Interference-Constrained IRS-aided SWIPT

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Abstract—We consider a spectrum underlay setup comprised by a primary and a secondary multiple-input single-output (MISO) broadcast system. The latter performs simultaneous wireless information and power transfer (SWIPT) with the aid of an intelligent reflecting surface (IRS). This system relies on joint transmit precoding and reflect beamforming to: i) compensate for the reverse inter-system interference (RISI) at the information decoding receivers (IDR) caused by the primary transmitter (PT); ii) suppress the forward ISI (FISI) at the PRs caused by the secondary transmitter (ST); and iii) mitigate the additional intra-primary-system interference caused by the reception at the PRs of IRS-reflected signals sent from the PT. Under this context, we propose an inter-system coordination protocol that enables acquisition at the ST of side information for interference management purposes. We also develop an alternating optimization algorithm based on semi-definite relaxation (SDR) to jointly design the active and passive beamforming vectors, so that the weighted sum-power at the energy harvesting receivers (EHR) of the secondary system is maximized subject to the quality-of-service (QoS) and interference constraints of the IDRs and the PRs, respectively. Finally, we derive low-complexity sub-optimal solutions based on fixed transmit precoding schemes. Numerical simulation results highlight the performance gains of the proposed designs over benchmark strategies and provide insights regarding the impact of various parameters on system performance.

Index Terms—Underlay spectrum sharing, simultaneous wireless information and power transfer (SWIPT), intelligent reflecting surface (IRS), joint active/passive beamforming optimization, inter-system coordination.

I. INTRODUCTION

The commercialization of the 5th generation (5G) standard for wireless communication has been followed by a proliferation of energy-constrained terminals, such as smartphones and Internet-of-Things (IoT) nodes, along with a rapid growth of the mobile data traffic volume [1], [2]. Energy-demanding tasks, such as video streaming and federated learning [3], can quickly drain the battery of these devices, while the apparent spectral scarcity can lead to bottlenecks. These trends urge us to combine simultaneous wireless information and power transfer (SWIPT) with spectrum underlay. The former paradigm integrates wireless power supply in the downlink (DL) to prolong the limited lifetime of such low-power user equipment and ensure uninterrupted operation [4], whereas the latter one virtually extends the spectrum via the concurrent use of licensed bands by colocated systems to facilitate the accommodation of the increased traffic levels [5]. The emerging private networks for industrial IoT represent a characteristic use case [6].

Intelligent reflecting surface (IRS) can enable the realization of this vision. This novel technology refers to a planar surface

consisting of a massive number of low-cost, passive reflecting elements that can independently introduce each a controllable phase shift to incident radio signals [7]. Hence, we can effectively suppress the interference at non-intended users and boost the received signal power at target users, thereby compensating for the deterioration of the energy harvesting (EH) efficiency and the data rate by the distance-dependent path loss and the incurred interference, respectively, in a cost- and energy-efficient manner. This is accomplished through passive beamforming, i.e., via joint adjustment of the IRS phase shifts.

In [8], [9], the authors consider an IRS-aided multiple-input single-output (MISO) broadcast setup for SWIPT with separate information decoding and EH receivers (IDR/EHR) and develop alternating optimization algorithms based on the semi-definite relaxation (SDR) method to jointly optimize the transmit (active) and reflect (passive) beamforming schemes, so that the minimum radio frequency (RF) power or the weighted sum-power at the EHRs, respectively, is maximized. In [10], on the other hand, they utilize penalty-based methods to minimize the transmit sum-power. The study [11] proposes an SDR-based algorithm to maximize the rate of a secondary MISO link that is colocated with multiple single-antenna primary receivers (PR). In [12], the authors derive an outage-constrained robust design against imperfect channel state information (CSI) regarding the effective secondary transmitter (ST)–PR link by solving second order cone programming (SOCP) problems to minimize the transmit power of a secondary MISO broadcast system that coexists with a single-antenna PR.

However, the combination of IRS-aided SWIPT with IRS-assisted spectrum underlay has not been investigated yet, to the best of our knowledge. Our main goal in this paper is to fill in this blank in the literature. Specifically, we consider a secondary IRS-aided multi-user MISO setup for SWIPT that is colocated with a primary MISO broadcast system. Under this context, we develop an SDR-based alternating optimization algorithm to jointly design the transmit precoding vectors and the IRS phase shifts, so that the weighted sum-power at the EHRs is maximized. We also derive low-complexity sub-optimal schemes based on linear precoding heuristics.

The contributions of this work that set it apart from prior relevant studies, on top of the study of IRS-aided SWIPT in a spectrum underlay regime as dictated by the aforementioned trends, are the following: i) We propose an inter-system coordination protocol that enables acquisition of side information at the ST for interference management purposes. ii) We take

into account in our design the additional “cascaded” inter-user- and self-interference (CIUSI) at the PRs attributed to the transmissions of interfering and useful data signals, respectively, from the spectrum-sharing-agnostic primary transmitter (PT) that reach these nodes via the corresponding cascaded PT-IRS-PR channels. iii) We consider the effect of the reverse inter-system interference (RISI) at the IDRs/EHRs induced by the PT, which is often ignored.

Numerical simulations reveal the performance gains of the proposed designs over benchmark strategies and provide insights on the performance impact of various parameters.

The remainder of the paper is organized as follows: Sec. II introduces the system and channel models and presents the proposed inter-system coordination protocol. Sec. III focuses on the proposed SDR-based scheme and iterative algorithm, as well as on the low-complexity sub-optimal alternatives based on linear precoding heuristics. Finally, Sec. IV presents the numerical simulation results and Sec. V provides the summary of this work, our conclusions, and a discussion regarding possible future extensions of this study.

Notation: x or X : a scalar; $\mathbf{x}$: a column vector; $\mathbf{X}$: a matrix; $\|\cdot\|$: the Euclidean norm; $(\cdot)^*$, $(\cdot)^T$, $(\cdot)^\dagger$, $(\cdot)^{-1}$, and $\text{Tr}(\cdot)$: the complex conjugate, transpose, complex conjugate transpose, and trace operators; $\text{diag}(\mathbf{x})$: a diagonal matrix with $\mathbf{x}$ on the main diagonal; $\text{diag}(\mathbf{X})$: a vector that is the main diagonal of $\mathbf{X}$; $\mathbf{X} \succeq \mathbf{0}$: a positive semi-definite (PSD) matrix; $\mathbf{0}_N$: the N -dimensional null vector; $\mathbf{I}_N$: the $N \times N$ identity matrix; $\mathcal{CN}(\cdot, \cdot)$: the circularly symmetric complex Gaussian distribution; $\mathbb{E}\{\cdot\}$: the expectation operator.

II. COORDINATION PROTOCOL AND SYSTEM MODEL

A. System Setup and Channel Model

The secondary system consists of a ST with M antennas that serves K_I active single-antenna IDRs and K_E active single-antenna EHRs on a single time-frequency resource with the assistance of an IRS that has N reflecting elements, as shown in Fig. 1. The primary system, in turn, is comprised by a PT with L antennas that serves U active single-antenna PRs over the respective MISO broadcast channel. Each transmitter is linked with each receiver via both a direct and an IRS-cascaded intra- or inter-system channel. These collocated systems operate over shared spectrum in time-division duplex (TDD) mode; thus, pilot-assisted reciprocity-based channel estimation applies universally, given that the IRS operates in full-duplex mode. We use the indexes $i \in \mathcal{K}_I \triangleq \{1, \dots, K_I\}$, $j \in \mathcal{K}_E \triangleq \{1, \dots, K_E\}$, and $u \in \mathcal{U} \triangleq \{1, \dots, U\}$ for the IDRs, EHRs, and PRs, respectively, unless it is explicitly stated otherwise.

The notation of the incident ST-IRS and PT-IRS; the direct ST-IDR i , ST-EHR j , ST-PR u , PT-PR u , PT-IDR i , and PT-EHR j ; and the reflect IRS-IDR i , IRS-EHR j , and IRS-PR u baseband channels is given in Fig. 1.

Let $\mathbf{v} = [v_1, \dots, v_N]^\dagger \in \mathbb{C}^N$ with $v_n = \alpha_n e^{j\theta_n}$ be the passive beamforming vector of the IRS, where $\alpha_n \in [0, 1]$ and $\theta_n \in [0, 2\pi)$ represent the reflection amplitude and phase shift, respectively, of the n -th IRS element, $n \in \mathcal{N} \triangleq \{1, \dots, N\}$.

We set the reflection amplitudes to unity, to maximize the received signal strength, i.e., $\alpha_n = |v_n| = 1$, $\forall n$. The cascaded ST-IRS-IDR i , ST-IRS-EHR j , and ST-IRS-PR u baseband channels, $\mathbf{H}_i \in \mathbb{C}^{N \times M}$, $\mathbf{G}_j \in \mathbb{C}^{N \times M}$, and $\mathbf{V}_u \in \mathbb{C}^{N \times M}$, as well as the respective effective baseband channels, $\mathbf{h}_i^\dagger \in \mathbb{C}^M$, $\mathbf{g}_j^\dagger \in \mathbb{C}^M$, and $\mathbf{v}_u^\dagger \in \mathbb{C}^M$, are defined as $\mathbf{H}_i \triangleq \text{diag}(\mathbf{h}_{r,i}^\dagger) \mathbf{H}$, $\mathbf{h}_i^\dagger \triangleq \mathbf{h}_{d,i}^\dagger + \mathbf{v}^\dagger \mathbf{H}_i$; $\mathbf{G}_j \triangleq \text{diag}(\mathbf{g}_{r,j}^\dagger) \mathbf{H}$, $\mathbf{g}_j^\dagger \triangleq \mathbf{g}_{d,j}^\dagger + \mathbf{v}^\dagger \mathbf{G}_j$; and $\mathbf{V}_u \triangleq \text{diag}(\mathbf{z}_{r,u}^\dagger) \mathbf{H}$, $\mathbf{v}_u^\dagger \triangleq \mathbf{v}_{d,u}^\dagger + \mathbf{v}^\dagger \mathbf{V}_u$. Similarly, the cascaded PT-IRS-PR u , PT-IRS-IDR i , and PT-IRS-EHR j baseband channels, $\mathbf{Z}_u \in \mathbb{C}^{N \times L}$, $\mathbf{U}_i \in \mathbb{C}^{N \times L}$, and $\mathbf{T}_j \in \mathbb{C}^{N \times L}$, as well as the respective effective baseband channels, $\mathbf{z}_u^\dagger \in \mathbb{C}^L$, $\mathbf{u}_i^\dagger \in \mathbb{C}^L$, and $\mathbf{t}_j^\dagger \in \mathbb{C}^L$, are defined as $\mathbf{Z}_u \triangleq \text{diag}(\mathbf{z}_{r,u}^\dagger) \mathbf{Z}$, $\mathbf{z}_u^\dagger \triangleq \mathbf{z}_{d,u}^\dagger + \mathbf{v}^\dagger \mathbf{Z}_u$; $\mathbf{U}_i \triangleq \text{diag}(\mathbf{h}_{r,i}^\dagger) \mathbf{Z}$, $\mathbf{u}_i^\dagger \triangleq \mathbf{u}_{d,i}^\dagger + \mathbf{v}^\dagger \mathbf{U}_i$; and $\mathbf{T}_j \triangleq \text{diag}(\mathbf{g}_{r,j}^\dagger) \mathbf{Z}$, $\mathbf{t}_j^\dagger \triangleq \mathbf{t}_{d,j}^\dagger + \mathbf{v}^\dagger \mathbf{T}_j$.

We assume quasi-static, frequency-flat, Rayleigh fading channels, except for the ST-EHR j , IRS-EHR j , and ST-IRS links, which are modeled as Rician fading channels due to the nodes’ adjacency [13], [14]. The path loss is modeled as $L = C_0 (d/d_0)^{-\gamma}$, where C_0 is the path loss at the reference distance $d_0 = 1$ m, d represents the separation distance between the nodes at the two ends of the considered link, and γ denotes the path loss exponent.

B. Inter-System Coordination Protocol

The system operation is divided in an uplink (UL) training and channel estimation phase followed by a DL information and energy transfer phase. It is assumed that the transmissions of the nodes in each system are synchronized, regardless of the operation phase. Next, we describe the proposed inter-system coordination protocol: i) The UL operation is further divided into two sub-phases. In the first one, the ST selects a predetermined passive beamforming vector $\tilde{\mathbf{v}} \in \mathbb{C}^N$ that is applied at the IRS and shares the knowledge of this vector with the PT. In the second sub-phase, on the other hand, the IRS is switched off, i.e., we set $\alpha_n = 0$, $\forall n$. ii) In each sub-phase, the PRs send known pilot signals to both the ST and the PT. Similarly, the IDRs and the EHRs send known pilot signals to the ST. Thus, the total number of pilots is $K_I + K_E + 2U$. These pilots enable the estimation of the respective effective (sub-phase 1) and direct (sub-phase 2) channels at the transmitters, which then compute the corresponding IRS-cascaded channels. Finally, the PT forwards the U cascaded PT-IRS-PRs channels ($N \times L$ matrices) to the ST and the U PRs share their interference power thresholds (IPT) with the ST.

C. System Model

The vector signals transmitted by the ST and the PT, $\mathbf{x}_{\text{ST}} \in \mathbb{C}^M$ and $\mathbf{x}_{\text{PT}} \in \mathbb{C}^L$, respectively, are given by

$$\mathbf{x}_{\text{ST}} = \sum_{i \in \mathcal{K}_I} \mathbf{w}_i s_i; \quad \mathbf{x}_{\text{PT}} = \sum_{u \in \mathcal{U}} \mathbf{f}_u c_u, \quad (1)$$

Fig. 1. System setup and channels.

where $\mathbf{w}_i \in \mathbb{C}^M$ and $\mathbf{f}_u \in \mathbb{C}^L$ denote the transmit precoding vectors assigned to IDR i and PR u , respectively, whereas $s_i \in \mathbb{C}$, which has zero mean and unit variance, and $c_u \sim \mathcal{CN}(0, 1)$ refer to the independent and identically distributed (i.i.d.) transmitted symbols destined for these users.

The complex baseband representation of the received signals at IDR i , EHR j , and PR u is given by $y_i^{\text{IDR}} = \mathbf{h}_i^{\dagger} \mathbf{x}_{\text{ST}} + \mathbf{u}_i^{\dagger} \mathbf{x}_{\text{PT}} + n_i$; $y_j^{\text{EHR}} = \mathbf{g}_j^{\dagger} \mathbf{x}_{\text{ST}} + \mathbf{t}_j^{\dagger} \mathbf{x}_{\text{PT}} + z_j$; and $y_u^{\text{PR}} = \mathbf{z}_u^{\dagger} \mathbf{x}_{\text{PT}} + \mathbf{v}_u^{\dagger} \mathbf{x}_{\text{ST}} + w_u$, where $\{n_i, z_j, w_u\}$ represents the zero-mean complex Gaussian noise at IDR i , EHR j , and PR u , respectively, with variance $\sigma_{x,y}^2$, where $\{x, y\} = \{\{n, i\}, \{z, j\}, \{w, u\}\}$.

Hence, by defining $I_i \triangleq \sum_{u \in \mathcal{U}} |\mathbf{u}_i^{\dagger} \mathbf{f}_u|^2 + \sigma_{n,i}^2$, the signal-to-interference-plus-noise-ratio (SINR) at IDR i is given by

$$\text{SINR}_i = \frac{|\mathbf{h}_i^{\dagger} \mathbf{w}_i|^2}{\sum_{k \in \mathcal{K}_I \setminus \{i\}} |\mathbf{h}_i^{\dagger} \mathbf{w}_k|^2 + I_i}, \quad (2)$$

while by defining $\hat{I}_j \triangleq \sum_{u \in \mathcal{U}} |\mathbf{t}_j^{\dagger} \mathbf{f}_u|^2$ and ignoring the negligible noise power, the RF power at EHR j writes as

$$E_j = \sum_{i \in \mathcal{K}_I} |\mathbf{g}_j^{\dagger} \mathbf{w}_i|^2 + \hat{I}_j. \quad (3)$$

The forward ISI (FISI) and CIUSI power at PR u is:

$$P_F^{(u)} = \sum_{i \in \mathcal{K}_I} |\mathbf{v}_u^{\dagger} \mathbf{w}_i|^2; \quad P_C^{(u)} = \sum_{q \in \mathcal{U}} |\mathbf{v}_u^{\dagger} \mathbf{Z}_u \mathbf{f}_q|^2. \quad (4)$$

III. PROPOSED BEAMFORMING SCHEME AND HEURISTICS

Since we cannot control the transmissions of the PT, we consider $\tilde{E}_j \triangleq \sum_{i \in \mathcal{K}_I} |\mathbf{g}_j^{\dagger} \mathbf{w}_i|^2$ as the effective received RF power at EHR j for our optimization purposes. Let $\omega_j \geq 0$ be the energy priority weight of EHR j and let us define $\mathbf{S} \in \mathbb{C}^{M \times M}$ as $\mathbf{S} \triangleq \sum_{j \in \mathcal{K}_E} \omega_j \mathbf{g}_j \mathbf{g}_j^{\dagger}$. Then, the optimization problem under study is formulated as:

$$(\text{P1}): \max_{\{\mathbf{w}_i\}, \mathbf{v}} \sum_{i \in \mathcal{K}_I} \mathbf{w}_i^{\dagger} \mathbf{S} \mathbf{w}_i \quad (5a)$$

$$\text{s.t.} \quad \frac{|\mathbf{h}_i^{\dagger} \mathbf{w}_i|^2}{\sum_{k \in \mathcal{K}_I \setminus \{i\}} |\mathbf{h}_i^{\dagger} \mathbf{w}_k|^2 + I_i} \geq \Gamma_i, \quad (5b)$$

$$\sum_{i \in \mathcal{K}_I} |\mathbf{v}_u^{\dagger} \mathbf{w}_i|^2 \leq P_I^{(u)}, \quad (5c)$$

$$\sum_{q \in \mathcal{U}} |\mathbf{v}_u^{\dagger} \mathbf{Z}_u \mathbf{f}_q|^2 \leq P_{\text{Th}}, \quad (5d)$$

$$\sum_{i \in \mathcal{K}_I} \|\mathbf{w}_i\|^2 \leq P_T, \quad (5e)$$

$$|v_n|^2 = 1, \quad \forall n \in \mathcal{N}, \quad (5f)$$

where Eqs. (5b)–(5f) refer to the SINR constraints of the IDRs, the FISI and CIUSI constraints of the PRs, the transmit sum-power constraint of the ST, and the unit-modulus constraints of the IRS phase shifts, whereas $\Gamma_i > 0$ and $P_I^{(u)} > 0$ denote the minimum required SINR at IDR i and the IPT of PR u , respectively, P_{Th} represents the (arbitrarily small) CIUSI threshold of each PR, and $P_T > 0$ stands for the transmit power budget of the ST. In order to tackle this challenging non-convex optimization problem, we develop an alternating maximization algorithm that iteratively updates the transmit and reflect beamforming vectors with the aid of the SDR method.

A. Transmit Precoding Vectors Optimization

For fixed $\mathbf{v}$, problem (P1) becomes:

$$(\text{P2}): \max_{\{\mathbf{w}_i\}} \sum_{i \in \mathcal{K}_I} \mathbf{w}_i^{\dagger} \mathbf{S} \mathbf{w}_i \quad \text{s.t. Eqs. (5b), (5c), (5e)}. \quad (6)$$

In order to solve this non-convex optimization problem, we apply the SDR method, i.e., we introduce rank-one PSD matrix variables $\mathbf{W}_i \in \mathbb{C}^{M \times M}$ defined as $\mathbf{W}_i \triangleq \mathbf{w}_i \mathbf{w}_i^{\dagger}$ and then we relax the non-convex rank-one constraints to obtain:

$$(\text{P3}): \max_{\{\mathbf{W}_i\}} \sum_{i \in \mathcal{K}_I} \text{Tr}(\mathbf{S} \mathbf{W}_i) \quad (7a)$$

$$\text{s.t.} \quad \frac{\text{Tr}(\mathbf{h}_i \mathbf{h}_i^{\dagger} \mathbf{W}_i)}{\sum_{k \in \mathcal{K}_I \setminus \{i\}} \text{Tr}(\mathbf{h}_i \mathbf{h}_i^{\dagger} \mathbf{W}_k) + I_i} \geq \frac{\Gamma_i}{1 + \Gamma_i}, \quad (7b)$$

$$\sum_{i \in \mathcal{K}_I} \text{Tr}(\mathbf{v}_u \mathbf{v}_u^{\dagger} \mathbf{W}_i) \leq P_I^{(u)}, \quad (7c)$$

$$\sum_{i \in \mathcal{K}_I} \text{Tr}(\mathbf{W}_i) \leq P_T, \quad (7d)$$

$$\mathbf{W}_i \succeq \mathbf{0}. \quad (7e)$$

(P3) is a convex semi-definite programming (SDP) problem. Thus, it can be solved in polynomial time by convex optimization software that utilizes interior-point methods, such as CVX [15].

B. Reflect Beamforming Vector Optimization

For given transmit precoding vectors $\{\mathbf{w}_i\}$, problem (P1) reduces to:

$$(P4): \max_{\mathbf{v}} \sum_{j \in \mathcal{K}_E} \omega_j \sum_{i \in \mathcal{K}_I} |\mathbf{g}_j^\dagger \mathbf{w}_i|^2 \quad (8a)$$

$$\text{s.t. Eqs. (5b)–(5d), Eq. (5f).} \quad (8b)$$

Let us define $\{a_{i,k}, b_{u,i}, c_{j,i}\} \in \mathbb{C}$, $\{\mathbf{a}_{i,k}, \mathbf{b}_{u,i}, \mathbf{c}_{j,i}, \mathbf{d}_{u,q}\} \in \mathbb{C}^N$, $\{\Phi_{i,k}, \Psi_{u,i}, \Lambda_{j,i}, \Omega_{u,q}\} \in \mathbb{C}^{\bar{N} \times \bar{N}}$, and $\bar{\mathbf{v}} \in \mathbb{C}^{\bar{N}}$ as

$$a_{i,k} \triangleq \mathbf{h}_{d,i}^\dagger \mathbf{w}_k; \quad \mathbf{a}_{i,k} \triangleq \mathbf{H}_i \mathbf{w}_k, \quad (9a)$$

$$b_{u,i} \triangleq \mathbf{v}_{d,u}^\dagger \mathbf{w}_i; \quad \mathbf{b}_{u,i} \triangleq \mathbf{V}_u \mathbf{w}_i, \quad (9b)$$

$$c_{j,i} \triangleq \mathbf{g}_{d,j}^\dagger \mathbf{w}_i; \quad \mathbf{c}_{j,i} \triangleq \mathbf{G}_j \mathbf{w}_i, \quad (9c)$$

$$\mathbf{d}_{u,q} \triangleq \mathbf{Z}_u \mathbf{f}_q, \quad (9d)$$

$$\Phi_{i,k} \triangleq [\mathbf{a}_{i,k} \mathbf{a}_{i,k}^\dagger, \mathbf{a}_{i,k} \mathbf{a}_{i,k}^*; \mathbf{a}_{i,k}^\dagger a_{i,k}, 0], \quad (9e)$$

$$\Psi_{u,i} \triangleq [\mathbf{b}_{u,i} \mathbf{b}_{u,i}^\dagger, \mathbf{b}_{u,i} \mathbf{b}_{u,i}^*; \mathbf{b}_{u,i}^\dagger b_{u,i}, 0], \quad (9f)$$

$$\Lambda_{j,i} \triangleq [\mathbf{c}_{j,i} \mathbf{c}_{j,i}^\dagger, \mathbf{c}_{j,i} \mathbf{c}_{j,i}^*; \mathbf{c}_{j,i}^\dagger c_{j,i}, 0], \quad (9g)$$

$$\Omega_{u,q} \triangleq [\mathbf{d}_{u,q} \mathbf{d}_{u,q}^\dagger, \mathbf{0}_N; \mathbf{0}_N, 0], \quad (9h)$$

$$\bar{\mathbf{v}} \triangleq [\mathbf{v}; 1], \quad (9i)$$

where $k \in \mathcal{K}_I$, $q \in \mathcal{U}$, and $\bar{N} \triangleq N + 1$. Next, we employ the SDR method, i.e., we introduce the rank-one PSD matrix variable $\mathbf{V} \in \mathbb{C}^{\bar{N} \times \bar{N}}$ defined as $\mathbf{V} \triangleq \bar{\mathbf{v}} \bar{\mathbf{v}}^\dagger$ and drop the non-convex rank-one constraint to obtain the following convex SDP problem, that can be efficiently solved by CVX:

$$(P5): \max_{\mathbf{V}} \sum_{j \in \mathcal{K}_E} \omega_j \sum_{i \in \mathcal{K}_I} \left(\text{Tr}(\Lambda_{j,i} \mathbf{V}) + |c_{j,i}|^2 \right) \quad (10a)$$

$$\text{s.t. } \text{Tr}(\Phi_{k,k} \mathbf{V}) + |a_{k,k}|^2 \geq \Gamma_i \left(\sum_{k \in \mathcal{K}_I \setminus \{i\}} \left(\text{Tr}(\Phi_{i,k} \mathbf{V}) + |a_{i,k}|^2 \right) + I_i \right), \quad (10b)$$

$$\sum_{i \in \mathcal{K}_I} \left(\text{Tr}(\Psi_{u,i} \mathbf{V}) + |b_{u,i}|^2 \right) \leq P_I^{(u)}, \quad (10c)$$

$$\sum_{q \in \mathcal{U}} \text{Tr}(\Omega_{u,q} \mathbf{V}) \leq P_{Th}, \quad (10d)$$

$$\mathbf{V}_{n,n} = 1, \quad n = 1, \dots, \bar{N}; \quad \mathbf{V} \succeq \mathbf{0}. \quad (10e)$$

C. Alternating Optimization Algorithm

In summary, in order to solve problem (P1), we alternating solve the SDR problems (P3) and (P5) in an iterative fashion, starting from the former, until we reach convergence or infeasibility arises. If the optimal solution of these problems is of rank one, then we can recover the optimal solution of the corresponding original problems (P2) and (P4) via eigen-value decomposition; otherwise, we can use Gaussian randomization

to obtain a sub-optimal, solution that guarantees an at least $\pi/4$ -approximation of the optimal objective value of (P1) [16].

D. Sub-Optimal Beamforming Schemes

In order to reduce the complexity associated with SDP, we consider sub-optimal linear precoding heuristics. Thus, we decompose the transmit precoding vectors as $\mathbf{w}_i = \sqrt{P_i} \bar{\mathbf{w}}_i$, where P_i denotes the power allocated to IDR i and $\bar{\mathbf{w}}_i$ represents the fixed power-normalized transmit beamforming direction, i.e., $\|\bar{\mathbf{w}}_i\|^2 = 1$. Let $H_{i,k} \triangleq |\mathbf{h}_i^\dagger \bar{\mathbf{w}}_k|^2$, $V_{u,i} \triangleq |\mathbf{v}_u^\dagger \bar{\mathbf{w}}_i|^2$, and $G_{j,i} \triangleq \omega_j |\mathbf{g}_j^\dagger \bar{\mathbf{w}}_i|^2$. Then, problem (P2) is reduced to the following convex problem:

$$(P6): \max_{\{P_i \geq 0\}} \sum_{j \in \mathcal{K}_E} \sum_{i \in \mathcal{K}_I} G_{j,i} P_i \quad (11a)$$

$$\text{s.t. } \left(\frac{1}{\Gamma_i + 1} \right) H_{i,i} P_i \geq \sum_{k \in \mathcal{K}_I \setminus \{i\}} H_{i,k} P_k + I_i, \quad (11b)$$

$$\sum_{i \in \mathcal{K}_I} V_{u,i} P_i \leq P_I^{(u)}, \quad (11c)$$

$$\sum_{i \in \mathcal{K}_I} P_i \leq P_T. \quad (11d)$$

E. Complexity Analysis

The complexity of problems (P3) and (P5) is dominated by the SDP constraints and is given by $\mathcal{O}(\sqrt{K_I M} (K_I^3 M^2 + K_I^2 M^3))$ and $\mathcal{O}(\sqrt{\bar{N}} (\bar{N}^2 + \bar{N}^3))$, respectively, while that of problem (P6) is dominated by the linear constraints and is given by $\mathcal{O}(\sqrt{3K_I + U} (3K_I^3 + UK_I^2))$ [17].

IV. NUMERICAL RESULTS

The EHR, IDR, and PR clusters have a radius of 2 m and their centers are located at (10,0), (40,0), and (50,0), respectively, while the ST, PT, and IRS are placed at (0,0), (90,0), and (10,10), respectively. (All values are in meters.) We assume that $M = L = 8$, $K_I = K_E = U = 2$, and $N = 64$. The path loss exponent is 2.2 for the ST-IRS, PT-IRS, ST-EHRs, and IRS-receivers links and 3.6 for any other link, whereas the mean path loss at reference distance $d_0 = 1$ m is $C_0 = -30$ dB. The Rician factors are 5 dB. We set $\omega_j = 1$, $\forall j \in \mathcal{K}_E$, $P_T = 2$ W, $\Gamma_i = \Gamma$, $\forall i \in \mathcal{K}_I$, and $P_{Th} = 10^{-6}$. We also set the noise power at -90 dBm for all receivers and the (relative to the noise power) IPT of each PR to 0 dB. The carrier frequency is 750 MHz. We compare the proposed scheme with the case where the secondary system is isolated, as well as with the cases where random IRS phase shifts are applied or where there is no IRS deployed, assuming either a spectrum underlay setup or a stand-alone secondary system as previously.

In Fig. 2, we compare the performance of the proposed scheme vs. the aforementioned benchmark strategies for varying SINR targets, while in Fig. 3 we comparatively evaluate it against various fixed precoding alternatives—namely, maximum ratio transmission (MRT), zero forcing (ZF), and

Fig. 2. Weighted sum-power vs. SINR threshold.

MRT/ZF, wherein the precoding vectors are linear combinations of the respective MRT and ZF vectors [17]—for varying number of IRS elements. We note that the proposed optimal scheme outperforms the other strategies as well as that the IRS enhances the performance of the system, while the use of random IRS phase shifts is essentially the same as not using an IRS. The performance gains of the IRS become more prominent for larger number of reflecting elements. The adaptation to the interference constraints incurs some performance degradation. Also, it is challenging to achieve the performance goal for stringent SINR requirements. Finally, MRT/ZF outperforms MRT, although it cancels part of the interference (which acts as additional energy source), because it “frees-up” degrees-of-freedom of the IRS through interference suppression. ZF precoding presents the worse performance.

V. SUMMARY

In this paper, we studied the joint active/passive beamforming design for an IRS-aided MISO SWIPT system in a spectrum underlay regime, taking into account the CIUSI and the RISI. We proposed an inter-system coordination protocol and developed an SDR-based design. We also derived low-complexity sub-optimal schemes based on fixed transmit precoding heuristics. Numerical simulations highlighted the performance gains of the proposed scheme over benchmark strategies, corroborated the beneficial role of the IRS, and provided insights regarding the impact of the QoS constraints on system performance. In the future, we plan to extend this work by deriving a robust design against imperfect CSI.

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Fig. 3. Weighted sum-power vs. the number of IRS elements.

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