DISTRIBUTED BEAMFORMING IN RELAY NETWORKS FOR ENERGY HARVESTING MULTI-GROUP MULTICAST SYSTEMS

Özlem Tuğfe Demir, T. Engin Tuncer

Electrical and Electronics Engineering Department, METU, Ankara, Turkey
{deozlem , etuncer}@metu.edu.tr

ABSTRACT

In this paper, simultaneous wireless information and power transfer (SWIPT) is considered for multi-group multicasting relay networks where there is no direct link between the source and destination nodes. Each source transmits its own multicast stream to a group of users with the help of single antenna relays which use amplify-and-forward relay protocol. Each user has energy harvesting capability. A part of the received signal is used for information decoding while the rest is used for energy harvesting. The design problem is to determine the complex relay weights and the power splitting ratios for the users. The resulting optimization problem is nonconvex and converted into a form suitable for quadratically constrained quadratic programming. In addition to the conventional relay beamforming, distributed phase-only beamformer design is also considered and both beamformer design problems are solved iteratively using feasible point pursuit-successive convex approximation algorithm. Several simulations are performed and the advantages of both approaches are outlined.

***Index Terms*—** Multi-group multicast beamforming, distributed beamforming, phase-only beamforming, SWIPT

1. INTRODUCTION

In modern wireless networks, radio frequency (RF) signals can be used for energy harvesting in addition to the information transmission. As a green and convenient method, SWIPT has drawn great attention recently [1]. SWIPT is an effective approach for mobile users and devices with limited battery. The idea of SWIPT is first introduced in [2] and then considered for multi-user systems in [1], [3], [4], [5], etc. There are basically two practical receiver architectures in SWIPT systems; power splitting (PS) and time switching (TS) respectively [1]. The previous works in multicasting area have usually considered PS scheme. In this case, users have a PS device by which the received signal is split into two streams with different powers, one for decoding information and the other for harvesting energy [3], [4]. In this paper, users are assumed to have PS capability.

We consider distributed beamforming, which is also referred as collaborative beamforming, where single antenna relays work as a virtual antenna array for helping the long distance communication between single antenna transmitters and users [6], [7]. Cooperative relaying is an energy efficient approach to increase spatial diversity. We study multi-group multicasting scenario where there are different multicast groups with users in each group interested in a common information. Each multicast stream is transmitted from one transmitter node and two-hop data transmission occurs. In the first phase, the source nodes transmit their multicast streams. In the next phase, the relays forward the amplified and phase adjusted version of their received signals to the users. The goal is to satisfy the signal-to-interference-plus-noise-ratio (SINR) and energy demands of the users simultaneously with minimum relay power.

While distributed beamforming is presented for multi-group multicasting relay networks in [7], this paper is the first work which elaborates the same problem for SWIPT to the best of our knowledge. The optimization problem for the relay weights and power splitting ratios of the users is nonconvex. First, it is converted to a more manageable form with quadratic and second order cone constraints. The resulting problem is suitable for the application of feasible point pursuit-successive convex approximation (FPP-SCA) algorithm proposed recently [8]. It is an effective method and has less worst-case computational complexity than the well-known semidefinite relaxation [9].

The first problem in this paper assumes that the relays can adjust their powers arbitrarily. However, phase-only distributed beamforming where all relays use the same power is presented as a greener approach in [10]. It is proved that the lifetime of the relay network increases with phase-only design which prevents the uneven battery utilization. Motivated by [10], we introduce phase-only distributed beamforming for multi-group multicasting scenario as a second problem. The resulting problem can easily be solved using exact penalty function and an extended version of FPP-SCA. Simulation results show the importance of the proposed algorithm for phase-only design by comparing it with the normalized distributed beamformer.

2. SYSTEM MODEL

Consider a wireless relay network where G transmitters (source nodes) transmit different multicast signals to N users (destination nodes) through M relays. All nodes in this network are equipped with a single antenna. It is assumed that there is no direct link between the source and destination nodes due to path losses. There are G multicast groups, $\{\mathcal{G}_1, ..., \mathcal{G}_G\}$, where $\mathcal{G}_k$ denotes the k^{th} multicast group of users. Each user wants to receive only one multicast stream, i.e., $\mathcal{G}_k \bigcap \mathcal{G}_l = \emptyset$. We consider the two-hop data transmission. In the first phase of the transmission, the transmitter nodes broadcast their signals to the relays and in the second phase, all relays simultaneously transmit the amplified and phase-adjusted version of their received signals to the destination nodes.

The received signal at the relays is $\mathbf{r} = \sum_{k=1}^{G} \mathbf{f}_k s_k + \mathbf{n}_r$, where s_k is the information symbol transmitted by the k^{th} source node, $\mathbf{f}_k = [\ f_{k,1}\ f_{k,2}\ ...\ f_{k,M}\ ]^T$, $f_{k,m}$ is the complex channel gain between the k^{th} source node and the m^{th} relay. $\mathbf{n}_r = [\ n_{r,1}\ n_{r,2}\ ...\ n_{r,M}\ ]^T$ is the relay noise vector and $\mathbf{r} = [\ r_1\ r_2\ ...\ r_M\ ]^T$ where r_m is the received signal at the m^{th} relay. The m^{th} relay multiplies its received signal, r_m, by a complex weight $w_m^{\star}$ and transmits the resulting signal, $t_m = w_m^{\star} r_m$, to the destination nodes. The transmitted signal from the relays is given as,

$\mathbf{t} = \mathbf{W}^H\mathbf{r}$ where $\mathbf{t} = [\ t_1\ t_2\ ...\ t_M\ ]^T$ and $\mathbf{W}$ is a diagonal matrix whose elements are complex conjugates of the complex weights, i.e., $\mathbf{W} = diag\{w_1, w_2,\ ..., w_M\}$. The received signal at the i^{th} user is, $y_i = \mathbf{g}_i^T\mathbf{t} + n_{A,i} = \mathbf{g}_i^T(\mathbf{W}^H\sum_{k=1}^{G}\mathbf{f}_k s_k + \mathbf{W}^H\mathbf{n}_r) + n_{A,i}$ where $\mathbf{g}_i = [\ g_{i,1}\ g_{i,2}\ ...\ g_{i,M}\ ]^T$ and $g_{i,m}$ denotes the complex channel gain between m^{th} relay and i^{th} destination. $n_{A,i}$ is the noise at the i^{th} receiver's antenna.

Defining $\mathbf{G}_i = diag\{g_{i,1}, g_{i,2}, ..., g_{i,M}\}$ and $\mathbf{w} = [\ w_1\ w_2\ ...\ w_M\ ]^T$, the received signal can be written as $y_i = \mathbf{w}^H\mathbf{G}_i(\sum_{k=1}^{G}\mathbf{f}_k s_k + \mathbf{n}_r) + n_{A,i}$. It is assumed that the information symbols s_k, the relay and the receiver noises are mutually uncorrelated in accordance with [6] and [7].

The signal at the i^{th} receiver is split into energy harvester (EH) and information decoder (ID) with the aid of a power splitter (PS) device. PS is assumed to be ideal without any induced noise. A part of the signal power denoted by $0 < \rho_i < 1$ is transmitted to ID while the remaining $1-\rho_i$ part is fed into EH. The signal at the ID of the i^{th} receiver can be expressed as,

$$y_{I,i} = \sqrt{\rho_i}(\mathbf{w}^H\mathbf{G}_i\sum_{k=1}^{G}\mathbf{f}_k s_k + \mathbf{w}^H\mathbf{G}_i\mathbf{n}_r + n_{A,i}) + n_{I,i} \quad (1)$$

where $n_{I,i}$ is the additional zero-mean Gaussian noise introduced by the ID of the i^{th} user. $n_{I,i}$ is independent of the source signals, $\mathbf{n}_r$ and $n_{A,i}$. Assuming that the i^{th} user is in the k^{th} multicast group, $\mathcal{G}_k$, the SINR for the i^{th} user is,

$$\frac{\mathbb{E}\{|\sqrt{\rho_i}\mathbf{w}^H\mathbf{G}_i\mathbf{f}_k s_k|^2\}}{\mathbb{E}\{|\sqrt{\rho_i}\mathbf{w}^H\mathbf{G}_i(\sum_{l\neq k}\mathbf{f}_l s_l + \mathbf{n}_r) + \sqrt{\rho_i}n_{A,i} + n_{I,i}|^2\}} \quad (2)$$

where $\mathbb{E}\{|\sqrt{\rho_i}\mathbf{w}^H\mathbf{G}_i\mathbf{f}_k s_k|^2\} = \rho_i P_k\mathbf{w}^H\mathbf{G}_i\mathbf{f}_k{\mathbf{f}_k}^H{\mathbf{G}_i}^H\mathbf{w}$ and $\mathbb{E}\{|\sqrt{\rho_i}\mathbf{w}^H\mathbf{G}_i(\sum_{l\neq k}\mathbf{f}_l s_l + \mathbf{n}_r) + \sqrt{\rho_i}n_{A,i} + n_{I,i}|^2\} = \rho_i\mathbf{w}^H\mathbf{G}_i(\sum_{l\neq k}P_l\mathbf{f}_l{\mathbf{f}_l}^H){\mathbf{G}_i}^H\mathbf{w} + \rho_i\sigma_r^2\mathbf{w}^H\mathbf{G}_i{\mathbf{G}_i}^H\mathbf{w} + \rho_i\sigma_{A,i}^2 + \sigma_{I,i}^2$ assuming that the channels are known in accordance with [7]. Here, the relay noise is assumed to be spatially white without loss of generality. P_k, σ_r^2, $\sigma_{A,i}^2$ and $\sigma_{I,i}^2$ denote the k^{th} source power, the noise variances of the relays, i^{th} receiver's antenna and ID, respectively. The signal fed into the EH of the i^{th} receiver can be expressed as,

$$y_{E,i} = \sqrt{1-\rho_i}(\mathbf{w}^H\mathbf{G}_i\sum_{k=1}^{G}\mathbf{f}_k s_k + \mathbf{w}^H\mathbf{G}_i\mathbf{n}_r + n_{A,i}) \quad (3)$$

Then, the power harvested by the EH of the i^{th} receiver is $\xi_i(1-\rho_i)(\mathbf{w}^H\mathbf{G}_i(\sum_{k=1}^{G}P_k\mathbf{f}_k{\mathbf{f}_k}^H){\mathbf{G}_i}^H\mathbf{w} + \sigma_r^2\mathbf{w}^H\mathbf{G}_i{\mathbf{G}_i}^H\mathbf{w} + \sigma_{A,i}^2)$ where $0 < \xi_i \leq 1$ is the energy conversion efficiency of the EH at the i^{th} receiver.

In the following part of this paper, beamformer weight vector, $\mathbf{w}$, and power splitting ratios, $\{\rho_i\}_{i=1}^N$, are designed for the relays and users respectively in a multi-group multicasting scenario.

3. QOS-AWARE DISTRIBUTED BEAMFORMING FOR SWIPT

In this paper, the relay beamformer is designed by using quality of service (QoS) approach [6], [7]. Hence, it is desired to minimize the total power transmitted from the relays by ensuring that the SINR and the harvested power at each user is above a certain threshold. The total transmitted power from the relays can be written as,

$$P_T = \sum_{m=1}^{M}\mathbb{E}\{|t_m|^2\} = \sum_{m=1}^{M}|w_m|^2\mathbb{E}\{|r_m|^2\} = \mathbf{w}^H\mathbf{D}\mathbf{w} \quad (4)$$

where $\mathbf{D}$ is the diagonal matrix whose elements are $\mathbb{E}\{|r_m|^2\}$, i.e., $\mathbf{D} = diag\{\mathbb{E}\{|r_1|^2\}, ..., \mathbb{E}\{|r_M|^2\}\}$. $\mathbb{E}\{|r_m|^2\} = \sum_{k=1}^{G}P_k|f_{k,m}|^2 + \sigma_r^2$.

Let us define $\mathbf{h}_{k,i} = \mathbf{G}_i\mathbf{f}_k$ and $\mathbf{Q}_{k,i} = \sum_{l\neq k}P_l\mathbf{h}_{l,i}{\mathbf{h}_{l,i}}^H$. The optimization problem to minimize the total transmitted relay power subject to user SINR and harvested power constraints can be written as,

$$\min_{\mathbf{w}\in\mathbb{C}^M, \{\rho_i\}_{i=1}^N} \quad \mathbf{w}^H\mathbf{D}\mathbf{w} \quad (5.a)$$

$$s.t.\ \frac{\rho_i P_k\mathbf{w}^H\mathbf{h}_{k,i}{\mathbf{h}_{k,i}}^H\mathbf{w}}{\rho_i\mathbf{w}^H(\mathbf{Q}_{k,i} + \sigma_r^2\mathbf{G}_i{\mathbf{G}_i}^H)\mathbf{w} + \rho_i\sigma_{A,i}^2 + \sigma_{I,i}^2} \geq \gamma_i, \quad (5.b)$$

$$\xi_i(1-\rho_i)(\mathbf{w}^H(P_k\mathbf{h}_{k,i}{\mathbf{h}_{k,i}}^H + \mathbf{Q}_{k,i} + \sigma_r^2\mathbf{G}_i{\mathbf{G}_i}^H)\mathbf{w} + \sigma_{A,i}^2) \geq \mu_i \quad (5.c)$$

$$0 < \rho_i < 1, \quad \forall i \in \mathcal{G}_k, \forall k \in \{1, ..., G\} \quad (5.d)$$

$$|w_m|^2 D_{m,m} \leq p_m, \quad m = 1, 2, ..., M \quad (5.e)$$

where γ_i and μ_i are the SINR and harvested power thresholds respectively for the i^{th} user. $D_{m,m}$ shows the m^{th} diagonal element of $\mathbf{D}$. p_m is the maximum allowable power for the m^{th} relay. The fact that relays may not want to use too much power due to their limited battery lifetime motivates us to include the individual power constraints in (5.e) [7]. The problem in (5) is not convex due to quadratic and coupled terms of $\mathbf{w}$ and ρ_i's [1].

Let us express (5) in a simpler way by decoupling $\mathbf{w}$ and ρ_i's. If we define $\mathbf{T}_{k,i} = P_k\mathbf{h}_{k,i}{\mathbf{h}_{k,i}}^H - \gamma_i(\mathbf{Q}_{k,i} + \sigma_r^2\mathbf{G}_i{\mathbf{G}_i}^H)$ and $\mathbf{S}_{k,i} = P_k\mathbf{h}_{k,i}{\mathbf{h}_{k,i}}^H + \mathbf{Q}_{k,i} + \sigma_r^2\mathbf{G}_i{\mathbf{G}_i}^H$, we can express (5) as follows,

$$\min_{\mathbf{w}\in\mathbb{C}^M, \{\rho_i\}_{i=1}^N} \quad \mathbf{w}^H\mathbf{D}\mathbf{w} \quad (6.a)$$

$$s.t.\ \mathbf{w}^H\mathbf{T}_{k,i}\mathbf{w} \geq \frac{\gamma_i\sigma_{I,i}^2}{\rho_i} + \gamma_i\sigma_{A,i}^2 \quad (6.b)$$

$$\mathbf{w}^H\mathbf{S}_{k,i}\mathbf{w} \geq \frac{\mu_i}{\xi_i(1-\rho_i)} - \sigma_{A,i}^2, \quad (6.c)$$

$$0 < \rho_i < 1, \quad \forall i \in \mathcal{G}_k, \forall k \in \{1, ..., G\} \quad (6.d)$$

$$|w_m|^2 D_{m,m} \leq p_m, \quad m = 1, 2, ..., M \quad (6.e)$$

Although $\frac{1}{\rho_i}$ and $\frac{1}{1-\rho_i}$ are convex functions of ρ_i for $0 < \rho_i < 1$ [1], the problem in (6) is not convex since the matrices $\mathbf{T}_{k,i}$ and $\mathbf{S}_{k,i}$ are not negative semidefinite. Recently, an efficient iterative method, FPP-SCA, is proposed for quadratically constrained quadratic programming (QCQP) problems in [8]. However, FPP-SCA algorithm in [8] cannot be applied for the current form of (6). The following lemma enables us to write (6.b) and (6.c) as quadratic constraints.

Lemma 1: There exists an optimum solution of (7), $\{\mathbf{w}_{opt}, \{\upsilon_{i_{opt}}, \kappa_{i_{opt}}\}_{i=1}^N\}$ such that $\upsilon_{i_{opt}} = \frac{1}{\rho_{i_{opt}}}$ and $\kappa_{i_{opt}} = \frac{1}{1-\rho_{i_{opt}}}$, $i = 1, ..., N$ where $\{\mathbf{w}_{opt}, \{\rho_{i_{opt}}\}_{i=1}^N\}$ is the optimum solution of (6).

$$\min_{\mathbf{w}\in\mathbb{C}^M, \{\upsilon_i, \kappa_i\}_{i=1}^N} \quad \mathbf{w}^H\mathbf{D}\mathbf{w} \quad (7.a)$$

$$s.t.\ \mathbf{w}^H\mathbf{T}_{k,i}\mathbf{w} \geq \gamma_i\sigma_{I,i}^2\upsilon_i + \gamma_i\sigma_{A,i}^2 \quad (7.b)$$

$$\mathbf{w}^H\mathbf{S}_{k,i}\mathbf{w} \geq \frac{\mu_i}{\xi_i}\kappa_i - \sigma_{A,i}^2 \quad (7.c)$$

$$\left\|\begin{matrix}\upsilon_i - \kappa_i \\ 2\end{matrix}\right\|_2 \leq \upsilon_i + \kappa_i - 2 \quad (7.d)$$

$$\forall\, i \in \mathcal{G}_k, \forall\, k \in \{1, ..., G\}$$

$$|w_m|^2 D_{m,m} \leq p_m, \quad m = 1, 2, ..., M \quad (7.e)$$

Proof: The modifications in (7) are the change of variables from ρ_i to υ_i and κ_i, and the second order cone constraint in (7.d) in place of (6.d). The condition in (7.d) implies the following inequality,

$$(\upsilon_i - \kappa_i)^2 + 4 \leq (\upsilon_i + \kappa_i - 2)^2$$
$$\upsilon_i^2 + \kappa_i^2 - 2\upsilon_i\kappa_i + 4 \leq \upsilon_i^2 + \kappa_i^2 + 2\upsilon_i\kappa_i - 4\upsilon_i - 4\kappa_i + 4$$
$$\upsilon_i + \kappa_i \leq \upsilon_i\kappa_i \quad (8)$$

Note that $\upsilon_i + \kappa_i \geq 2$ implying $\upsilon_i\kappa_i \geq 0$ by (8). If we divide (8) by $\upsilon_i\kappa_i$, we obtain the following inequality,

$$\frac{1}{\upsilon_i} + \frac{1}{\kappa_i} \leq 1 \quad (9)$$

At this point, let us assume that (9) is not satisfied with equality for at least one of the pairs $\{\upsilon_{i_{opt}}, \kappa_{i_{opt}}\}$ for the optimum solution. Then, we can scale $\{\upsilon_{i_{opt}}, \kappa_{i_{opt}}\}$ such that (9) is satisfied with equality without violating the SINR and harvested energy constraints. In this case, the other variables do not change and we have another optimum solution such that $\upsilon_{i_{opt}} = \frac{1}{\rho_{i_{opt}}}$, $\kappa_{i_{opt}} = \frac{1}{1-\rho_{i_{opt}}}$. Hence, it is always possible to find an optimum solution such that (9) is satisfied with equality. ■

The modified form of (6) in (7) is now suitable for the application of FPP-SCA.

4. FPP-SCA APPROACH

The problem in (7) is convex except the quadratic constraints in (7.b) and (7.c). In conventional successive convex approximation (SCA), $\mathbf{T}_{k,i}$ and $\mathbf{S}_{k,i}$ are partitioned into positive and negative semidefinite parts as $\mathbf{T}_{k,i} = \mathbf{T}_{k,i}^{(+)} + \mathbf{T}_{k,i}^{(-)}$ and $\mathbf{S}_{k,i} = \mathbf{S}_{k,i}^{(+)} + \mathbf{S}_{k,i}^{(-)}$ where $\mathbf{T}_{k,i}^{(+)}$, $\mathbf{S}_{k,i}^{(+)} \succeq 0$ (positive semidefinite matrices) and $\mathbf{T}_{k,i}^{(-)}$, $\mathbf{S}_{k,i}^{(-)} \preceq 0$ (negative semidefinite matrices) [11]. $\mathbf{T}_{k,i}$ and $\mathbf{S}_{k,i}$ can be decomposed simply as $\mathbf{T}_{k,i}^{(+)} = P_k\mathbf{h}_{k,i}\mathbf{h}_{k,i}{}^H$, $\mathbf{T}_{k,i}^{(-)} = -\gamma_i(\mathbf{Q}_{k,i} + \sigma_r^2\mathbf{G}_i\mathbf{G}_i{}^H)$ and $\mathbf{S}_{k,i}^{(+)} = \mathbf{S}_{k,i} = P_k\mathbf{h}_{k,i}\mathbf{h}_{k,i}{}^H + \mathbf{Q}_{k,i} + \sigma_r^2\mathbf{G}_i\mathbf{G}_i{}^H$. (7) is nonconvex due to the terms $\mathbf{w}^H\mathbf{T}_{k,i}^{(+)}\mathbf{w}$ and $\mathbf{w}^H\mathbf{S}_{k,i}^{(+)}\mathbf{w}$. For any vector $\mathbf{z} \in \mathbb{C}^M$, $(\mathbf{w}-\mathbf{z})^H\mathbf{T}_{k,i}^{(+)}(\mathbf{w}-\mathbf{z}) \geq 0$. Expanding the left-hand side of the inequality, we obtain, $\mathbf{w}^H\mathbf{T}_{k,i}^{(+)}\mathbf{w} \geq 2\,\mathrm{Re}\{\mathbf{z}^H\mathbf{T}_{k,i}^{(+)}\mathbf{w}\} - \mathbf{z}^H\mathbf{T}_{k,i}^{(+)}\mathbf{z}$. Using this bound, the nonconvex constraints in (7.b) and (7.c) can be replaced by the following convex constraints as follows,

$$\mathbf{w}^H\mathbf{T}_{k,i}^{(-)}\mathbf{w} + 2\,\mathrm{Re}\{\mathbf{z}^H\mathbf{T}_{k,i}^{(+)}\mathbf{w}\} - \mathbf{z}^H\mathbf{T}_{k,i}^{(+)}\mathbf{z} \geq \gamma_i\sigma_{I,i}^2\upsilon_i + \gamma_i\sigma_{A,i}^2$$
$$2\,\mathrm{Re}\{\mathbf{z}^H\mathbf{S}_{k,i}^{(+)}\mathbf{w}\} - \mathbf{z}^H\mathbf{S}_{k,i}^{(+)}\mathbf{z} \geq \frac{\mu_i}{\xi_i}\kappa_i - \sigma_{A,i}^2$$

SCA also known as convex-concave procedure, solves the problem iteratively by taking the previous iterate $\mathbf{w}$ as $\mathbf{z}$ in the current iteration. In this way, a sequence of feasible points are obtained with decreasing objective values [11]. The drawback of this method is that it requires an initial feasible point. In [8], the feasibility of SCA is improved by adding slack variables and a slack penalty to the original problem. If the original problem is feasible, these slack variables tend to go to zero. The steps of the FPP-SCA algorithm for the problem in (7) are given as follows.

Algorithm 1: FPP-SCA Algorithm for SWIPT with QoS-Aware Distributed Beamforming

Initialization: Set $k = 0$ and randomly generate an initial point $\mathbf{z}_0$.
Iterations: $k = k + 1$.

1) Solve the following problem in (10).

$$\min_{\mathbf{w}\in\mathbb{C}^M, \{\upsilon_i,\kappa_i\}_{i=1}^N, \{s_i,r_i\}_{i=1}^N} \mathbf{w}^H\mathbf{D}\mathbf{w} + \lambda\sum_{i=1}^N(s_i + r_i) \quad (10.a)$$
$$s.t.\ \mathbf{w}^H\mathbf{T}_{k,i}^{(-)}\mathbf{w} + 2\,\mathrm{Re}\{\mathbf{z}_{k-1}^H\mathbf{T}_{k,i}^{(+)}\mathbf{w}\} - \mathbf{z}_{k-1}^H\mathbf{T}_{k,i}^{(+)}\mathbf{z}_{k-1} + s_i \geq \gamma_i\sigma_{I,i}^2\upsilon_i + \gamma_i\sigma_{A,i}^2 \quad (10.b)$$
$$2\,\mathrm{Re}\{\mathbf{z}_{k-1}^H\mathbf{S}_{k,i}^{(+)}\mathbf{w}\} - \mathbf{z}_{k-1}^H\mathbf{S}_{k,i}^{(+)}\mathbf{z}_{k-1} + r_i \geq \frac{\mu_i}{\xi_i}\kappa_i - \sigma_{A,i}^2 \quad (10.c)$$
$$(7.d), (7.e)$$

where $\lambda \gg 1$ forces the slack variables $\{s_i, r_i\}_{i=1}^N$ towards zero.
2) Set $\mathbf{z}_k = \mathbf{w}_k$ where $\mathbf{w}_k$ is the optimum solution of (10) at the k^{th} iteration.
3) Terminate if the maximum iteration number, $k = k_{max}$, is reached or $||\mathbf{w}_k - \mathbf{z}_{k-1}|| \leq \epsilon$ for sufficiently small $\epsilon > 0$.
End:
4) Take the candidate beamformer weight vector $\mathbf{w}^\star$ as $\mathbf{w}_k$ and power splitting ratios $\rho_i^\star$ as $\frac{1}{\upsilon_{ik}}$ after scaling υ_{ik} and κ_{ik} such that $\frac{1}{\upsilon_{ik}} + \frac{1}{\kappa_{ik}} = 1$ where $\{\upsilon_{ik}, \kappa_{ik}\}_{i=1}^N$ is obtained by solving (10) at the k^{th} iteration.
5) Scale $\mathbf{w}^\star$ if necessary such that (6.b) and (6.c) are satisfied without violating (6.e).

The quadratic constraints in (10) can be easily formulated as second-order cone constraints. The worst-case complexity of solving (10) in second-order cone form is $O([M + 4N])^{3.5})$ (the number of variables is $M + 4N$) [8].

5. DISTRIBUTED PHASE-ONLY BEAMFORMING

In the previous section, the beamformer weight vector is designed such that the relays can adjust their powers arbitrarily. The major drawback of this approach is the uneven battery utilization of the relays, resulting a node running out of energy independent of the others. In this case, a new beamformer weight vector should be designed for the remaining relays [10]. Instead, we restrict the relays to consume the same amount of power, hence leading to phase-only beamformer. QoS-aware distributed phase-only beamforming problem can be written as,

$$\min_{\mathbf{w}\in\mathbb{C}^M, \{\upsilon_i,\kappa_i\}_{i=1}^N, p} p \quad (11.a)$$
$$s.t.\ |w_m|^2 D_{m,m} = p \quad (11.b)$$
$$p \leq p_m \quad m = 1, 2, ..., M \quad (11.c)$$
$$(7.b), (7.c), (7.d)$$

The constraints in (11.b) are not convex and not appropriate for FPP-SCA algorithm. It is possible to express (11) in a different form, i.e.,

$$\min_{\mathbf{w}\in\mathbb{C}^M, \{\upsilon_i,\kappa_i\}_{i=1}^N, p} p \quad (12.a)$$
$$s.t.\ |w_m|^2 D_{m,m} \leq p \quad (12.b)$$
$$|w_m|^2 D_{m,m} \geq p \quad (12.c)$$
$$p \leq p_m \quad m = 1, 2, ..., M \quad (12.d)$$
$$(7.b), (7.c), (7.d)$$

While the constraints in (12.b) are convex, the ones in (12.c) are not. We can use exact penalty function to move the constraints in (12.c) to the objective function as follows [12],

$$\min_{\mathbf{w}\in\mathbb{C}^M,\{\upsilon_i,\kappa_i\}_{i=1}^N,p} \quad p + \zeta \sum_{m=1}^{M} \max\{0, p - |w_m|^2 D_{m,m}\} \quad \text{(13.a)}$$

$$s.t. \quad \text{(7.b), (7.c), (7.d), (12.b), (12.d)}$$

Note that the terms in exact penalty function satisfy $\max\{0, p - |w_m|^2 D_{m,m}\} = p - |w_m|^2 D_{m,m}$ by (12.b) and exact penalty function can be written as $\zeta \sum_{m=1}^{M} \max\{0, p - |w_m|^2 D_{m,m}\} = \zeta(Mp - \mathbf{w}^H \mathbf{D}\mathbf{w})$. In this case, the objective function is not convex. A powerful approach to solve this type of exact penalty embedded problems is alternating minimization [13], [14]. In the following algorithm, we replace nonconvex $\zeta(Mp - \mathbf{w}^H \mathbf{D}\mathbf{w})$ term by $\zeta(Mp - \text{Re}\{\mathbf{z}_{k-1}{}^H \mathbf{D}\mathbf{w}\})$ and increase ζ in each iteration.

Algorithm 2: FPP-SCA Algorithm for SWIPT with QoS-Aware Distributed Phase-Only Beamforming

Initialization: Set $k = 0$ and randomly generate an initial point $\mathbf{z}_0$. Set a proper $\zeta > 0$ (Ex: $\zeta = 1$).
Iterations: $k = k + 1$.
1) Solve the following problem in (14).

$$\min_{\mathbf{w}\in\mathbb{C}^M,p,\{\upsilon_i,\kappa_i\}_{i=1}^N,\{s_i,r_i\}_{i=1}^N} \quad p + \lambda \sum_{i=1}^{N} (s_i + r_i)$$

$$+\zeta(Mp - \text{Re}\{\mathbf{z}_{k-1}{}^H \mathbf{D}\mathbf{w}\}) \quad \text{(14.a)}$$

$$s.t. \text{ (10.b), (10.c), (7.d), (12.b), (12.d)}$$

2) Set $\mathbf{z}_k = \mathbf{w}_k$ where $\mathbf{w}_k$ is the optimum solution of (14) at the k^{th} iteration.
3) Set $\zeta = \beta\zeta$ where $\beta > 1$ is a proper penalty scaling value.
4) Terminate if the maximum iteration number, $k = k_{max}$, is reached or $||\mathbf{w}_k - \mathbf{z}_{k-1}|| \leq \epsilon$ for sufficiently small $\epsilon > 0$.
End:
5) Take the candidate phase-only beamformer weight vector $\mathbf{w}^\star$ as $[\ \frac{w_{1k}}{|w_{1k}|}, \ \frac{w_{2k}}{|w_{2k}|}, \ \dots \ \frac{w_{Mk}}{|w_{Mk}|}\ ]^T$ and power splitting ratios $\rho_i^\star$ as $\frac{1}{\upsilon_{ik}}$ after scaling υ_{ik} and κ_{ik} such that $\frac{1}{\upsilon_{ik}} + \frac{1}{\kappa_{ik}} = 1$ where $\{\upsilon_{ik}, \kappa_{ik}\}_{i=1}^N$ is obtained by solving (14) at the k^{th} iteration.
5) Scale $\mathbf{w}^\star$ properly such that (6.b) and (6.c) are satisfied without violating (6.e).

6. SIMULATION RESULTS

In this part, the performance of the proposed algorithms are presented where CVX [15] is used in the implementations. Circularly symmetric random Gaussian channels with unit variances are considered. The total number of the relays is $M = 20$ and the source power for each multicast signal is $P_k = 10$ W. The noise variance and maximum allowable power for each relay are $\sigma_r^2 = 0.1$ and $p_i = 2$ W, respectively. The SINR threshold, γ, harvested power threshold, μ, antenna noise variance, σ_A^2, and ID noise variance, σ_I^2, are the same for each user, i.e., $\gamma = \gamma_i$, $\mu = \mu_i$ and $\sigma_A^2 = \sigma_{A,i}^2 = 0.1$, $\sigma_I^2 = \sigma_{I,i}^2 = 0.1$. The initial value of ζ, β, λ and ϵ in the proposed algorithms are taken as $\zeta = 1$, $\beta = 1.2$, $\lambda = 10$ and $\epsilon = 0.0001M$, respectively.

In the first experiment, single group multicasting scenario is considered, i.e., $G = 1$. The harvested power threshold is selected as $\mu = 0$ dB. Fig. 1 shows the total transmitted relay power for different SINR threshold, γ, values. The average of 100 random channel realizations is presented at each point in this figure. DB and DPOB stand for conventional and phase-only distributed beamformer designed with Algorithm 1 and 2, respectively. NDB-PO corresponds to the phase-only beamformer whose weight vector is obtained by normalizing each element of DB followed by a proper scaling. The transmitted power for DB is less than DPOB as expected due to higher degrees of freedom resulting from the arbitrary power adjustment. The performance gap between DPOB and NDB-PO approaches 4 dB for $N = 16$ users. Hence, just taking phase values of DB and adjusting power are not efficient for the design of phase-only beamformer. The proposed algorithm for DPOB performs much better than NDB-PO.

In the second experiment, there are $G = 2$ multicast groups with 4 users in each one, i.e., $N = 8$. Fig. 2 presents the total transmit relay power of DB, DPOB and NDB-PO for $\mu = 0$ and $\mu = 4$ dB. As μ increases, more power is needed for SWIPT as expected. The additional power to account for more energy harvesting (higher μ) decreases at high SINR threshold. Note that the average of 100 channel realizations where all methods are feasible, is presented at each point. While the power difference between DB and DPOB is not more than 2 dB, the performance of NDB-PO has degraded in comparison to single group multicasting scenario. At some points, the gap between DPOB and NDB-PO reaches 6 dB. In addition, the feasibility percentage of NDB-PO is significantly lower compared to DPOB especially at high SINR.

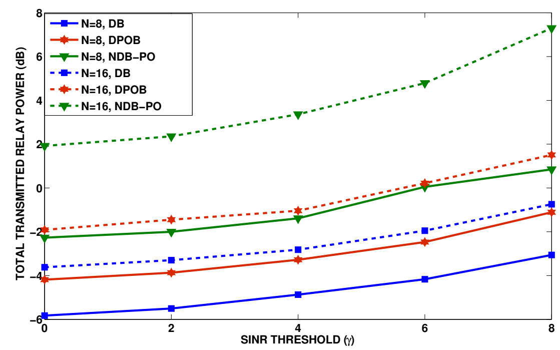

Fig. 1. Total transmitted relay power versus SINR threshold, γ for single group multicasting scenario.

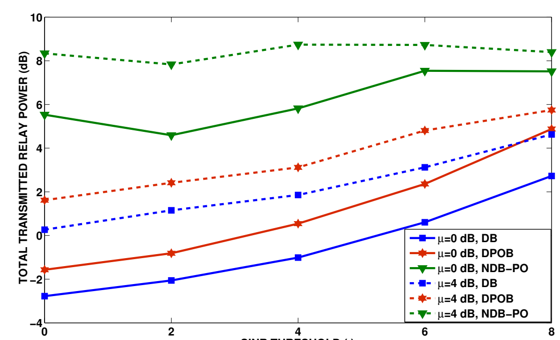

Fig. 2. Total transmitted relay power versus SINR threshold, γ for two-group multicasting scenario.

7. CONCLUSION

In this paper, joint distributed beamforming and receive power splitting for SWIPT multi-group multicast systems is considered. The nonconvex optimization problem is converted to a form suitable for the application of the FPP-SCA algorithm by introducing new variables. In addition to the conventional distributed beamforming, phase-only beamformer design is considered for an even battery utilization. An exact penalty function is used to deal with phase-only constraints. Both problems are solved iteratively and simulation results show the performance and efficiency of the proposed methods.

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