Optimal SWIPT Beamforming for MISO Interfering Broadcast Channels with Multi-Type Receivers

Qiang Li and Jingran Lin
School of Information and Communication Engineering,
University of Electronic Science and Technology of China, P. R. China, Chengdu, 611731
Email: {lq, jingranlin}@uestc.edu.cn

***Abstract*—Recently, transmit beamforming for simultaneous wireless information and power transfer (SWIPT) has received considerable attention. Extensive studies have been done on MISO/MIMO SWIPT beamforming for broadcast channels (BCs) and interfering broadcast channels (IBCs). However, for IBCs the optimal SWIPT beamforming solution is in general not available. In this work, we consider SWIPT beamforming for multiuser MISO IBCs with multi-type receives, including pure information receivers (IRs), pure energy receivers (ERs) and simultaneous information and energy receivers. A power minimization problem with SINR and power transfer constraints on the receivers is considered. This problem is shown to be NP-hard in general. In order to get an efficient SWIPT beamforming solution, the energy-signal-aided SWIPT beamforming scheme is employed at the transmission. We show that with the help of the energy signals, the resultant beamforming problem is no longer NP-hard, and can be optimally solved by semidefinite relaxation (SDR). The key to this is to apply a recently developed low-rank solution result on a class of semidefinite programs (SDPs) to pin down the SDR tightness. Simulation results also demonstrate the efficacy of the energy signals in reducing the transmit power.**

I. Introduction

Simultaneous wireless information and power transfer (SWIPT) is a means of using RF signal to achieve dual transmissions of information and energy to the information receivers (IRs) and the energy receivers (ERs), respectively. Due to the presence of ERs, the conventional transceiver designs for information only transmission may not adapt to SWIPT. As such, various transmit and receive designs catered for SWIPT have been proposed in recent endeavors; see [1] and the references therein. Two notable designs include the energy-signal-aided transmit strategy [2] and the power-splitting-based receive strategy [3], [4]. The former sends a dedicated energy signal along with the information signal to facilitate the energy transfer, while the latter splits the received signal into two parts, with one for information decoding and the other for energy conversion. Specifically, in [2] the authors first proposed the energy-signal-aided SWIPT beamforming for a single-cell multiuser multi-input single-output (MISO) downlink, where the IRs and ERs are separately located. A similar beamforming problem (without energy signal) was investigated in [4], where collocated information and energy receivers with power splitting are assumed. Along this line, SWIPT beamforming optimizations for MISO/MIMO broadcast channels and interfering channels have been extensively investigated; see [5]–[12] and the references therein. However, for interfering broadcast channels (IBCs), the optimal SWIPT beamformer is in general not available, except for some special cases [8], [9]; some suboptimal designs based on convex relaxation and successive convex approximation have been proposed in [5], [6] and [7], respectively.

This work was supported in part by the National Natural Science Foundation of China under grants 61531009 and 61671120, in part by the Fundamental Research Funds for the Central Universities under grants ZYGX2016J011 and ZYGX2016J007, and in part by the Sichuan Science and Technology Program under grant 2018JY0147.

In this work, we aim to conduct a unified study on and develop an optimal solution to SWIPT beamforming problem by considering MISO IBCs with multi-type receivers, where multiple base stations (BS) operate on the same frequency, and each BS severs a number of IRs, ERs and simultaneous information and energy receivers. A power minimization problem with quality-of-services (QoS) constraints on the receivers is formulated. This problem is nonconvex and NP-hard in general. To circumvent this difficulty, the energy-signal-aided SWIPT beamforming is employed. Interestingly, we show that the inclusion of the energy signals not only gives more degrees of freedom for transmission, it also makes the SWIPT beamforming for IBCs optimally solvable. The key to this is to leverage on the semidefinite relaxation (SDR) technique [13] and a recent low-rank SDR solution result [14] to pin down the tightness of the SDR for SWIPT beamforming.

II. System Model and Problem Statement

Consider K-cell MISO interfering broadcast channels, where the BS k is equipped with N_k antennas and serves I_k users for $k = 1, \ldots, K$. Depending on the requirements of the users, we consider the following three types of receivers in each cell:

i) pure information receiver (IR), who aims for information only.
ii) pure energy receiver (ER), who aims for energy only.
iii) simultaneous information and energy receiver, which receivers both information and energy by power splitting [3].

Let $\mathcal{T}_k^{(i)}$ $(i = 1, 2, 3)$ denote a collection of type i receivers in cell k. Then, $\sum_{i=1}^{3} |\mathcal{T}_k^{(i)}| = I_k$ and $\mathcal{T}_k^{(i)} \cap \mathcal{T}_{k'}^{(i')} = \emptyset,\ \forall\ (k, i) \neq (k', i')$. By convention, we set $\mathcal{T}_k^{(i)} = \emptyset$ if type i receivers are absent from cell k.

Assume that transmit beamforming is adopted at the BSs, and let $\boldsymbol{w}_{l_k} \in \mathbb{C}^{N_k}$ be the beamformer associated with the

ISBN 978-90-827970-1-5

information symbol of receiver $l \in \mathcal{T}_k^{(1)} \cup \mathcal{T}_k^{(3)}$ in the kth cell. The transmit signals at the BSs are given by

$$\boldsymbol{x}_k(t) = \sum_{l \in \mathcal{T}_k^{(1\cup 3)}} \boldsymbol{w}_{l_k} s_{l_k}(t), \quad \forall\, k \in \mathcal{K}, \tag{1}$$

where $\mathcal{K} \triangleq \{1, \ldots, K\}$; $\mathcal{T}_k^{(i\cup j)} \triangleq \mathcal{T}_k^{(i)} \cup \mathcal{T}_k^{(j)},\ i, j = 1, 2, 3$; $s_{l_k} \in \mathbb{C}$ is the information symbol intended for receiver $l \in \mathcal{T}_k^{(1\cup 3)}$ in cell k. Accordingly, the received signals can be expressed as

$$y_{l_k}(t) = \sum_{j \in \mathcal{K}} \boldsymbol{h}_{l_k,j}^H \boldsymbol{x}_j(t) + n_{l_k}(t),$$

where $\boldsymbol{h}_{l_k,j} \in \mathbb{C}^{N_j}$ represents the channel vector from BS j to receiver l in cell k; n_{l_k} is complex Gaussian noise with mean zero and variance $\sigma_{l_k}^2$. Consequently, for type 1 receivers, the received SINR is given by

$$\mathsf{SINR}_{l_k}^{(1)}(\{\boldsymbol{w}_{l_k}\}) = \frac{|\boldsymbol{h}_{l_k,k}^H \boldsymbol{w}_{l_k}|^2}{\sum_{(j,m)\neq(k,l)} |\boldsymbol{h}_{l_k,j}^H \boldsymbol{w}_{m_j}|^2 + \sigma_{l_k}^2} \tag{2}$$

for all $l \in \mathcal{T}_k^{(1)}, \forall\, k \in \mathcal{K}$. For type 2 receivers, the harvested energy is given by [3]

$$\mathsf{E}_{l_k}^{(2)}(\{\boldsymbol{w}_{l_k}\}) = \zeta_{l_k}^{(2)} \Big(\sum_{j=1}^{K} \sum_{m \in \mathcal{T}_j^{(1\cup 3)}} |\boldsymbol{h}_{l_k,j}^H \boldsymbol{w}_{m_j}|^2 \Big) \tag{3}$$

for all $l \in \mathcal{T}_k^{(2)}, \forall\, k \in \mathcal{K}$, where $0 < \zeta_{l_k}^{(2)} \leq 1$ denotes the energy conversion efficiency for the type 2 receiver l in cell k, $\forall\, k \in \mathcal{K}$. For type 3 receivers, by denoting $0 \leq \rho_{l_k} \leq 1$ as the power splitting ratio of receiver $l \in \mathcal{T}_k^{(3)}$ in cell k, the received SINR and the harvested energy are resp. given by [3]

$$\begin{aligned} &\mathsf{SINR}_{l_k}^{(3)}(\{\boldsymbol{w}_{l_k}, \rho_{l_k}\}) \\ &= \frac{\rho_{l_k} |\boldsymbol{h}_{l_k,k}^H \boldsymbol{w}_{l_k}|^2}{\rho_{l_k}\big(\sum_{(j,m)\neq(k,l)} |\boldsymbol{h}_{l_k,j}^H \boldsymbol{w}_{m_j}|^2 + \sigma_{l_k}^2\big) + \delta_{l_k}^2}, \\ &\mathsf{E}_{l_k}^{(3)}(\{\boldsymbol{w}_{l_k}, \rho_{l_k}\}) \\ &= \zeta_{l_k}^{(3)} (1 - \rho_{l_k}) \big(\sigma_{l_k}^2 + \textstyle\sum_{j=1}^{K} \sum_{m \in \mathcal{T}_j^{(1\cup 3)}} |\boldsymbol{h}_{l_k,j}^H \boldsymbol{w}_{m_j}|^2\big), \end{aligned} \tag{4}$$

for all $l \in \mathcal{T}_k^{(3)},\ k \in \mathcal{K}$, where $0 < \zeta_{l_k}^{(3)} \leq 1$ is defined similarly as $\zeta_{l_k}^{(2)}$, and $\delta_{l_k} > 0$ corresponds to the noise variance introduced after power splitting.

A classical SWIPT beamforming problem is formulated as follows:

$$\begin{aligned} \min_{\{\boldsymbol{w}_{l_k}, \rho_{l_k}\}} \ & \sum_{k \in \mathcal{K}} \sum_{l \in \mathcal{T}_k^{(1\cup 3)}} \|\boldsymbol{w}_{l_k}\|^2 \\ \text{s.t. } & \mathsf{SINR}_{l_k}^{(1)}(\{\boldsymbol{w}_{l_k}\}) \geq \gamma_{l_k}^{(1)},\ \forall\, l \in \mathcal{T}_k^{(1)},\ k \in \mathcal{K}, \\ & \mathsf{SINR}_{l_k}^{(3)}(\{\boldsymbol{w}_{l_k}, \rho_{l_k}\}) \geq \gamma_{l_k}^{(3)},\ \forall\, l \in \mathcal{T}_k^{(3)},\ k \in \mathcal{K}, \\ & \mathsf{E}_{l_k}^{(2)}(\{\boldsymbol{w}_{l_k}\}) \geq \eta_{l_k}^{(2)},\ \forall\, l \in \mathcal{T}_k^{(2)},\ k \in \mathcal{K}, \\ & \mathsf{E}_{l_k}^{(3)}(\{\boldsymbol{w}_{l_k}, \rho_{l_k}\}) \geq \eta_{l_k}^{(3)},\ \forall\, l \in \mathcal{T}_k^{(3)},\ k \in \mathcal{K}, \\ & 0 \leq \rho_{l_k} \leq 1,\ \forall\, l \in \mathcal{T}_k^{(3)},\ k \in \mathcal{K}, \end{aligned} \tag{5}$$

where $\gamma_{l_k}^{(i)}$ $(i = 1, 3)$ and $\eta_{l_k}^{(j)}$ $(j = 2, 3)$ are positive constants, specifying the received SINR and the energy transfer requirements for different types of receivers, resp. It is easy to show that problem (5) is NP-hard, since it includes the multicast beamforming problem, which is known to be NP-hard in general [15], as a special case via setting $K = 1$, $\mathcal{T}_1^{(3)} = \emptyset$ and $|\mathcal{T}_1^{(1)}| = 1$. To tackle this kind of beamforming problem, the SDR technique has been widely used to deliver an approximate solution [13].

Instead of directly attacking the SWIPT beamforming problem (5), herein we consider altering the transmission scheme by using the idea of energy-signal-aided SWIPT beamforming, which was first proposed by Xu *et al.* [2]. Specifically, each BS is allowed to send a dedicated energy signal along with the information signal to provide additional energy source for the energy receivers. With the energy signals, the transmit signal $\boldsymbol{x}_k(t)$ in (1) is modified as

$$\boldsymbol{x}_k(t) = \textstyle\sum_{l \in \mathcal{T}_k^{(1\cup 3)}} \boldsymbol{w}_{l_k} s_{l_k}(t) + \boldsymbol{z}_k(t), \quad \forall\, k \in \mathcal{K}, \tag{6}$$

where $\boldsymbol{z}_k \in \mathbb{C}^{N_k}$ is the information-independent random signal with mean zero and covariance matrix $\boldsymbol{\Phi}_k \in \mathbb{H}_+^{N_k}$ for all $k \in \mathcal{K}$. For now, we assume that IRs have full knowledge of the energy signal, and thus energy-signal cancelation can be performed before information decoding at IRs[1]. Consequently, the resulting SINRs for types 1 and 3 receivers have the same form as (2) and (4), resp. The harvested energies at types 2 and 3 receivers are modified as (7) and (8), resp.

Now, the energy-signal-aided SWIPT beamforming problem is formulated as

$$\begin{aligned} \min_{\{\boldsymbol{w}_{l_k}, \boldsymbol{\Phi}_k, \rho_{l_k}\}} \ & \sum_{k \in \mathcal{K}} \sum_{l \in \mathcal{T}_k^{(1\cup 3)}} \|\boldsymbol{w}_{l_k}\|^2 + \mathrm{Tr}(\boldsymbol{\Phi}_k) \\ \text{s.t. } & \mathsf{SINR}_{l_k}^{(1)}\big(\{\boldsymbol{w}_{l_k}\}\big) \geq \gamma_{l_k}^{(1)},\ \forall\, l \in \mathcal{T}_k^{(1)},\ k \in \mathcal{K}, \\ & \mathsf{SINR}_{l_k}^{(3)}\big(\{\boldsymbol{w}_{l_k}, \rho_{l_k}\}\big) \geq \gamma_{l_k}^{(3)},\ \forall\, l \in \mathcal{T}_k^{(3)},\ k \in \mathcal{K}, \\ & \mathsf{E}_{l_k}^{(2)}\big(\{\boldsymbol{w}_{l_k}, \boldsymbol{\Phi}_k\}\big) \geq \eta_{l_k}^{(2)},\ \forall\, l \in \mathcal{T}_k^{(2)},\ k \in \mathcal{K}, \\ & \mathsf{E}_{l_k}^{(3)}\big(\{\boldsymbol{w}_{l_k}, \boldsymbol{\Phi}_k, \rho_{l_k}\}\big) \geq \eta_{l_k}^{(3)},\ \forall\, l \in \mathcal{T}_k^{(3)},\ k \in \mathcal{K}, \\ & \boldsymbol{\Phi}_k \succeq \mathbf{0},\ 0 \leq \rho_{l_k} \leq 1,\ \forall\, l \in \mathcal{T}_k^{(3)},\ k \in \mathcal{K}, \end{aligned} \tag{9}$$

where we aim to minimize the total transmit power of all the BSs, and meanwhile satisfy QoS of all the receivers by jointly optimizing the information beamformers, energy signals' covariance matrices and the power splitting ratios of type 3 receivers. Clearly, problem (9) includes problem (5) as a special case by prefixing $\boldsymbol{\Phi}_k = \mathbf{0},\ \forall\, k \in \mathcal{K}$.

Problem (9) is nonconvex and appears more complex than problem (5). Interestingly, as we will see shortly, the inclusion of energy signals at the transmitters actually makes the SWIPT beamforming problem no longer NP-hard and optimally solvable.

[1]This is possible, because the energy signals convey no information and can be generated deterministically and known by IRs beforehand.

ISBN 978-90-827970-1-5 © EURASIP 2018

$$\mathsf{E}_{l_k}^{(2)}\big(\{\boldsymbol{w}_{l_k},\boldsymbol{\Phi}_k\}\big)=\zeta_{l_k}^{(2)}\Big(\sum_{j=1}^{K}(\boldsymbol{h}_{l_k,j}^H(\boldsymbol{\Phi}_j+\sum_{m\in\mathcal{T}_j^{(1\cup 3)}}\boldsymbol{w}_{m_j}\boldsymbol{w}_{m_j}^H)\boldsymbol{h}_{l_k,j})\Big),\ \forall\ l\in\mathcal{T}_k^{(2)},\ k\in\mathcal{K}, \tag{7}$$

$$\mathsf{E}_{l_k}^{(3)}\big(\{\boldsymbol{w}_{l_k},\boldsymbol{\Phi}_k,\rho_{l_k}\}\big)=\zeta_{l_k}^{(3)}(1-\rho_{l_k})\Big(\sigma_{l_k}^2+\sum_{j=1}^{K}\boldsymbol{h}_{l_k,j}^H(\boldsymbol{\Phi}_j+\sum_{m\in\mathcal{T}_j^{(1\cup 3)}}\boldsymbol{w}_{m_j}\boldsymbol{w}_{m_j}^H)\boldsymbol{h}_{l_k,j}\Big),\ \forall\ l\in\mathcal{T}_k^{(3)},\ k\in\mathcal{K}. \tag{8}$$

$$\min_{\{\boldsymbol{W}_{l_k},\boldsymbol{\Phi}_k,\rho_{l_k}\}}\ \sum_{k\in\mathcal{K}}\sum_{l\in\mathcal{T}_k^{(1\cup 3)}}\mathrm{Tr}(\boldsymbol{W}_{l_k})+\mathrm{Tr}(\boldsymbol{\Phi}_k) \tag{10a}$$

$$\text{s.t.}\ \frac{\mathrm{Tr}(\boldsymbol{H}_{l_k,k}\boldsymbol{W}_{l_k})}{\gamma_{l_k}^{(1)}}-\sum_{(j,m)\neq(k,l)}\mathrm{Tr}(\boldsymbol{H}_{l_k,j}\boldsymbol{W}_{m_j})\geq\sigma_{l_k}^2,\ \forall\ l\in\mathcal{T}_k^{(1)},\ k\in\mathcal{K}, \tag{10b}$$

$$\frac{\mathrm{Tr}(\boldsymbol{H}_{l_k,k}\boldsymbol{W}_{l_k})}{\gamma_{l_k}^{(3)}}-\sum_{(j,m)\neq(k,l)}\mathrm{Tr}(\boldsymbol{H}_{l_k,j}\boldsymbol{W}_{m_j})\geq\sigma_{l_k}^2+\frac{\delta_{l_k}^2}{\rho_{l_k}},\quad\forall\ l\in\mathcal{T}_k^{(3)},\ k\in\mathcal{K}, \tag{10c}$$

$$\zeta_{l_k}^{(2)}\Big(\sum_{j\in\mathcal{K}}\sum_{m\in\mathcal{T}_j^{(1\cup 3)}}\mathrm{Tr}(\boldsymbol{H}_{l_k,j}\boldsymbol{W}_{m_j})+\sum_{j\in\mathcal{K}}\mathrm{Tr}(\boldsymbol{H}_{l_k,j}\boldsymbol{\Phi}_j)\Big)\geq\eta_{l_k}^{(2)},\ \forall\ l\in\mathcal{T}_k^{(2)},\ k\in\mathcal{K}, \tag{10d}$$

$$\zeta_{l_k}^{(3)}\Big(\sigma_{l_k}^2+\sum_{j\in\mathcal{K}}\sum_{m\in\mathcal{T}_j^{(1\cup 3)}}\mathrm{Tr}(\boldsymbol{H}_{l_k,j}\boldsymbol{W}_{m_j})+\sum_{j\in\mathcal{K}}\mathrm{Tr}(\boldsymbol{H}_{l_k,j}\boldsymbol{\Phi}_j)\Big)\geq\frac{\eta_{l_k}^{(3)}}{(1-\rho_{l_k})},\ \forall\ l\in\mathcal{T}_k^{(3)},\ k\in\mathcal{K}, \tag{10e}$$

$$\boldsymbol{W}_{l_k}\succeq\boldsymbol{0},\ \forall\ l\in\mathcal{T}_k^{(1\cup 3)},\ \forall\ k\in\mathcal{K},\qquad\boldsymbol{\Phi}_k\succeq\boldsymbol{0},\ k\in\mathcal{K},\qquad 0\leq\rho_{l_k}\leq 1,\forall\ l\in\mathcal{T}_k^{(3)},\ k\in\mathcal{K}, \tag{10f}$$

where $\boldsymbol{H}_{l_k,j}\triangleq\boldsymbol{h}_{l_k,j}\boldsymbol{h}_{l_k,j}^H,\ \forall\ l,k,j.$

III. An Optimal Solution to Problem (9)

Problem (9) can be handled by the SDR technique. By denoting $\boldsymbol{W}_{l_k}=\boldsymbol{w}_{l_k}\boldsymbol{w}_{l_k}^H$ for all $l\in\mathcal{T}_k^{(1\cup 3)}$, $k\in\mathcal{K}$ and relaxing the nonconvex rank-one constraint on $\boldsymbol{W}_{l_k}$, we obtain the SDR of problem (9), which is shown in (10). Problem (10) is a convex optimization problem, which can be efficiently solved with off-the-shelf optimization softwares. In general, the optimal $\boldsymbol{W}_{l_k}^\star$ of the SDR (10) may not be of rank one. However, for the considered problem, we have the following result:

Theorem 1. *Suppose that problem* (10) *is feasible. Then, there exists an optimal solution for problem* (10)*, say* $\{\boldsymbol{W}_{l_k}^\star,\boldsymbol{\Phi}_k^\star,\rho_{l_k}^\star\}$*, such that* $\mathrm{rank}(\boldsymbol{W}_{l_k}^\star)=1,\ \forall\ l\in\mathcal{T}_k^{(1\cup 3)},\ k\in\mathcal{K}$*. Moreover, such an optimal solution can be efficiently constructed. Therefore, problem* (9) *can be optimally solved by solving its SDR problem* (10).

Proof. Theorem 1 is proved by construction. We divide the proof into the following two steps:

Step 1: Suppose that we have solved problem (10) and obtained an optimal solution $\{\widehat{\boldsymbol{W}}_{l_k},\widehat{\boldsymbol{\Phi}}_k,\widehat{\rho}_{l_k}\}$. In order to construct a rank-one optimal $\boldsymbol{W}_{l_k}^\star$, let us first study the solution property of the following problem, which is obtained by fixing all the variables in problem (10) at $\{\widehat{\boldsymbol{W}}_{l_k},\widehat{\boldsymbol{\Phi}}_k,\widehat{\rho}_{l_k}\}$, except for those related to cell k, i.e., $\{\{\boldsymbol{W}_{l_k}\}_{l\in\mathcal{T}_k^{(1\cup 3)}},\boldsymbol{\Phi}_k\}$:

$$\begin{aligned}\min_{\{\boldsymbol{W}_{l_k}\}_{l\in\mathcal{T}_k^{(1\cup 3)}},\boldsymbol{\Phi}_k}\ &\sum_{l\in\mathcal{T}_k^{(1\cup 3)}}\mathrm{Tr}(\boldsymbol{W}_{l_k})+\mathrm{Tr}(\boldsymbol{\Phi}_k)\\ \text{s.t.}\ &\frac{\mathrm{Tr}(\boldsymbol{H}_{l_k,k}\boldsymbol{W}_{l_k})}{\gamma_{l_k}^{(1)}}-\sum_{m\neq l}\mathrm{Tr}(\boldsymbol{H}_{l_k,k}\boldsymbol{W}_{m_k})\geq\alpha_{l_k},\forall l\in\mathcal{T}_k^{(1)}\\ &\frac{\mathrm{Tr}(\boldsymbol{H}_{l_k,k}\boldsymbol{W}_{l_k})}{\gamma_{l_k}^{(3)}}-\sum_{m\neq l}\mathrm{Tr}(\boldsymbol{H}_{l_k,k}\boldsymbol{W}_{m_k})\geq\beta_{l_k},\forall l\in\mathcal{T}_k^{(3)}\\ &\sum_{m\in\mathcal{T}_k^{(1\cup 3)}}\mathrm{Tr}(\boldsymbol{H}_{l_k,k}\boldsymbol{W}_{m_k})+\mathrm{Tr}(\boldsymbol{H}_{l_k,k}\boldsymbol{\Phi}_k)\geq\theta_{l_k},\forall l\in\mathcal{T}_k^{(2)}\\ &\sum_{m\in\mathcal{T}_k^{(1\cup 3)}}\mathrm{Tr}(\boldsymbol{H}_{l_k,k}\boldsymbol{W}_{m_k})+\mathrm{Tr}(\boldsymbol{H}_{l_k,k}\boldsymbol{\Phi}_k)\geq\phi_{l_k},\forall l\in\mathcal{T}_k^{(3)}\\ &\boldsymbol{W}_{l_k}\succeq\boldsymbol{0},\quad\boldsymbol{\Phi}_k\succeq\boldsymbol{0},\forall l\in\mathcal{T}_k^{(3)},\end{aligned} \tag{11}$$

where $\alpha_{l_k}=\sigma_{l_k}^2+\sum_{j\neq k,\forall m}\mathrm{Tr}(\boldsymbol{H}_{l_k,j}\widehat{\boldsymbol{W}}_{m_j})$, $\beta_{l_k}=\sigma_{l_k}^2+\frac{\delta_{l_k}^2}{\widehat{\rho}_{l_k}}+\sum_{j\neq k,\forall m}\mathrm{Tr}(\boldsymbol{H}_{l_k,j}\widehat{\boldsymbol{W}}_{m_j})$, $\theta_{l_k}=\eta_{l_k}^{(2)}/\zeta_{l_k}^{(2)}-\zeta_{l_k}^{(2)}\Big(\sum_{j\neq k}\sum_{m\in\mathcal{T}_j^{(1\cup 3)}}\mathrm{Tr}(\boldsymbol{H}_{l_k,j}\widehat{\boldsymbol{W}}_{m_j})+\sum_{j\neq k}\mathrm{Tr}(\boldsymbol{H}_{l_k,k}\widehat{\boldsymbol{\Phi}}_k)\Big)$, $\phi_{l_k}=\frac{\eta_{l_k}^{(3)}}{\zeta_{l_k}^{(3)}(1-\widehat{\rho}_{l_k})}-\sum_{j\neq k}\sum_{m\in\mathcal{T}_j^{(1\cup 3)}}\mathrm{Tr}(\boldsymbol{H}_{l_k,j}\widehat{\boldsymbol{W}}_{m_j})-\sum_{j\neq k}\mathrm{Tr}(\boldsymbol{H}_{l_k,j}\widehat{\boldsymbol{\Phi}}_j)-\sigma_{l_k}^2$.

To identify the solution property of problem (11), we need the following key lemma:

ISBN 978-90-827970-1-5 © EURASIP 2018

Lemma 1. **([14, Corollary 1])** *Consider the following SDP*

$$\begin{aligned}\min_{\{\boldsymbol{X}_i\}_{i=1}^{m+1}} \quad & \textstyle\sum_{i=1}^{m+1} \mathrm{Tr}(\boldsymbol{C}_i \boldsymbol{X}_i) \\ \text{s.t.} \quad & \mathrm{Tr}(\boldsymbol{A}_{ii}\boldsymbol{X}_i) \geq \sum_{\substack{j=1,\\ j\neq i}}^{m+1} \mathrm{Tr}(\boldsymbol{A}_{ij}\boldsymbol{X}_j) + b_i,\ i=1,\ldots,m \\ & \textstyle\sum_{j=1}^{m+1} \mathrm{Tr}(\boldsymbol{F}_{ij}\boldsymbol{X}_j) \leq d_i,\ i=1,\ldots,p, \\ & \boldsymbol{X}_1,\ldots,\boldsymbol{X}_{m+1} \succeq \mathbf{0},\end{aligned} \tag{12}$$

where $\boldsymbol{A}_{ij}, \boldsymbol{C}_i, \boldsymbol{F}_{ij} \in \mathbb{H}^n$ for all i, j, and $b_i, d_i \in \mathbb{R}$ for all i. Suppose that the following conditions hold:

i) *$\boldsymbol{C}_i \succeq \boldsymbol{C}_{m+1}$ for all $i \in \{1,\ldots,m\}$;*
ii) *$\boldsymbol{A}_{j,i} \succeq \boldsymbol{A}_{j,m+1}$ for all $i, j \in \{1,\ldots,m\}$, $i \neq j$;*
iii) *$\boldsymbol{F}_{j,i} \succeq \boldsymbol{F}_{j,m+1}$ for all $i \in \{1,\ldots,m\}$, $j \in \{1,\ldots,p\}$;*
iv) *$\boldsymbol{A}_{ii} + \boldsymbol{A}_{i,m+1} \succeq \mathbf{0}$ and $\mathrm{rank}(\boldsymbol{A}_{ii} + \boldsymbol{A}_{i,m+1}) = 1$, for all $i \in \{1,\ldots,m\}$.*
v) *any optimal solution $(\boldsymbol{X}_1^\star,\ldots,\boldsymbol{X}_{m+1}^\star)$ to problem (12) has $\boldsymbol{X}_i^\star \neq \mathbf{0}$ for $i=1,\ldots,m$.*

Then, there exists an optimal solution to problem (12) whose ranks satisfy

$$\mathrm{rank}(\boldsymbol{X}_i^\star) = 1,\ i=1,\ldots,m.$$

Moreover, such an optimal solution can be efficiently constructed[2].

One can check that problem (11) can be converted into the form of problem (12), and moreover, all the above five conditions in Lemma 1 are satisfied. In particular, we have $\boldsymbol{X}_i = \boldsymbol{W}_{l_k}$, $\boldsymbol{X}_{m+1} = \boldsymbol{\Phi}_k$, $\boldsymbol{C}_i = \boldsymbol{C}_{m+1} = \boldsymbol{I}$, $\boldsymbol{A}_{j,i} \succeq \mathbf{0}$, $\boldsymbol{A}_{j,m+1} = \mathbf{0}$, $\boldsymbol{F}_{j,i} = \boldsymbol{F}_{j,m+1}$, $\boldsymbol{A}_{ii} + \boldsymbol{A}_{i,m+1} = \boldsymbol{A}_{ii} \succeq \mathbf{0}$ and $\mathrm{rank}(\boldsymbol{A}_{ii}) = \mathrm{rank}(\boldsymbol{H}_{l_k,k}) = \mathrm{rank}(\boldsymbol{h}_{l_k,k}\boldsymbol{h}_{l_k,k}^H) = 1$. In addition, it is easy to see that any optimal $\boldsymbol{W}_{l_k}$ to problem (11) must be nonzero, for otherwise the first two sets of constraints will be violated. Therefore, by Lemma 1, there exists a rank-one optimal $\boldsymbol{W}_{l_k}, \forall\, l \in \mathcal{T}_k^{(1\cup 3)}$ for problem (11).

<u>*Step 2*</u>: For ease of exposition, let us define $\mathcal{M}_k(\{\widehat{\boldsymbol{W}}_{l_j}, \widehat{\boldsymbol{\Phi}}_j\}_{j\neq k})$ as the rank-one optimal solution construction or mapping function for problem (11), i.e.,

$$\left(\{\boldsymbol{w}_{l_k}^\star\}_{l\in\mathcal{T}_k^{(1\cup3)}}, \boldsymbol{\Phi}_k^\star\right) = \mathcal{M}_k\left(\{\widehat{\boldsymbol{W}}_{l_j}, \widehat{\boldsymbol{\Phi}}_j\}_{j\neq k}\right),$$

where $(\{\boldsymbol{w}_{l_k}^\star(\boldsymbol{w}_{l_k}^\star)^H\}_{l\in\mathcal{T}_k^{(1\cup3)}}, \boldsymbol{\Phi}_k^\star)$ is an optimal solution of problem (11). Then, we employ the following procedure to iteratively construct rank-one matrices $\{\boldsymbol{w}_{l_k}^\star(\boldsymbol{w}_{l_k}^\star)^H\}_{l,k}$:

1: **for** $k = 1,\ldots,K$ **do**
2: $\quad\left(\{\boldsymbol{w}_{l_k}^\star\}_{l\in\mathcal{T}_k^{(1\cup3)}}, \boldsymbol{\Phi}_k^\star\right) = \mathcal{M}_k\left(\{\widehat{\boldsymbol{W}}_{l_j}, \widehat{\boldsymbol{\Phi}}_j\}_{j\neq k}\right)$;
3: $\quad$ set $\widehat{\boldsymbol{W}}_{l_k} = \boldsymbol{w}_{l_k}^\star(\boldsymbol{w}_{l_k}^\star)^H,\ \forall l \in \mathcal{T}_k^{(1\cup3)}$ and $\widehat{\boldsymbol{\Phi}}_k = \boldsymbol{\Phi}_k^\star$
4: **end for**
5: **output** $(\boldsymbol{W}_{l_k}^\star, \boldsymbol{\Phi}_k^\star, \rho_{l_k}^\star) = (\widehat{\boldsymbol{W}}_{l_k}, \widehat{\boldsymbol{\Phi}}_k, \widehat{\rho}_{l_k}),\ \forall\ l,\ k.$

[2]Due to the page limit, readers are referred to [14, Corollary 1] for the details of the construction.

Now, the remaining issue is to show that $\{\boldsymbol{W}_{l_k}^\star, \boldsymbol{\Phi}_k^\star, \rho_{l_k}^\star\}$ returned by the above procedure is optimal for problem (10). This can be easily verified, because the above procedure can be seen as a block coordinate descent (BCD) update of the variables of problem (10) with the initialization $\{\widehat{\boldsymbol{W}}_{l_k}, \widehat{\boldsymbol{\Phi}}_k, \widehat{\rho}_{l_k}\}$, which is optimal for problem (10) [recall in the very beginning of the proof, we have assumed $\{\widehat{\boldsymbol{W}}_{l_k}, \widehat{\boldsymbol{\Phi}}_k, \widehat{\rho}_{l_k}\}$ is obtained by solving problem (10)]. According to the basic property of BCD update, it is known that each block update of variables leads to a solution no worse than the one before update. Therefore, after one cycle of BCD update, the above procedure ends up with a solution no worse than the initialization. Since the initialization is already optimal for problem (10), the solution returned by BCD update must be optimal. This completes the proof. ■

Remark 1. When IRs have no a prior knowledge of the energy signals, the resulting SINRs of types 1 and 3 receivers are modified as (13) and (14), resp. Following the above development, it can be shown that the SDR of problem (9) [with $\mathsf{SINR}_{l_k}^{(1)}$ and $\mathsf{SINR}_{l_k}^{(3)}$ replaced by (13) and (14), resp.] is still tight. Since the proof is identical to that of Theorem 1, we omit it for brevity.

IV. Simulation Results

In this section, we use Monte-Carlo simulations to demonstrate the effectiveness of our design by comparing it with the no-energy-signal design [cf. (5)]. The simulation settings are as follows: $K = 3$, $N_k = 10$, $|\mathcal{T}_k^{(i)}| = 2$ for all i and k. For simplicity, we assume that all receivers have the same SINR threshold, power transfer threshold and energy conversion efficiency, i.e., $\gamma_{l_k}^{(1)} = \gamma_{l_k}^{(3)} = \gamma$, $\eta_{l_k}^{(2)} = \eta_{l_k}^{(3)} = \eta$ and $\zeta_{l_k} = \zeta$. The noise level at reception is fixed at -40 dbm, i.e., $\sigma_{l_k}^2 = \delta_{l_k}^2 = -40$ dbm. The entries of the channel $\boldsymbol{h}_{l_k}, \forall\ l, k$ are randomly generated following i.i.d. complex Gaussian distribution with mean zero and variance 0.01. All the results were obtained by averaging over 100 random channel trials.

In Figure 1, we plot the total transmit power consumptions of the two designs versus the power transfer threshold η by fixing $\gamma = 3$ dB. Since problem (5) is NP-hard, herein we plot the SDR result, a lower bound of the power consumption of the no-energy-signal design, as a benchmark. From the figure, we see that with help of the energy signal, the total transmission power can be significantly reduced. The benefit of using energy signal becomes more prominent when either the ERs have more stringent energy requirement or the energy conversion efficiency ζ is low. This is expected, since for the no-energy-signal scheme, the IRs would suffer from strong interuser interference when ERs have stringent energy transfer requirements, thereby leading to inefficient SWIPT. However, with the help of the energy signal, the interuser interference problem can be well addressed. To further illustrate the importance of the energy signal, we also calculated the ratio of the energy signal's power in the transmit signal under the same setting as Figure 1. The result is shown in Figure 2. Clearly, more power is allocated to the energy signals for larger η.

ISBN 978-90-827970-1-5

$$\mathsf{SINR}^{(1)}_{l_k}\big(\{\boldsymbol{w}_{l_k},\boldsymbol{\Phi}_k\}\big)=\frac{\boldsymbol{h}^H_{l_k,k}\boldsymbol{w}_{l_k}\boldsymbol{w}^H_{l_k}\boldsymbol{h}_{l_k,k}}{\sum_{(j,m)\neq(k,l)}\boldsymbol{h}^H_{l_k,j}\boldsymbol{w}_{m_j}\boldsymbol{w}^H_{m_j}\boldsymbol{h}_{l_k,j}+\sum_{j=1}^{K}\boldsymbol{h}^H_{l_k,j}\boldsymbol{\Phi}_j\boldsymbol{h}_{l_k,j}+\sigma^2_{l_k}},\quad \forall\, l\in\mathcal{T}^{(1)}_k,\ k\in\mathcal{K}, \tag{13}$$

$$\mathsf{SINR}^{(3)}_{l_k}\big(\{\boldsymbol{w}_{l_k},\boldsymbol{\Phi}_k,\rho_{l_k}\}\big)=\frac{\rho_{l_k}\boldsymbol{h}^H_{l_k,k}\boldsymbol{w}_{l_k}\boldsymbol{w}^H_{l_k}\boldsymbol{h}_{l_k,k}}{\rho_{l_k}\Big(\sum_{(j,m)\neq(k,l)}\boldsymbol{h}^H_{l_k,j}\boldsymbol{w}_{m_j}\boldsymbol{w}^H_{m_j}\boldsymbol{h}_{l_k,j}+\sum_{j=1}^{K}\boldsymbol{h}^H_{l_k,j}\boldsymbol{\Phi}_j\boldsymbol{h}_{l_k,j}+\sigma^2_{l_k}\Big)+\delta^2_{l_k}},\ \forall\, l\in\mathcal{T}^{(3)}_k, k\in\mathcal{K}. \tag{14}$$

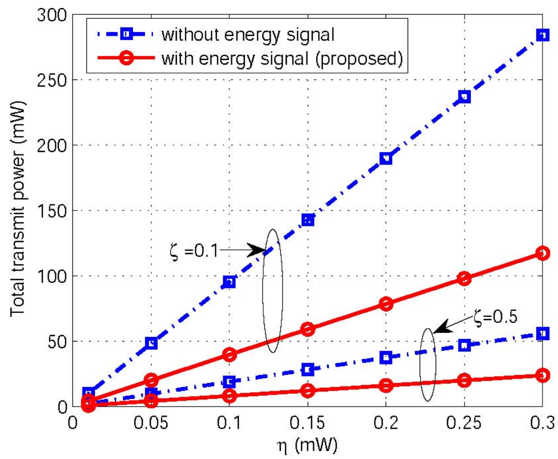

Fig. 1. The total transmit power vs. the energy transfer threshold η.

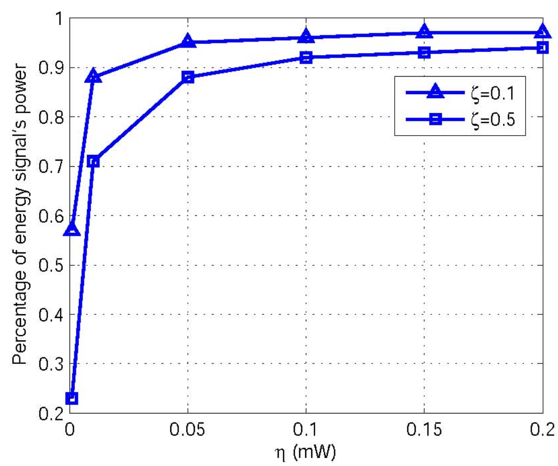

Fig. 2. Percentage of energy signal's power in the transmit signal.

V. Conclusion

We have considered energy-signal-aided SWIPT beamforming for interfering broadcast channels (IBCs) with multi-type receivers. We prove that the optimal beamformer can be computed with its SDR, thereby yielding a tractable approach to SWIPT beamforming for IBCs. This tractability is in sharp contrast to the NP-hardness of the same beamforming problem without using energy signal. Our proof and numerical results demonstrate that including energy signal into transmission does not only facilitate the beamformer optimization, it also efficiently reduces the transmission power.

References

[1] Y. Zeng, B. Clerckx, and R. Zhang, "Communications and signals design for wireless power transmission," *IEEE Trans. Commun.*, vol. 65, no. 5, pp. 2264–2290, May 2017.

[2] J. Xu, L. Liu, and R. Zhang, "Multiuser MISO beamforming for simultaneous wireless information and power transfer," *IEEE Trans. Sig. Process.*, vol. 62, no. 18, pp. 4798–4810, Sept. 2014.

[3] R. Zhang and C. K. Ho, "MIMO broadcasting for simultaneous wireless information and power transfer," *IEEE Trans. Wireless Commun.*, vol. 12, no. 5, pp. 1989–2001, May 2013.

[4] Q. Shi, L. Liu, W. Xu, and R. Zhang, "Joint transmit beamforming and receive power splitting for MISO SWIPT systems," *IEEE Trans. Wireless Commun.*, vol. 13, no. 6, pp. 3269–3280, Jun. 2014.

[5] Q. Shi, W. Xu, T.-H. Chang, Y. Wang, and E. Song, "Joint beamforming and power splitting for MISO interference channel with SWIPT: An SOCP relaxation and decentralized algorithm," *IEEE Trans. Sig. Process.*, vol. 62, no. 23, pp. 6194–6208, Dec. 2014.

[6] S. Timotheou, I. Krikidis, G. Zheng, and B. Ottersten, "Beamforming for MISO interference channels with QoS and RF energy transfer," *IEEE Trans. Wireless Commun.*, vol. 13, no. 5, pp. 2646–2658, May 2014.

[7] C. Shen, W.-C. Li, and T.-H. Chang, "Wireless information and energy transfer in multi-antenna interference channel," *IEEE Trans. Sig. Process.*, vol. 62, no. 23, pp. 6249–6264, Dec. 2014.

[8] H. Lee, S.-R. Lee, K.-J. Lee, H.-B. Kong, and I. Lee, "Optimal beamforming designs for wireless information and power transfer in MISO interference channels," *IEEE Trans. Wireless Commun.*, vol. 14, no. 9, pp. 4810–4821, Sept. 2015.

[9] A. Öçelikkale and T. M. Duman, "Linear precoder design for simultaneous information and energy transfer over two-user MIMO interference channels," *IEEE Trans. Wireless Commun.*, vol. 14, no. 10, pp. 1687–1690, Oct. 2015.

[10] M. Sheng, L. Wang, X. Wang, Y. Zhang, C. Xu, and J. Li, "Energy efficient beamforming in MISO heterogeneous cellular networks with wireless information and power transfer," *IEEE Jour. Sele. Areas Commun.*, vol. 34, no. 4, pp. 954–968, Apr. 2016.

[11] J. Rubio, A. Pascual-Iserte, D. P. Palomar, and A. Goldsmith, "Joint optimization of power and data transfer in multiuser MIMO systems," *IEEE Trans. Sig. Process.*, vol. 65, no. 1, pp. 212–227, Jan. 2017.

[12] H. Zhang, A. Dong, S. Jin, and D. Yuan, "Joint transceiver and power splitting optimization for multiuser MIMO SWIPT under MSE QoS constraints," *IEEE Trans. Vehicular Tech.*, vol. 66, no. 8, pp. 7123–7135, Aug. 2017.

[13] Z.-Q. Luo, W.-K. Ma, A. M.-C. So, Y. Ye, and S. Zhang, "Semidefinite relaxation of quadratic optimization problems," *IEEE Sig. Process. Mag.*, vol. 27, no. 3, pp. 20–34, May 2010.

[14] Q. Li and W.-K. Ma, "A new low-rank solution result for a semidefinite program problem subclass with applications to transmit beamforming optimization," in *Proc. IEEE Int. Conf. on Acoustics, Speech, and Sig. Process. (ICASSP)*, Mar. 2016, pp. 3446–3450.

[15] N. D. Sidiropoulos, T. N. Davidson, and Z.-Q. Luo, "Transmit beamforming for physical-layer multicasting," *IEEE Trans. Sig. Process.*, vol. 54, no. 3, pp. 2239–2251, Jun. 2006.