MULTIUSER MISO BEAMFORMING FOR SIMULTANEOUS WIRELESS INFORMATION AND POWER TRANSFER

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ABSTRACT

This paper studies a multiuser multiple-input single-output (MISO) broadcast system for simultaneous wireless information and power transfer (SWIPT), where a multi-antenna access point (AP) sends information and energy simultaneously via beamforming to multiple single-antenna receivers. We maximize the weighted sum-power transferred to energy harvesting (EH) receivers subject to a set of minimum signal-to-interference-and-noise ratio (SINR) constraints at information decoding (ID) receivers. In particular, we consider two types of ID receivers, namely Type I and Type II receivers, without and with the capability of cancelling the interference from energy signals, respectively. For each type of ID receivers, we formulate the joint information and energy transmit beamforming problem as a non-convex quadratically constrained quadratic program (QCQP), for which the globally optimal solution is obtained by applying the technique of semidefinite relaxation (SDR). It is shown that for Type I ID receivers, dedicated energy beamforming is not needed to achieve the optimal solution, while for Type II ID receivers, employing no more than one energy beam is optimal.

***Index Terms*—** Wireless power, simultaneous wireless information and power transfer (SWIPT), energy harvesting, beamforming, semidefinite relaxation (SDR).

1. INTRODUCTION

Harvesting energy from the environment is a promising solution to achieve an energy neutralization goal for energy constrained wireless networks. Among other harvestable energy sources such as wind and solar, ambient radio signals can be a viable new source for wireless energy harvesting. On the other hand, radio signals have been widely used for wireless information transmission. Hence, simultaneous wireless information and power transfer (SWIPT) is an emerging research area that receives increasing attention.

SWIPT for point-to-point single-antenna channels has been studied in [1–3], where the rate-energy tradeoffs in wireless information and power transfer were characterized under different channel setups. Motivated by the great success of multi-antenna techniques in wireless communication, SWIPT for multiple-input multiple-output (MIMO) channels has been investigated in [4–6] and [7] for wireless broadcast and relay systems, respectively, but limited to the case with only two information/energy receivers.

However, in order to implement SWIPT practically, there are remaining challenges. For example, practical wireless information and energy receivers operate with very different power sensitivity (e.g., -10dBm for energy receivers versus -60dBm for information receivers). Furthermore, practical circuits for wireless energy harvesting are not yet able to decode the information directly and vice versa. To tackle these challenges, in this paper we propose a multi-antenna

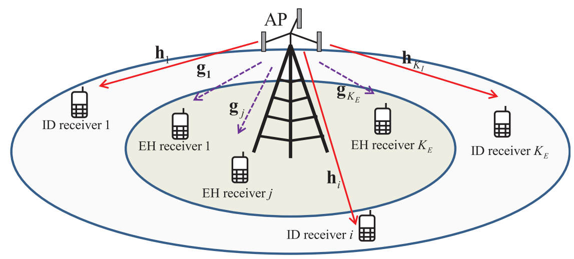

Fig. 1. A MISO broadcast system for simultaneous wireless information and power transfer (SWIPT).

or multiple-input single-output (MISO) broadcast system for SWIPT as shown in Fig. 1. In this system, a multi-antenna access point (AP) transmits simultaneously to multiple (more than two) single-antenna receivers for either information decoding (ID) or energy harvesting (EH). To exploit the "near-far" channel conditions in the multiuser system, receivers near the AP are scheduled for EH while receivers more distant from the AP are scheduled for ID. This scheduling rule is designed to be consistent with the difference in receive power requirements for EH and ID receivers. Furthermore, the multi-antenna AP sends both information and energy at the same time with properly designed beamforming weights and power control to balance the tradeoffs between information and energy broadcasting. Under this setup, we study the joint information and energy transmit beamforming design to maximize the weighted sum-power transferred to EH receivers subject to a set of minimum signal-to-interference-and-noise ratio (SINR) constraints for ID receivers. In particular, we consider two types of ID receivers, namely *Type I* and *Type II* receivers, *without* and *with* the capability of cancelling the interference from energy signals, respectively. For each type of ID receivers, the optimization problem is formulated as a non-convex quadratically constrained quadratic program (QCQP), for which the globally optimal solution is obtained by applying the technique of semidefinite relaxation (SDR). Interestingly, it is shown that for Type I ID receivers, dedicated energy beamforming is not needed to achieve the optimal solution, while for Type II ID receivers, employing no more than one energy beam is optimal.

2. SYSTEM MODEL AND PROBLEM FORMULATION

We consider a multiuser MISO downlink system for SWIPT over one single frequency band as shown in Fig. 1. It is assumed that there are K_I ID receivers and K_E EH receivers, denoted by $\mathcal{K_I} = \{1, \ldots, K_I\}$ and $\mathcal{K_E} = \{1, \ldots, K_E\}$, respectively. Suppose that the AP is equipped with M antennas, $M > 1$, and each receiver is equipped with one single antenna. In this paper, we consider linear beamforming at the transmitter for SWIPT and each ID/EH receiver is assigned with one dedicated information/energy beam without loss of generality. Hence, the transmitted signal from the AP is given by

$$\boldsymbol{x} = \sum_{i\in\mathcal{K}_\mathcal{I}} \boldsymbol{w}_i s_i^{\mathrm{ID}} + \sum_{j\in\mathcal{K}_\mathcal{E}} \boldsymbol{v}_j s_j^{\mathrm{EH}}, \tag{1}$$

where $\boldsymbol{w}_i \in \mathbb{C}^{M\times 1}$ and $\boldsymbol{v}_j \in \mathbb{C}^{M\times 1}$ are the beamforming vectors for ID receiver i and EH receiver j, respectively; s_i^{ID} and s_j^{EH} are the information-bearing signal for ID receiver i and energy-carrying signal for EH receiver j, respectively. For information signals, Gaussian inputs are assumed, i.e., s_i^{ID}'s are independent and identically distributed (i.i.d) circularly symmetric complex Gaussian (CSCG) random variables each with zero mean and unit variance, denoted by $s_i^{\mathrm{ID}} \sim \mathcal{CN}(0,1), \forall i \in \mathcal{K}_\mathcal{I}$. For energy signals, since s_j^{EH} carries no information, it can be any arbitrary random signal provided that its power spectral density satisfies certain regulations on microwave radiation. Without loss of generality, we assume that s_j^{EH}'s are independent white sequences from an arbitrary distribution with $\mathbb{E}\left(|s_j^{\mathrm{EH}}|^2\right) = 1, \forall j \in \mathcal{K}_\mathcal{E}$, where $\mathbb{E}(\cdot)$ denotes the expectation and $|\cdot|$ denotes the absolute value. It is further assumed that s_i^{ID}'s and s_j^{EH}'s are independent. Suppose that the AP has a transmit sum-power constraint P; from (1) we have $\mathbb{E}(\boldsymbol{x}^H\boldsymbol{x}) = \sum_{i\in\mathcal{K}_\mathcal{I}} \|\boldsymbol{w}_i\|^2 + \sum_{j\in\mathcal{K}_\mathcal{E}} \|\boldsymbol{v}_j\|^2 \le P$, where $\|\cdot\|$ denotes the Euclidean norm of a complex vector.

We assume a quasi-static fading environment and denote $\boldsymbol{h}_i \in \mathbb{C}^{1\times M}$ and $\boldsymbol{g}_j \in \mathbb{C}^{1\times M}$ as the channel vectors from the AP to ID receiver i and EH receiver j, respectively, where $\boldsymbol{h}_i$'s and $\boldsymbol{g}_j$'s are independently distributed. It is further assumed that the AP knows perfectly the instantaneous values of $\boldsymbol{h}_i$'s and $\boldsymbol{g}_j$'s, while each receiver knows its own instantaneous channel. The discrete-time baseband signal at the ith ID receiver is thus given by

$$y_i^{\mathrm{ID}} = \boldsymbol{h}_i\boldsymbol{x} + z_i,\ \forall i \in \mathcal{K}_\mathcal{I}, \tag{2}$$

where $z_i \sim \mathcal{CN}(0,\sigma_i^2)$ is the i.i.d Gaussian noise at the ith ID receiver. With linear transmit beamforming, each ID receiver is in general interfered with by the signals from all other non-intended information beams and energy beams. Since energy beams carry no information but only pseudorandom signals that are known at both the AP and ID receivers prior to transmission, their resulting interference can be cancelled at each ID receiver if such an operation is implemented. We thus consider two types of ID receivers, namely Type I and Type II receivers, which possess and do not possess the capability of cancelling the interference from energy signals, respectively. Therefore, for the ith ID receiver with Type I or Type II receiver, the corresponding SINR can be expressed as

$$\mathtt{SINR}_i^{(\mathrm{I})} = \frac{|\boldsymbol{h}_i\boldsymbol{w}_i|^2}{\sum\limits_{k\neq i,k\in\mathcal{K}_\mathcal{I}} |\boldsymbol{h}_i\boldsymbol{w}_k|^2 + \sum\limits_{j\in\mathcal{K}_\mathcal{E}} |\boldsymbol{h}_i\boldsymbol{v}_j|^2 + \sigma_i^2}, \forall i \in \mathcal{K}_\mathcal{I}, \tag{3}$$

$$\mathtt{SINR}_i^{(\mathrm{II})} = \frac{|\boldsymbol{h}_i\boldsymbol{w}_i|^2}{\sum\limits_{k\neq i,k\in\mathcal{K}_\mathcal{I}} |\boldsymbol{h}_i\boldsymbol{w}_k|^2 + \sigma_i^2},\ \forall i \in \mathcal{K}_\mathcal{I}. \tag{4}$$

On the other hand, for energy transfer, due to the broadcast property of wireless channels, the energy carried by all information and energy beams, i.e., both $\boldsymbol{w}_i$'s and $\boldsymbol{v}_j$'s, can be harvested at each EH receiver. As a result, the harvested power for the jth EH receiver, denoted by Q_j, is proportional to the total power received [4], i.e.,

$$Q_j = \zeta\left(\sum_{k\in\mathcal{K}_\mathcal{I}} |\boldsymbol{g}_j\boldsymbol{w}_k|^2 + \sum_{k\in\mathcal{K}_\mathcal{E}} |\boldsymbol{g}_j\boldsymbol{v}_k|^2\right),\ \forall j \in \mathcal{K}_\mathcal{E}, \tag{5}$$

where $0 < \zeta < 1$ is the energy harvesting efficiency.

Our objective is to maximize the weighted sum-power transferred to all EH receivers subject to individual SINR constraints at different ID receivers, given by $\gamma_i, i \in \mathcal{K}_\mathcal{I}$. Denote α_j as the energy weight (which can be assigned separately based on the energy need of each individual EH receiver) for EH receiver j, $\alpha_j \ge 0$, and define $\boldsymbol{G} = \zeta \sum_{j\in\mathcal{K}_\mathcal{E}} \alpha_j \boldsymbol{g}_j^H \boldsymbol{g}_j$, where the superscript H represents the conjugate transpose operation. Then from (5) the weighted sum-power harvested by EH receivers can be expressed as $\sum_{j\in\mathcal{K}_\mathcal{E}} \alpha_j Q_j = \sum_{i\in\mathcal{K}_\mathcal{I}} \boldsymbol{w}_i^H\boldsymbol{G}\boldsymbol{w}_i + \sum_{j\in\mathcal{K}_\mathcal{E}} \boldsymbol{v}_j^H\boldsymbol{G}\boldsymbol{v}_j$. Thus, the optimization problems for Type I and Type II ID receivers are formulated as

$$\begin{aligned}(\mathtt{P1})\ \max_{\{\boldsymbol{w}_i\},\{\boldsymbol{v}_j\}}\ & \sum_{i\in\mathcal{K}_\mathcal{I}} \boldsymbol{w}_i^H\boldsymbol{G}\boldsymbol{w}_i + \sum_{j\in\mathcal{K}_\mathcal{E}} \boldsymbol{v}_j^H\boldsymbol{G}\boldsymbol{v}_j \\ \mathtt{s.t.}\ & \mathtt{SINR}_i^{(\mathrm{I})} \ge \gamma_i,\ \forall i \in \mathcal{K}_\mathcal{I} \\ & \sum_{i\in\mathcal{K}_\mathcal{I}} \|\boldsymbol{w}_i\|^2 + \sum_{j\in\mathcal{K}_\mathcal{E}} \|\boldsymbol{v}_j\|^2 \le P\end{aligned}$$

and

$$\begin{aligned}(\mathtt{P2})\ \max_{\{\boldsymbol{w}_i\},\{\boldsymbol{v}_j\}}\ & \sum_{i\in\mathcal{K}_\mathcal{I}} \boldsymbol{w}_i^H\boldsymbol{G}\boldsymbol{w}_i + \sum_{j\in\mathcal{K}_\mathcal{E}} \boldsymbol{v}_j^H\boldsymbol{G}\boldsymbol{v}_j \\ \mathtt{s.t.}\ & \mathtt{SINR}_i^{(\mathrm{II})} \ge \gamma_i,\ \forall i \in \mathcal{K}_\mathcal{I} \\ & \sum_{i\in\mathcal{K}_\mathcal{I}} \|\boldsymbol{w}_i\|^2 + \sum_{j\in\mathcal{K}_\mathcal{E}} \|\boldsymbol{v}_j\|^2 \le P,\end{aligned}$$

respectively. Both problems (P1) and (P2) maximize a convex quadratic function with $\boldsymbol{G}$ being positive semidefinite, i.e., $\boldsymbol{G} \succeq \boldsymbol{0}$; thus they are in general nonconvex QCQPs [8], for which the globally optimal solutions are difficult to be found in general. Prior to solving these two problems, we first have a check on their feasibility, i.e., whether a given set of SINR constraints for ID receivers can be met under the given transmit sum-power constraint P. It can be observed from (P1) and (P2) that both problems are feasible if and only if their feasibility is guaranteed by ignoring all EH receivers, i.e., setting $\alpha_j = 0$ and $\boldsymbol{v}_j = \boldsymbol{0}, \forall j \in \mathcal{K}_\mathcal{E}$. Thus, the feasibility of both (P1) and (P2) can be verified by solving the following problem:

$$\begin{aligned}&\mathtt{find}\ \{\boldsymbol{w}_i\} \\ &\mathtt{s.t.}\ \mathtt{SINR}_i^{(\mathrm{II})} \ge \gamma_i,\ \forall i \in \mathcal{K}_\mathcal{I} \\ &\sum_{i\in\mathcal{K}_\mathcal{I}} \|\boldsymbol{w}_i\|^2 \le P.\end{aligned} \tag{6}$$

Problem (6) can be solved by the standard interior point method via transforming it into a second-order cone programming (SOCP) [9], or by an uplink-downlink duality based fixed-point iteration algorithm [10]. Hence, in the rest of this paper, we focus on the case when (P1) and (P2) are both feasible.

Moreover, consider the other extreme case with no ID receivers, i.e., $\mathcal{K}_\mathcal{I} = \phi$, in which both (P1) and (P2) are reduced to

$$\begin{aligned}\max_{\{\boldsymbol{v}_j\}}\ & \sum_{j\in\mathcal{K}_\mathcal{E}} \boldsymbol{v}_j^H\boldsymbol{G}\boldsymbol{v}_j \\ \mathtt{s.t.}\ & \sum_{j\in\mathcal{K}_\mathcal{E}} \|\boldsymbol{v}_j\|^2 \le P.\end{aligned} \tag{7}$$

Let ξ_E and $\boldsymbol{v}_E$ be the dominant eigenvalue and its corresponding eigenvector of $\boldsymbol{G}$, respectively. Then it can be verified based on a similar proof of [4, Proposition 2.1] that the optimal value of (7) is $\xi_E P$, which is attained by $\boldsymbol{v}_j^{\rm EH} = \sqrt{q_j^{\rm EH}}\boldsymbol{v}_E, j \in \mathcal{K}_\mathcal{E}$ for any set of $q_j^{\rm EH} \geq 0$ satisfying $\sum\limits_{j\in\mathcal{K}_\mathcal{E}} q_j^{\rm EH} = P$. Accordingly, all energy beams are aligned with the same direction as $\boldsymbol{v}_E$. Thus, without loss of generality, it is practically preferable to use only one energy beam, i.e., $\boldsymbol{v}_j^{\rm EH} = \sqrt{P}\boldsymbol{v}_E$ for any $j \in \mathcal{K}_\mathcal{E}$ and $\boldsymbol{v}_k^{\rm EH} = \boldsymbol{0}$, $\forall k \in \mathcal{K}_\mathcal{E}, k \neq j$. The main advantage of this single-energy-beam solution is its lowest complexity for beamforming implementation. For convenience, we refer to the beamformer $\sqrt{P}\boldsymbol{v}_E$ as the optimal energy beamformer (OeBF).

3. OPTIMAL SOLUTION

In this section, we study the two non-convex QCQPs in $(\texttt{P1})$ and $(\texttt{P2})$, and derive their optimal solutions in the general case. For non-convex QCQPs, it is known that SDR is an efficient method to obtain good approximate solutions [11]. In the following, by applying SDR and exploiting the problem structures, we show that the globally optimal solutions for both $(\texttt{P1})$ and $(\texttt{P2})$ can be obtained efficiently.

First, consider $(\texttt{P1})$ for the case of Type I ID receivers. Define the following matrices: $\boldsymbol{W}_i = \boldsymbol{w}_i\boldsymbol{w}_i^H, \forall i \in \mathcal{K}_\mathcal{I}$ and $\boldsymbol{W}_E = \sum\limits_{j\in\mathcal{K}_\mathcal{E}} \boldsymbol{v}_j\boldsymbol{v}_j^H$. Then, it follows that $\texttt{rank}(\boldsymbol{W}_i) \leq 1, \forall i \in \mathcal{K}_\mathcal{I}$, and $\texttt{rank}(\boldsymbol{W}_E) \leq \texttt{min}(M, K_E)$. By ignoring the above rank constraints on $\boldsymbol{W}_i$'s and $\boldsymbol{W}_E$, the SDR of $(\texttt{P1})$ is given by

$$
\begin{aligned}
(\texttt{SDR1}):\ \max_{\{\boldsymbol{W}_i\},\boldsymbol{W}_E}\ & \sum_{i\in\mathcal{K}_\mathcal{I}} \texttt{tr}(\boldsymbol{G}\boldsymbol{W}_i) + \texttt{tr}(\boldsymbol{G}\boldsymbol{W}_E)\\
\texttt{s.t.}\ & \frac{\texttt{tr}(\boldsymbol{h}_i^H\boldsymbol{h}_i\boldsymbol{W}_i)}{\gamma_i} - \sum_{k\neq i, k\in\mathcal{K}_\mathcal{I}} \texttt{tr}(\boldsymbol{h}_i^H\boldsymbol{h}_i\boldsymbol{W}_k)\\
& - \texttt{tr}(\boldsymbol{h}_i^H\boldsymbol{h}_i\boldsymbol{W}_E) - \sigma_i^2 \geq 0, \forall i \in \mathcal{K}_\mathcal{I},\\
& \sum_{i\in\mathcal{K}_\mathcal{I}} \texttt{tr}(\boldsymbol{W}_i) + \texttt{tr}(\boldsymbol{W}_E) \leq P,\\
& \boldsymbol{W}_i \succeq \boldsymbol{0}, \forall i \in \mathcal{K}_\mathcal{I},\ \ \boldsymbol{W}_E \succeq \boldsymbol{0}.
\end{aligned}
$$

Let the optimal solution of $(\texttt{SDR1})$ be $\boldsymbol{W}_i^\star, \forall i \in \mathcal{K}_\mathcal{I}$ and $\boldsymbol{W}_E^\star$. Then we have the following proposition.

Proposition 3.1. *For the case of Type I ID receivers, the optimal solution of* $(\texttt{SDR1})$ *satisfies:* $\texttt{rank}(\boldsymbol{W}_i^\star) = 1$, $\forall i \in \mathcal{K}_\mathcal{I}$ *and* $\texttt{rank}(\boldsymbol{W}_E^\star) \leq 1$*; furthermore, there always exists one optimal solution with* $\boldsymbol{W}_E^\star = \boldsymbol{0}$.

Proof. A sketch of the proof is provided here, while its details will be presented in the journal version of this paper [12]. First, the dual problem of $(\texttt{SDR1})$ is given by

$$
\begin{aligned}
(\texttt{SDR1.D}):\ \min_{\{\lambda_i\},\beta}\ & \beta P - \sum_{i\in\mathcal{K}_\mathcal{I}} \lambda_i\sigma_i^2\\
\texttt{s.t.}\ & \boldsymbol{A}_i \preceq \boldsymbol{0}, \forall i \in \mathcal{K}_\mathcal{I}\\
& \boldsymbol{C}_1 \preceq \boldsymbol{0},
\end{aligned}
$$

where $\boldsymbol{A}_i = \boldsymbol{G} + \frac{\lambda_i\boldsymbol{h}_i^H\boldsymbol{h}_i}{\gamma_i} - \sum\limits_{k\neq i,k\in\mathcal{K}_\mathcal{I}} \lambda_k\boldsymbol{h}_k^H\boldsymbol{h}_k - \beta\boldsymbol{I}$, $\forall i \in \mathcal{K}_\mathcal{I}$; $\boldsymbol{C}_1 = \boldsymbol{G} - \sum\limits_{k\in\mathcal{K}_\mathcal{I}} \lambda_k\boldsymbol{h}_k^H\boldsymbol{h}_k - \beta\boldsymbol{I}$; and λ_i and β are the dual variables corresponding to the ith SINR constraint and the transmit sum-power constraint in $(\texttt{SDR1})$, respectively. Since $(\texttt{SDR1})$ is convex and satisfies the Salter's condition [8], strong duality holds between $(\texttt{SDR1})$ and $(\texttt{SDR1.D})$. Let $\{\lambda_i^\star\}$ and $\beta^\star$ be the optimal solution of $(\texttt{SDR1.D})$, and the resulting $\{\boldsymbol{A}_i\}$ and $\boldsymbol{C}_1$ be $\{\boldsymbol{A}_i^\star\}$ and $\boldsymbol{C}_1^\star$, respectively. Then by complementary slackness conditions, we have

$$\texttt{tr}\left(\boldsymbol{A}_i^\star\boldsymbol{W}_i^\star\right) = 0,\ \forall i \in \mathcal{K}_\mathcal{I} \tag{8}$$

$$\texttt{tr}\left(\boldsymbol{C}_1^\star\boldsymbol{W}_E^\star\right) = 0. \tag{9}$$

Next, we prove the proposition by considering the following two cases: $\lambda_i^\star = 0, \forall i \in \mathcal{K}_\mathcal{I}$, and there exists at least one $\bar{i} \in \mathcal{K}_\mathcal{I}$ with $\lambda_{\bar{i}}^\star > 0$.

First, the case with $\lambda_i^\star = 0, \forall i \in \mathcal{K}_\mathcal{I}$, corresponds to $\boldsymbol{A}_i^\star = \boldsymbol{C}_1^\star = \boldsymbol{G} - \beta^\star\boldsymbol{I}, \forall i \in \mathcal{K}_\mathcal{I}$. In this case, it can be easily shown from (8) and (9) that $\texttt{rank}(\boldsymbol{W}_i^\star) = 1$, $\forall i \in \mathcal{K}_\mathcal{I}$ and $\texttt{rank}(\boldsymbol{W}_E^\star) \leq 1$, and there always exists an optimal solution with $\boldsymbol{W}_E^\star = \boldsymbol{0}$.

Second, for the case where there exists at least one $\bar{i} \in \mathcal{K}_\mathcal{I}$ with $\lambda_{\bar{i}}^\star > 0$, it can be shown from (8) and (9) that $\boldsymbol{W}_E^\star$ should satisfy $\left(\boldsymbol{G} - \beta^\star\boldsymbol{I}\right)\boldsymbol{W}_E^\star = \boldsymbol{0}$ and $\boldsymbol{h}_{\bar{i}}^H\boldsymbol{h}_{\bar{i}}\boldsymbol{W}_E^\star = \boldsymbol{0}$ at the same time. Due to the fact that $\boldsymbol{h}_i$'s and $\boldsymbol{g}_j$'s are independently distributed, we have $\boldsymbol{W}_E^\star = \boldsymbol{0}$, or equivalently $\texttt{rank}(\boldsymbol{C}_1^\star) = M$. Furthermore, since $\boldsymbol{C}_1^\star = \boldsymbol{A}_i^\star - \lambda_i^\star(1 + \frac{1}{\gamma_i})\boldsymbol{h}_i^H\boldsymbol{h}_i, \forall i \in \mathcal{K}_\mathcal{I}$, it can be verified that $\texttt{rank}(\boldsymbol{A}_i^\star) = M - 1$ or equivalently $\texttt{rank}(\boldsymbol{W}_i^\star) = 1$ due to (8). Therefore, the proposition is proved. ☐

From Proposition 3.1, it follows that the optimal solution of $(\texttt{SDR1})$ satisfies the rank constraints, and thus the globally optimal solution of $(\texttt{P1})$ can always be obtained by solving $(\texttt{SDR1})$. Note that $(\texttt{SDR1})$ is a semidefinite programming (SDP), which can be efficiently solved by existing software, e.g., CVX [13]. Furthermore, it is observed that there always exists one optimal solution of $(\texttt{P1})$ with $\boldsymbol{W}_E^\star = 0$ or equivalently $\boldsymbol{v}_j = \boldsymbol{0}$, $\forall j \in \mathcal{K}_\mathcal{E}$, which implies that dedicated energy beamforming is not needed for achieving the maximum weighted harvested sum-power in $(\texttt{P1})$. This can be intuitively explained as follows. Since Type I ID receivers cannot cancel the interference from energy signals, employing energy beams will increase the interference power and as a result degrade the SINR at each ID receiver. Thus, the optimal transmission strategy is to adjust the weights and power values of information beams solely to maximize the weighted harvested sum-power.

Next, consider $(\texttt{P2})$ for the case of Type II ID receivers. Similarly to $(\texttt{P1})$, the SDR of $(\texttt{P2})$ can be expressed as

$$
\begin{aligned}
(\texttt{SDR2}):\ \max_{\{\boldsymbol{W}_i\},\boldsymbol{W}_E}\ & \sum_{i\in\mathcal{K}_\mathcal{I}} \texttt{tr}(\boldsymbol{G}\boldsymbol{W}_i) + \texttt{tr}(\boldsymbol{G}\boldsymbol{W}_E)\\
\texttt{s.t.}\ & \frac{\texttt{tr}(\boldsymbol{h}_i^H\boldsymbol{h}_i\boldsymbol{W}_i)}{\gamma_i} - \sum_{k\neq i, k\in\mathcal{K}_\mathcal{I}} \texttt{tr}(\boldsymbol{h}_i^H\boldsymbol{h}_i\boldsymbol{W}_k)\\
& - \sigma_i^2 \geq 0, \forall i \in \mathcal{K}_\mathcal{I}\\
& \sum_{i\in\mathcal{K}_\mathcal{I}} \texttt{tr}(\boldsymbol{W}_i) + \texttt{tr}(\boldsymbol{W}_E) \leq P\\
& \boldsymbol{W}_i \succeq \boldsymbol{0}, \forall i \in \mathcal{K}_\mathcal{I},\ \ \boldsymbol{W}_E \succeq \boldsymbol{0}.
\end{aligned}
$$

Let the optimal solution of $(\texttt{SDR2})$ be $\boldsymbol{W}_i^*, \forall i \in \mathcal{K}_\mathcal{I}$ and $\boldsymbol{W}_E^*$. We then have the following proposition.

Proposition 3.2. *For the case of Type II ID receivers, the optimal solution of* $(\texttt{SDR2})$ *satisfies:* $\texttt{rank}(\boldsymbol{W}_i^*) = 1, \forall i \in \mathcal{K}_\mathcal{I}$*, and* $\boldsymbol{W}_E^* = q^*\boldsymbol{v}_E\boldsymbol{v}_E^H$ *with* $0 \leq q^* \leq P$.

Proof. A sketch of the proof is provided here, while its details will be presented in [12]. First, the dual problem of (SDR2) is written as

$$
\begin{aligned}
(\texttt{SDR2.D}): \min_{\{\lambda_i\},\beta} \ & \beta P - \sum_{i\in\mathcal{K}_\mathcal{I}} \lambda_i \sigma_i^2 \\
\texttt{s.t.} \ & \boldsymbol{A}_i \preceq \boldsymbol{0}, \forall i \in \mathcal{K}_\mathcal{I} \\
& \boldsymbol{C}_2 \preceq \boldsymbol{0},
\end{aligned}
$$

where $\boldsymbol{C}_2 = \boldsymbol{G} - \beta \boldsymbol{I}$. Let $\{\lambda_i^*\}$ and β^* be the optimal solution of (SDR2.D), and the resulting $\{\boldsymbol{A}_i\}$ and $\boldsymbol{C}_2$ be $\{\boldsymbol{A}_i^*\}$ and $\boldsymbol{C}_2^*$, respectively. By complementary slackness conditions, we can show

$$\texttt{tr}\left(\boldsymbol{A}_i^* \boldsymbol{W}_i^*\right) = 0, \ \forall i \in \mathcal{K}_\mathcal{I}, \tag{10}$$

$$\texttt{tr}\left(\boldsymbol{C}_2^* \boldsymbol{W}_E^*\right) = 0. \tag{11}$$

Next, we prove the proposition by considering the following two cases: $\lambda_i^* = 0, \forall i \in \mathcal{K}_\mathcal{I}$, and there exists at least one $\bar{i} \in \mathcal{K}_\mathcal{I}$ with $\lambda_{\bar{i}}^* > 0$.

First, the case with $\lambda_i^* = 0, \forall i \in \mathcal{K}_\mathcal{I}$, corresponds to $\boldsymbol{A}_i^* = \boldsymbol{C}_2^* = \boldsymbol{G} - \beta^* \boldsymbol{I}, \forall i \in \mathcal{K}_\mathcal{I}$. In this case, it can be easily shown from (10) and (11) that $\texttt{rank}(\boldsymbol{W}_i^*) = 1, \forall i \in \mathcal{K}_\mathcal{I}$, and $\boldsymbol{W}_E^* = q^* \boldsymbol{v}_E \boldsymbol{v}_E^H$.

Second, for the case where there exists at least one $\bar{i} \in \mathcal{K}_\mathcal{I}$ with $\lambda_{\bar{i}}^* > 0$, it can be easily verified that $\texttt{rank}(\boldsymbol{C}_2^*) \geq M - 1$ and then from (11) that $\boldsymbol{W}_E^* = q^* \boldsymbol{v}_E \boldsymbol{v}_E^H$ with $0 \leq q^* \leq P$. Furthermore, by noting that $\boldsymbol{A}_i^* = \boldsymbol{C}_2^* + \frac{\lambda_i^* \boldsymbol{h}_i^H \boldsymbol{h}_i}{\gamma_i} - \sum_{k\neq i, k\in\mathcal{K}_\mathcal{I}} \lambda_k^* \boldsymbol{h}_k^H \boldsymbol{h}_k, \forall i \in \mathcal{K}_\mathcal{I}$, and using the fact that $\boldsymbol{h}_i$'s and $\boldsymbol{g}_j$'s are independently distributed, we can show that $\texttt{rank}(\boldsymbol{A}_i^*) = M - 1, \forall i \in \mathcal{K}_\mathcal{I}$, always holds; thus it follows from (10) that $\texttt{rank}(\boldsymbol{W}_i^*) = 1, \ \forall i \in \mathcal{K}_\mathcal{I}$. The proposition is thus proved. □

Based on Proposition 3.2, we can obtain the globally optimal solution of (P2) by solving (SDR2) via CVX. Meanwhile, since $\boldsymbol{W}_E^* = q^* \boldsymbol{v}_E \boldsymbol{v}_E^H$, all energy beams should align with $\boldsymbol{v}_E$, the same direction as the OeBF. Similarly to problem (7), in this case we can choose to send only one energy beam to minimize the complexity of beamforming implementation at the transmitter as well as the energy signal interference cancellation at all ID receivers by setting $\boldsymbol{v}_j = \sqrt{q^*} \boldsymbol{v}_E$ for any $j \in \mathcal{K}_\mathcal{E}$ and $\boldsymbol{v}_k^* = \boldsymbol{0}, \forall k \in \mathcal{K}_\mathcal{E}, k \neq j$.

By comparing the optimal solutions for (P1) and (P2), we can infer that their difference lies in that whether or not energy beamforming is employed. Note that the optimal value of (P2) is in general an upper bound on that of (P1) since any feasible solution of (P1) is also feasible for (P2), but not necessarily vice versa. If in Proposition 3.2 $q^* = 0$, then the upper bound is tight; however, if $q^* > 0$, then a higher weighted sum-power for EH receivers is achievable with Type II ID receivers. Therefore, the benefit of using Type II ID receivers can be realized by employing no more than one energy beam at the cost of implementing an interference cancellation (with *a priori* known energy signals) at each ID receiver.

Remark 3.1. *The strong duality between* (P1) *or* (P2) *and their SDRs can also be verified using the rank reduction techniques for separable SDPs as proposed in [14]. However, only existence of rank-one solutions for the studied SDRs can be inferred from [14], while in this paper we provide more direct proofs by exploiting the specific problem structures, which reveal more insights to the optimal beamforming design.*

4. NUMERICAL RESULTS

In this section, we provide numerical examples to validate our results. We assume that the signal attenuation from the AP to all EH receivers is 30dB corresponding to the same distance of 1 meter, and that to all ID receivers is 70dB at the same distance of 20 meters. The channel vectors $\boldsymbol{g}_i$'s and $\boldsymbol{h}_i$'s are randomly generated from i.i.d. Rayleigh fading with the average power as specified above. We set $P = 1$Watt (W) or 30dBm, $\zeta = 50\%$, $\sigma_i^2 = -50$dBm, and $\gamma_i = \gamma, \forall i \in \mathcal{K}_\mathcal{I}$. We also set $\alpha_j = \frac{1}{K_E}, \forall j \in \mathcal{K}_\mathcal{E}$; thus the average harvested power of all EH receivers is considered. Fig. 2 compares the average harvested power obtained by solving (P1) for Type I ID receivers and (P2) for Type II ID receivers versus SINR constraint γ with different values of K_I and fixed $M = 4, K_E = 2$. It is observed that Type I and Type II ID receivers have the same performance when $K_I = 1$, for which a detailed proof will be given in [12]. For $K_I = 2$ and 4, Type I and Type II ID receivers have similar performance when γ is either very large or small, while the latter outperforms the former notably for moderate values of γ. The reasons are as follows. When γ is very small, it can be shown that aligning all information beams in the direction of the OeBF is not only feasible but also optimal for both (P1) and (P2); thus the same optimal solution holds for both problems. When γ is very large (under which both (P1) and (P2) are still feasible), it is optimal to allocate all transmit power to information beams to ensure that the SINR constraints at all ID receivers are met; as a result, transmit power allocated to energy beams is zero regardless of which type of ID receivers used, and thus the same optimal solution holds for both problems. For moderate values of γ, the performance gap between Type I and Type II ID receivers is due to the use of one dedicated energy beam in (P2). For example, as shown in Fig. 2, a 46% average harvested power gain is achieved by Type II ID receivers than Type I ID receivers with $\gamma = 10$dB and $K_I = 4$, thanks to the cancellation of (known) energy signals at ID receivers.

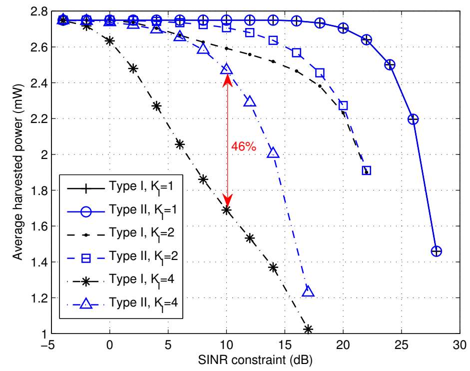

Fig. 2. Average harvested power versus SINR constraint.

5. CONCLUSION

This paper studies the joint information and energy transmit beamforming in a multiuser MISO broadcast channel for simultaneous wireless information and power transfer (SWIPT). The weighted sum-power harvested by EH receivers is maximized subject to individual SINR constraints for ID receivers. Considering two types of ID receivers without or with the interference cancellation capability, the design problems are formulated as two non-convex QCQPs, which are solved optimally by applying the technique of SDR. The results of this paper provide useful guidelines for practically optimally designing multi-antenna SWIPT systems with receiver-location-based information and energy scheduling.

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