Optimal MIMO Multicast Transceiver Design for Simultaneous Information and Power Transfer

Aissa Ikhlef, *Member, IEEE*

***Abstract*—We consider transceiver design for a MIMO multicast channel for simultaneous wireless information and power transfer. We assume that common information is intended for a subset of users, called information decoders (IDs), and the other users, called energy harvesters (EHs), harvest energy from the received signals. Assuming linear receivers at the IDs, we jointly design the precoder at the source and the receivers at the IDs according to two criteria. In the first criterion, we minimize the worst case mean square error (MSE) under source transmit power and harvested energy constraints. In the second criterion, we maximize the total harvested energy at the EHs under source transmit power and worst case MSE constraints. We formulate both problems as semidefinite programming (SDP) problems that we optimally solve using interior point algorithms. Simulation results show the importance of designing the transceivers in order to achieve a desired tradeoff among the source transmit power, MSEs at the IDs, and harvested energy at the EHs.**

***Index Terms*—MIMO multicasting, transceiver design, energy harvesting, simultaneous information and power transfer.**

I. Introduction

Recently, energy harvesting in wireless communication networks have attracted much interest due to its ability in prolonging the network lifetime as well as achieving greener communications. Traditionally, the energy[1] is harvested from the surrounding environment, such as solar, wind, etc. Due to recent advances in energy harvesting via radio frequency (RF) electromagnetic signals [1] simultaneous wireless information and power transfer (SWIPT) has become possible and can be of great practical interest. However, until recently, wireless communication systems were optimized only for information transfer and consequently they may not be optimal for simultaneous transfer of both information and power. Hence, to achieve both efficient information and power transfer, wireless communication systems need to be redesigned taking into account both information and power transfer requirements.

The first work on SWIPT in [2] studied the fundamental tradeoff between the rates at which energy and reliable information can be transmitted in a single-input single-output (SISO) system. Later, Grover and Sahai [3] extended [2] to frequency selective channels. SWIPT for MIMO broadcast system, MIMO interference channel with two users, and multiple access and multi-hop channels was studied in [4], [5], and [6], respectively. All the above works concentrated on the characterization of the rate-energy region and the design of the covariance matrix of the transmit signal. More recently the authors in [7] studied a multiuser multiple-input single-output (MISO) downlink system for SWIPT. In [8], the authors considered SWIPT for MISO multicasting systems. To the author's best knowledge, no work on practical joint design of the source precoder and receivers for a MIMO spatial multiplexing SWIPT system exists yet for any network topology.

In this letter, we consider a MIMO multicast system consisting of a source node and a number of destination nodes [9], [10]. Multicasting systems, such as media streaming and mobile TV, are of practical interest and we believe are very suitable for SWIPT. In this work, we assume that a subset of destinations, for which common information is intended, referred to as information decoders (IDs), decode the information, while the rest of destinations, called energy harvesters (EHs), harvest energy from the received signals. In particular, we jointly design the source precoder and the receivers at the IDs according to two criteria. In the first criterion, we minimize the worst case mean square error (MSE) subject to the source transmit power and harvested energy constraints. In the second criterion, we maximize the total harvested energy at the EHs under source transmit power and worst case MSE constraints. In both criteria, we assume that the receivers at the IDs are linear and take into account the limited storage capacity of the batteries at the EHs. We formulate both problems as semidefinite programming (SDP) problems and solve them optimally using interior point algorithms. We also evaluate the performance of the proposed designs and discuss the obtained gains. We note that this work is different from the works in [7], [8] in several aspects. In particular, [7] and [8] considered a multiuser MISO downlink system where each destination node uses a power splitting approach to both decode information and harvest energy. However, in this work we consider a MIMO multicast system and each destination node is either an EH or ID node. Moreover, [7] and [8] investigated joint transmit beamforming and receive power splitting while we consider joint source precoder and IDs receivers design where the IDs are equipped with linear receivers.

II. System Model

We consider a MIMO multicast channel with one source S, which is equipped with M transmit antennas, and $K+L$ destinations, each equipped with N antennas, as shown in Fig. 1. We assume that each destination node can either decode information or harvest energy but not both at the same

Aissa Ikhlef was with Toshiba Research Europe Limited, Bristol, BS1 4ND, UK. He is now with the School of Electrical and Electronic Engineering, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK (e-mail: aissa.ikhlef@ncl.ac.uk).

[1]In this paper, we use energy and power interchangeably.

time[2]. Note that each destination node can switch between information decoding and energy harvesting modes according to a given selection criterion[3]. In the following, we assume that K and L destinations were selected for information decoding and energy harvesting, respectively. Let $\mathbf{s} \in \mathbb{C}^{M\times 1}$ denote the transmit signal from the source to all ID nodes. The elements of the transmit signal are assumed to be independent and identically distributed (i.i.d.) with unit power, i.e., $\mathbb{E}[\mathbf{s}\mathbf{s}^H] = \mathbf{I}_M$, where $\mathbb{E}[\cdot]$ denotes the statistical expectation and $\mathbf{I}_M$ is the $M \times M$ identity matrix. The transmitted symbols can be drawn from any constellation, e.g., PSK or QAM. We assume spatial multiplexing and $\mathbf{s}$ is precoded using precoding matrix $\mathbf{B} \in \mathbb{C}^{M\times M}$ before transmission. The signal received at the ith ID node, $\mathbf{y}_{\mathrm{ID}_i} \in \mathbb{C}^{N\times 1}$, is given by

$$\mathbf{y}_{\mathrm{ID}_i} = \mathbf{H}_i\mathbf{B}\mathbf{s} + \mathbf{n}_{\mathrm{ID}_i},\ i = 1,\dots,K \tag{1}$$

where $\mathbf{H}_i \in \mathbb{C}^{N\times M}$ is the channel matrix between the source and the ith ID, and $\mathbf{n}_{\mathrm{ID}_i} \in \mathbb{C}^{N\times 1}$ is the additive white Gaussian noise with zero mean and covariance matrix $\mathbb{E}\left[\mathbf{n}_{\mathrm{ID}_i}\mathbf{n}_{\mathrm{ID}_i}^H\right] = \sigma^2_{\mathrm{ID}_i}\mathbf{I}_N$ at the ith ID. The signal received at the ith EH, $\mathbf{y}_{\mathrm{EH}_j} \in \mathbb{C}^{N\times 1}$, is given by

$$\mathbf{y}_{\mathrm{EH}_j} = \mathbf{G}_j\mathbf{B}\mathbf{s} + \mathbf{n}_{\mathrm{EH}_j},\ j = 1,\dots,L \tag{2}$$

where $\mathbf{G}_j \in \mathbb{C}^{N\times M}$ is the channel matrix between the source and the jth EH and $\mathbf{n}_{\mathrm{EH}_j} \in \mathbb{C}^{N\times 1}$ is the additive white Gaussian noise with zero mean and covariance matrix $\mathbb{E}\left[\mathbf{n}_{\mathrm{EH}_j}\mathbf{n}_{\mathrm{EH}_j}^H\right] = \sigma^2_{\mathrm{EH}_j}\mathbf{I}_N$ at the jth EH. For notational convenience and without loss of generality, we assume that the noise variance is the same at all the receiving nodes, IDs and EHs, i.e., $\sigma_n^2 = \sigma^2_{\mathrm{ID}_1} = \cdots = \sigma^2_{\mathrm{ID}_K} = \sigma^2_{\mathrm{EH}_1} = \cdots = \sigma^2_{\mathrm{EH}_L}$.

To recover the transmitted signal, the IDs use linear receivers[4], $\mathbf{W}_i \in \mathbb{C}^{N\times M}$, $i = 1,\dots,K$. The signal at the output of the receiver at the ith ID, is given by

$$\hat{\mathbf{s}}_i = \mathbf{W}_i^H\mathbf{y}_{\mathrm{ID}_i} = \mathbf{W}_i^H\mathbf{H}_i\mathbf{B}\mathbf{s} + \mathbf{W}_i^H\mathbf{n}_{\mathrm{ID}_i}. \tag{3}$$

To measure the performance of the retrieved signals, we consider the MSE criterion. The MSE at the output of the receiver of the ith ID can be obtained as

$$\begin{aligned}\mathrm{MSE}_i &\triangleq \mathrm{tr}\left(\mathbb{E}\left[(\hat{\mathbf{s}}_i - \mathbf{s})(\hat{\mathbf{s}}_i - \mathbf{s})^H\right]\right)\\ &= \mathrm{tr}\left(\left(\mathbf{W}_i^H\mathbf{H}_i\mathbf{B} - \mathbf{I}_M\right)\left(\mathbf{W}_i^H\mathbf{H}_i\mathbf{B} - \mathbf{I}_M\right)^H + \sigma_n^2\mathbf{W}_i^H\mathbf{W}_i\right)\end{aligned} \tag{4}$$

where $\mathrm{tr}(\mathbf{A})$ denotes the trace of matrix $\mathbf{A}$. The receiver that minimizes (4) is the well-known linear minimum mean square error (LMMSE) receiver, given by

$$\mathbf{W}_i = \left(\mathbf{H}_i\mathbf{B}\mathbf{B}^H\mathbf{H}_i^H + \sigma_n^2\mathbf{I}_N\right)^{-1}\mathbf{H}_i\mathbf{B},\ i = 1,\dots,K. \tag{5}$$

The source transmit power is $P_S = \mathrm{tr}\left(\mathbf{B}\mathbf{B}^H\right)$ and the harvested energy at the jth EH is given by

$$e_j = \alpha\mathrm{tr}\left(\mathbf{G}_j\mathbf{B}\mathbf{B}^H\mathbf{G}_j^H + \sigma_n^2\mathbf{I}_N\right) \tag{6}$$

[2]The reason behind this assumption is that with current circuit technologies it is not yet possible for a node to decode information and harvest energy at the same time [4].

[3]Selecting a node for information decoding or energy harvesting can be a function of, e.g., quality of the links, available power in the battery, etc. Note that the selection criterion is beyond the scope of this paper.

[4]Here, we assume linear receivers due to their low complexity. However, other types of receivers, such as decision feedback equalizers, can be used.

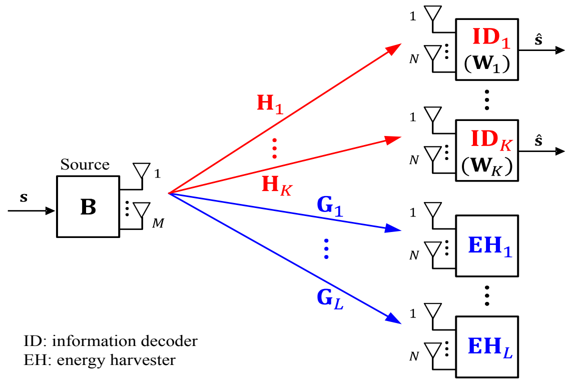

Fig. 1. A MIMO multicast channel consisting of one source, K IDs, and L EHs.

where $\alpha \le 1$ is a constant that accounts for the energy conversion loss at the transducer [4].

III. Worst Case MSE Minimization Based Design

In this section, we aim at designing the source precoder and the receivers at the IDs via the minimization of the worst case MSE at the IDs subject to source transmit power and total harvested power constraints. This criterion is of interest when we wish to optimize the quality of service (QoS), here MSE, as well as ensuring fairness among the IDs, given that we have a limited available source transmit power and a minimum total power that needs to be harvested by the EHs, that cannot be relaxed. The corresponding optimization problem is formulated as

$$\min_{\mathbf{B},\{\mathbf{W}_i\}_{i=1,\cdots,K}} \ \max_i \ \mathrm{MSE}_i \tag{7a}$$

$$\text{s.t.}\ \ \mathrm{tr}\left(\mathbf{B}\mathbf{B}^H\right) \le P_{s,max} \tag{7b}$$

$$\alpha\mathrm{tr}\left(\mathbf{G}_j\mathbf{B}\mathbf{B}^H\mathbf{G}_j^H + \sigma_n^2\mathbf{I}_N\right) \ge \xi_j,\ j = 1,\dots,L \tag{7c}$$

$$\alpha\,\mathrm{tr}\left(\mathbf{G}_j\mathbf{B}\mathbf{B}^H\mathbf{G}_j^H + \sigma_n^2\mathbf{I}_N\right) \le e_{max,j},\ j = 1,\dots,L \tag{7d}$$

where $P_{s,max}$ is the maximum allowable source transmit power, ξ_j is the minimum power that needs to be harvested by the jth EH, and $e_{max,j}$ is the available storage space in the battery of the jth EH. Constraints (7b) and (7c) ensure that the transmit power is less or equal to the maximum allowable transmit power, $P_{s,max}$, at the source node and that the power that needs to be harvested by the jth EH is at least equal to ξ_j, respectively. Constraint (7d) ensures that the harvested power by each EH is less or equal to the empty storage space in its battery. Note that $\xi_j \le e_{max,j}$ should be satisfied so that the problem may be feasible.

It is obvious that optimization problem (7) is not convex due to the product between the source precoder and ID receivers, and hence it is difficult to solve optimally. Observe that the constraints in (7) do not depend on $\mathbf{W}_i$, $i = 1,\dots,K$, and hence the receivers that minimize the cost function in (7) are the well-known LMMSE receivers, given in (5). Substituting

(5) into (7), and after some manipulations, yields

$$\begin{aligned} \min_{\mathbf{B}} \quad & \max_i \sigma_n^2 \text{tr}\left(\left(\sigma_n^2 \mathbf{I}_M + \mathbf{B}^H \mathbf{H}_i^H \mathbf{H}_i \mathbf{B}\right)^{-1}\right) && \text{(8a)} \\ \text{s.t.} \quad & \text{tr}\left(\mathbf{B}\mathbf{B}^H\right) \le P_{s,max} && \text{(8b)} \\ & \text{tr}\left(\mathbf{G}_j \mathbf{B}\mathbf{B}^H \mathbf{G}_j^H\right) \ge \xi_j',\ j = 1, \ldots, L && \text{(8c)} \\ & \text{tr}\left(\mathbf{G}_j \mathbf{B}\mathbf{B}^H \mathbf{G}_j^H\right) \le e_{max,j}',\ j = 1, \ldots, L && \text{(8d)} \end{aligned}$$

where $\xi_j' = \xi_j/\alpha - N\sigma_n^2$ and $e_{max,j}' = e_{max,j}/\alpha - N\sigma_n^2$.

Let us assume that problem (8) is feasible and proceed with solving it. Using the equality $\text{tr}\left(\left(\sigma_n^2 \mathbf{I}_M + \mathbf{B}^H \mathbf{H}_i^H \mathbf{H}_i \mathbf{B}\right)^{-1}\right) = \text{tr}\left(\left(\sigma_n^2 \mathbf{I}_N + \mathbf{H}_i \mathbf{B}\mathbf{B}^H \mathbf{H}_i^H\right)^{-1}\right) + M - N$ and $\mathbf{F} = \mathbf{B}\mathbf{B}^H$, problem (8) can be equivalently recast as

$$\begin{aligned} \min_{\mathbf{F} \succeq 0, \tau} \quad & \tau && \text{(9a)} \\ \text{s.t.} \quad & \text{tr}\left(\mathbf{F}\right) \le P_{s,max} && \text{(9b)} \\ & \text{tr}\left(\mathbf{G}_j \mathbf{F} \mathbf{G}_j^H\right) \ge \xi_j',\ j = 1, \ldots, L && \text{(9c)} \\ & \text{tr}\left(\mathbf{G}_j \mathbf{F} \mathbf{G}_j^H\right) \le e_{max,j}',\ j = 1, \ldots, L && \text{(9d)} \\ & \text{tr}\left(\left(\sigma_n^2 \mathbf{I}_N + \mathbf{H}_i \mathbf{F} \mathbf{H}_i^H\right)^{-1}\right) \le \tau,\ i = 1, \ldots, K. && \text{(9e)} \end{aligned}$$

where τ is a real-valued slack variable. Introducing $\left(\sigma_n^2 \mathbf{I}_N + \mathbf{H}_i \mathbf{F} \mathbf{H}_i^H\right)^{-1} \preceq \mathbf{T}_i$, which, using the Schur complement, can be recast in a linear inequality form as

$$\begin{bmatrix} \mathbf{T}_i & \mathbf{I}_N \\ \mathbf{I}_N & \sigma_n^2 \mathbf{I}_N + \mathbf{H}_i \mathbf{F} \mathbf{H}_i^H \end{bmatrix} \succeq 0, \tag{10}$$

constraint (9e) is equivalent to

$$\begin{cases} \text{tr}\left(\mathbf{T}_i\right) \le \tau \\ \begin{bmatrix} \mathbf{T}_i & \mathbf{I}_N \\ \mathbf{I}_N & \sigma_n^2 \mathbf{I}_N + \mathbf{H}_i \mathbf{F} \mathbf{H}_i^H \end{bmatrix} \succeq 0. \end{cases} \tag{11}$$

Hence, using (11), problem (9) is equivalent to

$$\begin{aligned} \min_{\mathbf{F} \succeq 0, \tau, \mathbf{T}_i} \quad & \tau \\ \text{s.t.} \quad & \text{tr}\left(\mathbf{F}\right) \le P_{s,max} \\ & \text{tr}\left(\mathbf{G}_j \mathbf{F} \mathbf{G}_j^H\right) \ge \xi_j',\ j = 1, \ldots, L \\ & \text{tr}\left(\mathbf{G}_j \mathbf{F} \mathbf{G}_j^H\right) \le e_{max,j}',\ j = 1, \ldots, L \\ & \text{tr}\left(\mathbf{T}_i\right) \le \tau,\ i = 1, \ldots, K \\ & \begin{bmatrix} \mathbf{T}_i & \mathbf{I}_N \\ \mathbf{I}_N & \sigma_n^2 \mathbf{I}_N + \mathbf{H}_i \mathbf{F} \mathbf{H}_i^H \end{bmatrix} \succeq 0,\ i = 1, \ldots, K. \end{aligned} \tag{12}$$

This is a convex SDP problem and we can solve it optimally using interior point algorithms. In particular, here, we use the convex optimization toolbox CVX [11] to solve problem (9) at a complexity order of at most $\mathcal{O}\left(\left(M^2 + K + 2L + 1\right)^{3.5}\right)$ [9]. Once we have the optimal solution $\mathbf{F}^\star$ of problem (9), the optimal solution $\mathbf{B}^\star$ can simply be computed using the eigen-decomposition of $\mathbf{F}^\star$, which is given by $\mathbf{F}^\star = \mathbf{U}^\star \mathbf{\Lambda}^\star \mathbf{U}^{\star H}$. $\mathbf{U}^\star$ is a unitary matrix containing the eigenvectors of $\mathbf{F}^\star$ and $\mathbf{\Lambda}^\star$ is a diagonal matrix containing the corresponding eigenvalues. Hence, the set of optimal precoder matrices is $\mathbf{B}^\star = \mathbf{U}^\star \mathbf{\Lambda}^{\star \frac{1}{2}} \mathbf{P}$, where $\mathbf{P}$ is an arbitrary unitary matrix. In this letter, we have chosen $\mathbf{P} = \mathbf{I}_M$. Now, we can compute the LMMSE receivers at the IDs by substituting $\mathbf{B}^\star$ into (5).

IV. Harvested Energy Maximization Based Design

In this section, assuming LMMSE receivers at the IDs, we design the source precoder via the maximization of the total harvested energy under source transmit power and QoS constraints. This criterion is interesting since both transmit power and QoS are very important requirements and, in general, cannot be relaxed. The corresponding optimization problem can be formulated as

$$\begin{aligned} \max_{\mathbf{B}} \quad & \sum_{j=1}^{L} \alpha \text{tr}\left(\mathbf{G}_j \mathbf{B}\mathbf{B}^H \mathbf{G}_j^H + \sigma_n^2 \mathbf{I}_N\right) \\ \text{s.t.} \quad & \text{tr}\left(\mathbf{B}\mathbf{B}^H\right) \le P_{s,max} \\ & \text{tr}\left(\mathbf{G}_j \mathbf{B}\mathbf{B}^H \mathbf{G}_j^H\right) \le e_{max,j}',\ j = 1, \ldots, L \\ & \min_i \sigma_n^2 \text{tr}\left(\left(\sigma_n^2 \mathbf{I}_M + \mathbf{B}^H \mathbf{H}_i^H \mathbf{H}_i \mathbf{B}\right)^{-1}\right) \le \rho \end{aligned} \tag{13}$$

where ρ is the maximum allowable MSE at the output of each ID receiver. Let us assume that problem (13) is feasible and solve it. Similar to Section III, after some manipulations, problem (13) can be reformulated as an SDP problem that is given by

$$\begin{aligned} \max_{\mathbf{F} \succeq 0, \mathbf{T}_i} \quad & \sum_{j=1}^{L} \text{tr}\left(\mathbf{G}_j \mathbf{F} \mathbf{G}_j^H\right) \\ & \text{tr}\left(\mathbf{F}\right) \le P_{s,max} \\ & \text{tr}\left(\mathbf{G}_j \mathbf{F} \mathbf{G}_j^H\right) \le e_{max,j}',\ j = 1, \ldots, L \\ & \begin{bmatrix} \mathbf{T}_i & \mathbf{I}_N \\ \mathbf{I}_N & \sigma^2 \mathbf{I}_M + \mathbf{H}_i \mathbf{F} \mathbf{H}_i^H \end{bmatrix} \succeq 0,\ i = 1, \cdots, K \\ & \text{tr}\left(\mathbf{T}_i\right) \le \rho',\ i = 1, \cdots, K \end{aligned} \tag{14}$$

where $\rho' = (\rho + N - L)/\sigma_n^2$. This is a convex SDP problem and we can solve it optimally using interior point algorithms. In particular, here, we use the convex optimization toolbox CVX [11] to solve problem (13) at a complexity order of at most $\mathcal{O}\left(\left(M^2 + K + L + 1\right)^{3.5}\right)$ [9]. Similar to Section III, we can use the eigen-decomposition to get the optimal $\mathbf{B}^\star$ from $\mathbf{F}^\star$.

Remark 1: Another way to design the source precoder and the IDs receivers is by minimizing the source transmit power under harvested energy and worst case MSE constraints. This problem is omitted due to space limitation. However, the corresponding optimization problem can be formulated and solved in a similar fashion to the optimization problems in Sections III and IV.

V. Simulation Results

In this section, we assess the performance of the proposed solutions. We assume that the transmitted symbols are drawn from a 4-QAM constellation. Moreover, we assume that the entries of $\mathbf{H}_j$ and $\mathbf{G}_j$ are i.i.d. zero mean complex Gaussian random variables with variance $d^{-\eta}$, where d is the distance in meters between the source and each receiving node (ID or EH) and η is the path loss. In the following, we assume $\eta = 2.7$, and an energy conversion loss factor of $\alpha = 0.8$. We note that all the results are obtained by averaging over 10^3 realizations of the channels.

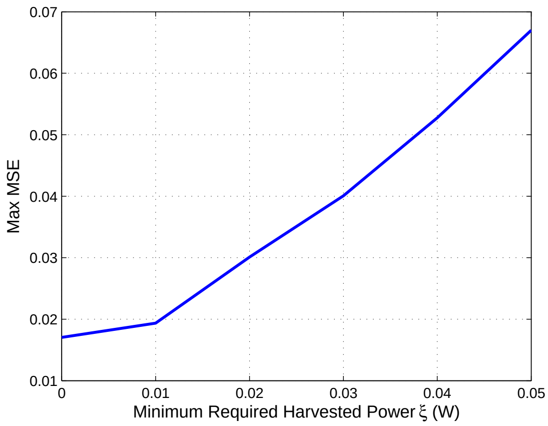

Fig. 2. MSE at the IDs vs. the minimum required harvested power ξ for $K = 2$ IDs and $L = 2$ EHs. We assume $P_{s,max} = 1\ W$, $M = N = 2$ antennas, $d = 5\ m$, and an average receive SNR of 30 dB.

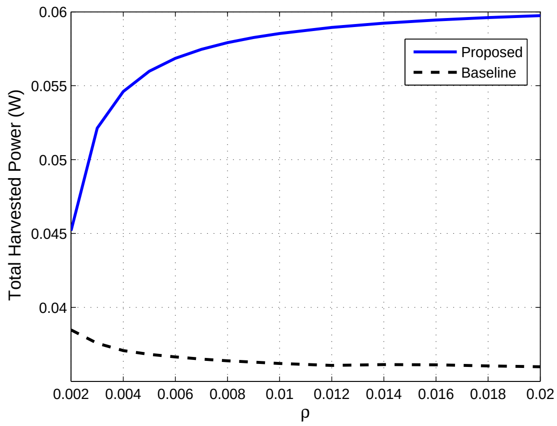

Fig. 3. Total harvested power vs. the maximum allowable MSE ρ at IDs. We assume $d = 5\ m$, $K = 2$ IDs, $L = 2$ EHs, $M = N = 2$ antennas, $P_{s,max} = 1\ W$ and $\sigma_n^2 = 10^{-4}\ W$.

Fig. 2 shows the worst case MSE at the IDs vs. the minimum required harvested power ξ at each energy harvester for $K = 2$ IDs and $L = 2$ EHs. We assume $P_{s,max} = 1$ watt (W), $d = 5\ m$, $M = N = 2$ antennas, and an average signal-to-noise ratio (SNR) of 30 dB at each receive antenna. Since optimization problem (12) is not always feasible, we only take into consideration the solutions when the problem is feasible to plot Fig. 2. We observe that the performance in terms of MSE degrades as the minimum required harvested power increases. This is because it is not possible to simultaneously minimize the MSEs at the IDs and maximize the harvested power.

Fig. 3 shows the total harvested power at the EHs vs. the maximum allowable MSE ρ at the IDs. We assume $\sigma_n^2 = 10^{-4}\ W$, $d = 5\ m$, $K = 2$ IDs, $L = 2$ EHs, and $M = N = 2$ antennas. We compare the proposed scheme with the scheme, referred to as *Baseline*, in which the optimization problem is a feasibility problem with source transmit power and worst case MSE constraints. We observe that the smaller ρ the smaller the harvested power. This is expected since to achieve smaller MSEs, the source directs the beams towards the IDs and hence less power can be harvested at the EHs. We also notice that for $\rho \geq 0.016$, the amount of the harvested power is almost constant. This is due to the fact that for a large ρ, the worst case MSE constraints are not active most of the time. We also notice that the proposed scheme performs better than the baseline scheme since in the latter we just satisfy the source transmit power and worst case MSE constraints without maximizing the harvested energy at the EHs. From Figs. 2 and 3, we can conclude that it is important to design the transceivers taking into account the tradeoffs among the source transmit power, the MSEs at the IDs, and the harvested energy at the EHs. Moreover, the performance gains of the schemes may be useful for the communication system designer to decide whether it is better to redesign the system by taking into account the energy harvesting aspect or to just keep the existing system design (conventional). For example, if the performance gains of the conventional and energy harvesting systems are very close, then redesigning the system may not be justified.

VI. Conclusion

We investigated the joint source precoder and IDs receivers design for MIMO multicast channels for SWIPT. In particular, we assumed linear receivers at the IDs and considered two criteria to compute the source precoder and IDs receivers. In the first criterion, we minimized the worst case MSE at the IDs subject to constraints on the source transmit power and harvested power at the EHs. In the second criterion, we maximized the total harvested energy at the EHs subject to source transmit power and worst case MSE at the IDs. To optimally solve the two optimization problems, we reformulated them as SDP problems. Numerical results showed the effectiveness of the proposed solutions and the tradeoff among source transmit power, MSE at the IDs, and harvested energy at the EHs.

References

[1] P. Nintanavongsa, U. Muncuk, D. Lewis, and K. Chowdhury, "Design optimization and implementation for RF energy harvesting circuits," *IEEE J. Emerg. and Sel. Topics in Circuits and Syst.*, vol. 2, no. 1, pp. 24–33, Mar. 2012.

[2] L. R. Varshney, "Transporting information and energy simultaneously," in *IEEE Int. Symposium on Inform. Theory*, Jul. 2008, pp. 1612–1616.

[3] P. Grover and A. Sahai, "Shannon meets tesla: Wireless information and power transfer," in *IEEE Int. Symposium on Inform. Theory*, Jun. 2010, pp. 2363–2367.

[4] 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.

[5] J. Park and B. Clerckx, "Joint wireless information and energy transfer in a two-user MIMO interference channel," *IEEE Trans. Wireless Commun.*, vol. 12, no. 8, pp. 4210–4221, Aug. 2013.

[6] A. M. Fouladgar and O. Simeone, "On the transfer of information and energy in multi-user systems," *IEEE Commun. Lett.*, vol. 16, no. 11, pp. 1733–1736, Nov. 2012.

[7] 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. 3269–3279, Jun. 2014.

[8] M. R. A. Khandaker and K. K. Wong, "SWIPT in MISO multicasting systems," *IEEE Commun. Lett.*, vol. 3, no. 3, pp. 277–280, Jun. 2014.

[9] N. D. Sidiropoulos, T. N. Davidson, and Z.-Q. Luo, "Transmit beamforming for physical-layer multicasting," *IEEE Trans. Signal Process.*, vol. 54, no. 6, pp. 2239–2251, Jun. 2006.

[10] H. Zhu, N. Prasad, and S. Rangarajan, "Precoder design for physical layer multicasting," *IEEE Trans. Signal Process.*, vol. 60, no. 11, pp. 5932–5947, Nov. 2012.

[11] M. Grant and S. Boyd, "CVX: Matlab software for disciplined convex programming, version 2.0 beta," http://cvxr.com/cvx, Sep. 2013.