which contributes to EH, but acts as interference during ID. At $-30 < P_{\max}^{\text{DL}} < 30$ dB, NO-FH outperforms NO-FF by approximately 0.8 bps/Hz. This is because NO-FH experience $K/2$ interfering signals with unequal power allocation, while NO-FF experiences $K - 1$ interfering signals. Also, in low power regime, e.g., $-30 < P_{\max}^{\text{DL}} < -10$ dB, SD-FF achieves higher performance gain than NO-FF, owing to the ability of SDMA to handle interference in low power regimes.

Fig. 2(e) and (f) illustrates the performance of the UL sum-rate versus $P_{\max}^{\text{DL}}$. As expected, RSMA schemes with-RIS consistently outperforms NOMA and SDMA schemes in all scenarios. For instance, when $P_{\max}^{\text{DL}} = 20$ dB, RS-FF achieves 13.5% sum-rate gain over NO-FF and SD-FF. Similarly, RS-FH and RS-HH achieves 9.3% and 9.5%, respectively, over their corresponding NO-FH and NO-HH counterparts. In comparison to the DL, the UL attains a higher sum-rate gains due to the larger number of messages being decoded at the FD-AP. Furthermore, Fig. 2(g) demonstrates the total power harvested versus $P_{\max}^{\text{DL}}$. The harvested power increases with $P_{\max}^{\text{DL}}$ for all schemes, implying higher UL power budget. RSMA harvest more power than NOMA and SDMA schemes because energy is harvested from the common, private and energy streams. Also, RS-HH harvest more energy due to the absence of FD

induced SI affecting the DL beamformer. The non-RIS case is shown in Fig. 2(h).

IV. CONCLUSION

This paper analyzes an FD RSMA-enabled IPAC for RIS-assisted SWIPT networks, where DL information and dedicated energy transmission, UL RSMA transmission, and EH are jointly considered. From the validated results, it is shown that the proposed RSIPAC system improves SE and harvested power compared with NOMA and SDMA benchmarks.

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