Sum Rate Maximization for Full Duplex Wireless-Powered Communication Networks

Van-Dinh Nguyen, Hieu V. Nguyen, Gil-Mo Kang, Hyeon Min Kim, and Oh-Soon Shin*
School of Electronic Engineering, Soongsil University, Korea
*Corresponding author (E-mail: osshin@ssu.ac.kr)

***Abstract*—We consider a full duplex multiuser multiple-input multiple-output system and study the sum rate maximization in a wireless powered communication networks. We assume that the users of uplink (UL) channel have no available power supply and thus a harvest-then-transmit protocol is utilized. Specifically, the base station (BS) first conveys simultaneously the energy to all UL users via energy beamforming and also transmit the information to all users in the downlink (DL) channel via information beamforming. Then, the users in the UL channel send their independent information to the BS using their harvested energy in the second phase. Since the utility function of the sum rate maximization is nonconvex, and thus, the optimal solution is difficult to find in general. To solve this problem, we propose an iterative algorithm to obtain suboptimal solution based on semidefinite program in each iteration. Simulation results demonstrate that the proposed design outperforms the conventional design.**

I. Introduction

Energy harvesting (EH) has received large attention due to the capability of prolonging the lifetime of wireless networks under energy constraints such as sensor node. Recently, the harvested energy can be extracted from a radio-frequency (RF) signal since the RF signal carries both the information and energy. The authors in [1] have advocated the use of RF signals to harvest energy along with the information transfer. Therefore, EH technique has the potential to provide unlimited energy while achieving self-sustaining green communications [2]–[4].

Moreover, the full duplex (FD) transmission has enormous potential to improve the spectral efficiency of the half duplex (HD) mode without requiring extra bandwidth or transmit power. The major challenge in FD technique is the residual self-interference (SI) from the transmit antennas to the receive antennas at a base station (BS). Therefore it is important that the residual SI is sufficiently canceled. A wide range of residual SI mitigation measures was investigated in [5]. More recently, the FD transmission has been studied in the context of multiuser multiple-input multiple-output (MU-MIMO), where the BS is employed to improve the total spectral efficiency of downlink (DL) and uplink (UL) channels [6].

In this paper, we study the potential of the FD MU-MIMO system with jointly designing of DL energy transfer and UL information transmission in wireless-powered communication networks (WPCNs). Specifically, the BS first transmits simultaneously information and energy to the DL and UL users, respectively. We assume that the users in UL channel have no available power supply and thus a harvest-then-transmit protocol is applied to harvest-and-store energy for UL transmission. We are interested in the problem of join beamformer design to maximize the total sum rate under the sum power and UL rate constraints. Unfortunately, the problem design is neither convex nor concave. As a result, the proposed problem is an intractable fractional program, and thus, the optimal solution is difficult to achieve in general. To solve this problem, we first convert the original problem to an equivalent and tractable form. Consequently, we propose an iterative algorithm to efficiently solve approximate convex problems. Numerical results show fast convergence of the proposed algorithm and greatly improve the sytem performance over conventional approaches.

Notation: Bold lower and upper case letters represent vectors and matrices, respectively; $\mathbf{X}^H$, $\mathbf{X}^T$, $\mathrm{tr}(\mathbf{X})$, and $\mathrm{rank}(\mathbf{X})$ are the Hermitian transpose, normal transpose, trace, and rank of $\mathbf{X}$, respectively. $\|\cdot\|$ and $|\cdot|$ denote the Euclidean norm of a matrix or vector and the absolute value of a complex scalar, respectively. $\mathbf{x} \sim \mathcal{CN}(\boldsymbol{\eta}, \boldsymbol{Z})$ means that $\mathbf{x}$ is a random vector following a complex circular Gaussian distribution with mean $\boldsymbol{\eta}$ and covariance matrix $\boldsymbol{Z}$. The notation $\mathbf{X} \succeq \mathbf{0}$ represents a positive semidefinite matrix $\mathbf{X}$. $\mathbb{H}^N$ denotes the set of $N \times N$ complex Hermitian matrices. $\nabla_{\mathbf{x}} f(\mathbf{x})$ represents the gradient of $f(\cdot)$ with respect to vector $\mathbf{x}$.

II. System Model

A. Signal Model

We consider the FD MU-MIMO system with a BS sending information to K users in the DL channel, and receiving information from L users in the UL channel. The BS operates in the full-duplex mode where it can transmit and receive at the same time over the same frequency band as illustrated in Fig. 1. It is assumed that BS is equipped with M receive antennas and N transmit antennas, while all other nodes are equipped with a single antenna. The sets of users in the DL and UL channels are denoted by $\mathcal{D} \triangleq \{\mathsf{D}_1, \mathsf{D}_2, \cdots, \mathsf{D}_K\}$ and $\mathcal{U} \triangleq \{\mathsf{U}_1, \mathsf{U}_2, \cdots, \mathsf{U}_L\}$, respectively. In this paper we adopt the "harvest-and-then-trasnmit" protocol proposed in [3] as illustrated in Fig. 2, which is described as follows. During the first fraction αT $(0 < \alpha < 1)$ of each transmission block time, T, the BS transfers energy to all U_ℓ's and information to all D_k's simultaneously, while in the remaining $(1-\alpha)T$ fraction of the transmission block time, all U_ℓ's use their independent

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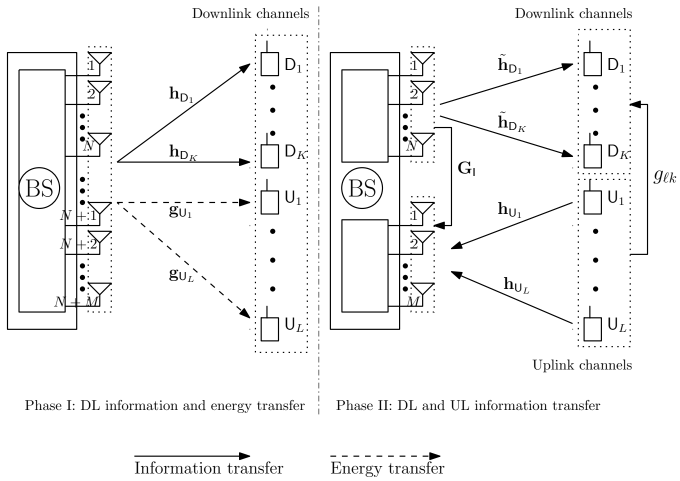

Fig. 1. A WPCN with wireless energy transfer in the downlink channel and wireless information transfer in both uplink and downlink channels.

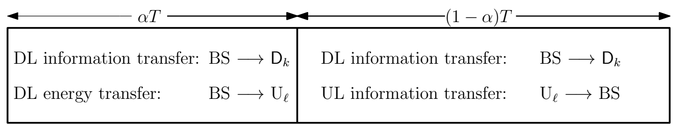

Fig. 2. The harvest-and-then-transmit protocol for the uplink transmission [3].

harvested energy from the DL to transmit their independent information to the BS via the UL transmission.

The BS operates in FD mode at the same time as shown in phase II in Fig. 1, which creates a residual SI channel between N transmit antennas and M receive antennas and a co-channel interference caused by users in the UL to those in the DL. The residual SI channel can be denoted as $\sqrt{\rho}\mathbf{G}_\mathsf{I} \in \mathbb{C}^{N\times M}$, where $\mathbf{G}_\mathsf{I}$ is a fading loop channel and $0 \le \rho \le 1$ is used for modeling the effect of passive SI suppression [5]. Furthermore, the UL channel also creates a co-channel interference (CCI) to the DL channel. The CCI from user U_ℓ to user D_k is denoted as $g_{\ell k}$.

In this paper we propose a cooperation between the DL and UL transmissions which is described as follows. The BS is allowed to transmit with total number of antennas $(M+N)$ in DL channel, and in return, the BS helps to transfer energy to all $\mathsf{U}_\ell \in \mathcal{U}$ in the first phase. This purpose creates two additional benefits: more degrees of freedom are added to the BS in DL channel and all U_ℓ's can harvest more energy from the RF signal of DL transmission in return. The baseband transmit signal at the BS in phase I is then expressed as

$$\mathbf{x}_1 = \sum\nolimits_{k=1}^{K} \mathbf{w}_{1,k} x_k + \mathbf{v}_e \tag{1}$$

where $\mathbf{w}_{1,k} \in \mathbb{C}^{(N+M)\times 1}$ denotes the k-th information beam, $x_k \sim \mathcal{CN}(0,1)$ is its information-carrying signal transmitted to user $\mathsf{D}_k \in \mathcal{D}$, and $\mathbf{v}_e \in \mathbb{C}^{(N+M)\times 1}$ denotes the energy beam transferred to all users in set $\mathcal{U}$. We further assume that the energy beam $\mathbf{v}_e$ whose elements are zero-mean complex Gaussian random variables with covariance matrix $\mathbf{V}$, i.e., $\mathbf{v}_e \sim \mathcal{CN}(\mathbf{0},\mathbf{V})$, where $\mathbf{V} \in \mathbb{H}^{(N+M)}$ and $\mathbf{V} \succeq \mathbf{0}$. The received signal in the DL at D_k and U_ℓ is, respectively, written as

$$\begin{aligned} y_{\mathsf{D}_k} &= \mathbf{h}_{\mathsf{D}_k}^H \mathbf{w}_{1,k} x_k + \sum\nolimits_{i=1,i\neq k}^{K} \mathbf{h}_{\mathsf{D}_k}^H \mathbf{w}_{1,i} x_i + \mathbf{h}_{\mathsf{D}_k}^H \mathbf{v}_e + n_{\mathsf{D}_k} \\ y_{\mathsf{U}_\ell} &= \sum\nolimits_{k=1}^{K} \mathbf{g}_{\mathsf{U}_\ell}^H \mathbf{w}_{1,k} x_k + \mathbf{g}_{\mathsf{U}_\ell}^H \mathbf{v}_e + n_{\mathsf{U}_\ell} \end{aligned} \tag{2}$$

where $\mathbf{h}_{\mathsf{D}_k} \in \mathbb{C}^{(N+M)\times 1}$ and $\mathbf{g}_{\mathsf{U}_\ell} \in \mathbb{C}^{(N+M)\times 1}$ are the channel vector from the BS to user D_k and U_ℓ, respectively, which are given by

$$\begin{aligned} \mathbf{h}_{\mathsf{D}_k} &= [\underbrace{h_{\mathsf{D}_k,1},\cdots,h_{\mathsf{D}_k,N}}_{\tilde{\mathbf{h}}_{\mathsf{D}_k}}, h_{\mathsf{D}_k,(N+1)},\cdots,h_{\mathsf{D}_k,(N+M)}]^T \\ \mathbf{g}_{\mathsf{U}_\ell} &= [g_{\mathsf{U}_\ell,1},\cdots,g_{\mathsf{U}_\ell,N},\underbrace{g_{\mathsf{U}_\ell,(N+1)},\cdots,g_{\mathsf{U}_\ell,(N+M)}}_{\tilde{\mathbf{g}}_{\mathsf{U}_\ell}}]^T. \end{aligned} \tag{3}$$

$n_{\mathsf{D}_k} \sim \mathcal{CN}(0,\sigma_k^2)$ and $n_{\mathsf{U}_\ell} \sim \mathcal{CN}(0,\sigma_\ell^2)$ are the additive white Gaussian noise (AWGN). Due to the broadcast nature of wireless channels, the harvested energy at user U_ℓ can be formulated as

$$E_{\mathsf{U}_\ell} = \eta\alpha T \mathbb{E}[y_{\mathsf{U}_\ell}] = \eta\alpha T \Big(\sum_{k=1}^{K} |\mathbf{g}_{\mathsf{U}_\ell}^H \mathbf{w}_{1,k}|^2 + \mathbf{g}_{\mathsf{U}_\ell}^H \mathbf{V} \mathbf{g}_{\mathsf{U}_\ell}\Big) \tag{4}$$

where η denotes the energy conversion efficiency at the receiver, and the receiver noise can be negligible compared to energy transfer from the BS in practice. Then, the average transmit power available for U_ℓ in the UL channel (Phase II) of information transmission is given by

$$p_{\mathsf{U}_\ell}^{\mathrm{eh}} = \frac{\eta\alpha}{(1-\alpha)} \Big(\sum\nolimits_{k=1}^{K} |\mathbf{g}_{\mathsf{U}_\ell}^H \mathbf{w}_{1,k}|^2 + \mathbf{g}_{\mathsf{U}_\ell}^H \mathbf{V} \mathbf{g}_{\mathsf{U}_\ell}\Big). \tag{5}$$

From (2), the signal-to-interference-plus-noise ratios (SINR) of for decoding x_k signal at D_k in phase I is expressed as

$$\gamma_{1,k} = \frac{|\mathbf{h}_{\mathsf{D}_k}^H \mathbf{w}_{1,k}|^2}{\sum_{i=1,i\neq k}^{K} |\mathbf{h}_{\mathsf{D}_k}^H \mathbf{w}_{1,i}|^2 + \mathbf{h}_{\mathsf{D}_k}^H \mathbf{V} \mathbf{h}_{\mathsf{D}_k} + \sigma_k^2}. \tag{6}$$

In the phase II, each U_ℓ uses its harvested energy from the first phase to transmit information to the BS, as illustrated in Fig. 2. The received signal in the DL at D_k and in the UL at the BS is, respectively, written as

$$\begin{aligned} \tilde{y}_{\mathsf{D}_k} &= \tilde{\mathbf{h}}_{\mathsf{D}_k}^H \mathbf{w}_{2,k} x_k + \sum_{i=1,i\neq k}^{K} \tilde{\mathbf{h}}_{\mathsf{D}_k}^H \mathbf{w}_{2,i} x_i + \sum_{\ell=1}^{L} \sqrt{p_\ell} g_{\ell k} v_\ell + n_{\mathsf{D}_k} \\ \mathbf{y}_\mathsf{U} &= \sum\nolimits_{\ell=1}^{L} \sqrt{p_\ell} \mathbf{h}_{\mathsf{U}_\ell} v_\ell + \sqrt{\rho} \sum\nolimits_{k=1}^{K} \mathbf{G}_\mathsf{I}^H \mathbf{w}_{2,k} x_k + \mathbf{n}_\mathsf{U} \end{aligned} \tag{7}$$

where $\tilde{\mathbf{h}}_{\mathsf{D}_k} \in \mathbb{C}^{N\times 1}$ and $\mathbf{w}_{2,k} \in \mathbb{C}^{N\times 1}$ are the channel vector and information beam for user D_k in the phase II, respectively, $p_\ell \in \mathbb{C}$, $\mathbf{h}_{\mathsf{U}_\ell} \in \mathbb{C}^{M\times 1}$ and $v_\ell \sim \mathcal{CN}(0,1)$ are the transmit power, the channel vector, and the transmitted information of user U_ℓ, respectively, $\mathbf{n}_\mathsf{U}$ denotes the receiver AWGN at the BS and it is assumed to be $\mathbf{n}_\mathsf{U} \sim \mathcal{CN}(\mathbf{0}, \tilde{\sigma}_\ell^2 \mathbf{I})$. For a channel remain constant during a transmission block time, we assume that $\tilde{\mathbf{h}}_{\mathsf{D}_k}$ corresponds to first N elements of $\mathbf{h}_{\mathsf{D}_k}$ in (3). In addition, we assume that the UL and DL channels hold via reciprocity, which means that $\mathbf{h}_{\mathsf{U}_\ell} = \tilde{\mathbf{g}}_{\mathsf{U}_\ell}, \forall \ell$, where $\tilde{\mathbf{g}}_{\mathsf{U}_\ell}$ is defined in (3). The SINR at D_k in the phase II can be expressed as

$$\gamma_{2,k} = \frac{|\tilde{\mathbf{h}}_{\mathsf{D}_k}^H \mathbf{w}_{2,k}|^2}{\sum_{i=1,i\neq k}^K |\tilde{\mathbf{h}}_{\mathsf{D}_k}^H \mathbf{w}_{2,i}|^2 + \sum_{\ell=1}^L p_\ell |g_{\ell k}|^2 + \sigma_k^2}. \quad (8)$$

For simplicity, we adopt the minimum mean square error and successive interference cancellation (MMSE-SIC) decoder at the BS to maximize the received SINR of U_ℓ. As a result, assume that the decoding order is from U_1 to U_L, the SINR for decoding U_ℓ's information is expressed as [8]

$$\gamma_\ell = p_\ell \mathbf{h}_{\mathsf{U}_\ell}^H \mathbf{Q}_\ell^{-1} \mathbf{h}_{\mathsf{U}_\ell} \quad (9)$$

where $\mathbf{p} \triangleq [p_1, p_2, \cdots, p_L]^T$ and $\mathbf{Q}_\ell = \sum_{j>\ell}^L p_j \mathbf{h}_{\mathsf{U}_j} \mathbf{h}_{\mathsf{U}_j}^H + \rho \sum_{k=1}^K \mathbf{G}_{\mathsf{I}}^H \mathbf{w}_{2,k} \mathbf{w}_{2,k}^H \mathbf{G}_{\mathsf{I}} + \tilde{\sigma}_\ell^2 \mathbf{I}$. Assuming perfect CSI at both transmitter and receiver sides, the achieved sum rate (SR) of DL transmission is

$$R_{\mathsf{D}} = \alpha \sum_{k=1}^K \log(1+\gamma_{1,k}) + (1-\alpha) \sum_{k=1}^K \log(1+\gamma_{2,k}). \quad (10)$$

Similarly, the achieved SR of UL transmission is

$$R_{\mathsf{U}} = (1-\alpha) \sum_{\ell=1}^L \log(1+\gamma_\ell). \quad (11)$$

B. Problem Formulation

The problem of the joint design of $\mathbf{p}$, $\mathbf{w}_1$, $\mathbf{w}_2$, $\mathbf{V}$, and α is generally expressed as

$$\begin{aligned}
&\underset{\mathbf{p},\{\mathbf{w}_{1,k}\},\{\mathbf{w}_{2,k}\},\mathbf{V},\alpha}{\text{maximize}} \quad R_{\mathsf{D}} + R_{\mathsf{U}} && (12a)\\
&\text{s.t.}\ R_{\mathsf{U}_\ell} \geq \bar{R}_{\mathsf{U}},\ \forall \ell = 1,\cdots,L && (12b)\\
&\quad 0 \leq p_\ell \leq p_{\mathsf{U}_\ell}^{\text{eh}},\ \forall \ell = 1,\cdots,L && (12c)\\
&\quad \|\mathbf{w}_1\|^2 + \|\mathbf{w}_2\|^2 + \text{tr}(\mathbf{V}) \leq P_{\mathsf{BS}} && (12d)\\
&\quad 0 < \alpha < 1, \mathbf{V} \succeq \mathbf{0} && (12e)
\end{aligned}$$

where $R_{\mathsf{U}_\ell} \triangleq (1-\alpha)\log(1+\gamma_\ell)$ and P_{BS} is the maximum transmit power at the BS. We observe that the maximization of the objective value in (12) is mainly contributed by R_{D} since it has available power supply. This means that the rate allocation would be unfair and the UL users may receive a low rate. To avoid such a case, the constraints in (12b) impose a QoS requirement on the UL user U_ℓ, i.e., the data rate of each user should be larger than a given threshold $\bar{R}_{\mathsf{U}}$.

III. Optimal Solution

In this section, we propose an iterative algorithm based on semi-definite relaxation (SDP). To facilitate SDP relaxation, we define $\mathbf{W}_{1,k} = \mathbf{w}_{1,k}\mathbf{w}_{1,k}^H$ and $\mathbf{W}_{2,k} = \mathbf{w}_{2,k}\mathbf{w}_{2,k}^H$ for all k, and rewrite problem (12) in terms of $\mathbf{W}_{1,k}$ and $\mathbf{W}_{2,k}$ as

$$\begin{aligned}
&\underset{\mathbf{p},\mathbf{W}_1,\mathbf{W}_2,\mathbf{V},\alpha}{\text{maximize}} \quad R_{\mathsf{D}} + R_{\mathsf{U}} && (13a)\\
&\text{s.t.}\ R_{\mathsf{U}_\ell} \geq \bar{R}_{\mathsf{U}},\ \forall \ell = 1,\cdots,L && (13b)\\
&\quad 0 \leq p_\ell \leq p_{\mathsf{U}_\ell}^{\text{eh}},\ \forall \ell = 1,\cdots,L && (13c)\\
&\quad \sum_{k=1}^K \big(\text{tr}(\mathbf{W}_{1,k}) + \text{tr}(\mathbf{W}_{2,k})\big) + \text{tr}(\mathbf{V}) \leq P_{\mathsf{BS}} && (13d)\\
&\quad 0 < \alpha < 1; \mathbf{V} \succeq \mathbf{0}; \mathbf{W}_{1,k}, \mathbf{W}_{2,k} \succeq \mathbf{0}, \forall k && (13e)\\
&\quad \text{rank}(\mathbf{W}_{1,k}) = 1, \text{rank}(\mathbf{W}_{2,k}) = 1, \forall k && (13f)
\end{aligned}$$

where $\mathbf{W}_1 = \{\mathbf{W}_{1,k}\}$, $\mathbf{W}_2 = \{\mathbf{W}_{2,k}\}$. It should be noted that R_{D} and R_{U} are neither concave nor convex with p_ℓ and $(\{\mathbf{W}_{1,k}\}, \{\mathbf{W}_{2,k}\})$, respectively. Consequently, problem (13) is a nonconvex program even dropping the constraint (13f), which is generally difficult to solve. For a tractable problem, we propose a joint design to solve the problem (13) locally. We note that the relaxed problem of (13) is concave in α and then can be solved by a simple one dimensional search. Thus, in the rest of this paper, we focus on solving (13) with a given value α. To start with, the relaxed problem of (13) (by dropping the rank constraints) is reformulated by following monotonicity of logarithmic function as

$$\begin{aligned}
&\underset{\mathbf{p},\mathbf{W}_1,\mathbf{W}_2,\mathbf{V}}{\text{maximize}} \ \alpha \prod_{k=1}^K (1+\gamma_{1,k}) + \\
&\qquad (1-\alpha) \prod_{k=1}^K (1+\gamma_{2,k}) \prod_{\ell=1}^L (1+\gamma_\ell) && (14a)\\
&\text{s.t.}\ (1+\gamma_\ell)^{(1-\alpha)} \geq e^{\bar{R}_{\mathsf{U}}},\ \forall \ell = 1,\cdots,L && (14b)\\
&\quad (13c), (13d), (13e). && (14c)
\end{aligned}$$

By introducing new optimization variables $\mathbf{z}_1 = \{z_{1,k}\}$, $\mathbf{z}_2 = \{z_{2,k}\}$, $\mathbf{v} = \{v_\ell\}$, $\boldsymbol{\phi} = \{\phi_\ell\}$, and $\boldsymbol{\omega} = \{\omega_\ell\}$, we can equivalently rewrite (14) as

$$\begin{aligned}
&\underset{\substack{\mathbf{p},\mathbf{W}_1,\mathbf{W}_2,\mathbf{V},\\ \mathbf{z}_1,\mathbf{z}_2,\mathbf{v},\boldsymbol{\phi},\boldsymbol{\omega}}}{\text{maximize}} \ \alpha \prod_{k=1}^K z_{1,k} + (1-\alpha) \prod_{k=1}^K z_{2,k} \prod_{\ell=1}^L v_\ell && (15a)\\
&\text{s.t.}\ 1+\gamma_{1,k} \geq z_{1,k}, \forall k && (15b)\\
&\quad 1+\gamma_{2,k} \geq z_{2,k}, \forall k && (15c)\\
&\quad 1+\gamma_\ell \geq v_\ell, \forall \ell && (15d)\\
&\quad p_{\mathsf{U}_\ell}^{\text{eh}} \geq \phi_\ell, \forall \ell && (15e)\\
&\quad v_\ell \geq \omega_\ell, \forall \ell && (15f)\\
&\quad \omega_\ell \geq e^{\bar{R}_{\mathsf{U}}/(1-\alpha)},\ \phi_\ell \geq p_\ell, \forall \ell && (15g)\\
&\quad z_{1,k} \geq 1, z_{2,k} \geq 1, \forall k;\ v_\ell \geq 1, \forall \ell && (15h)\\
&\quad (13d), (13e). && (15i)
\end{aligned}$$

The main challenging of solving (15) is due to nonconvex constraints (15b), (15c), and (15d). To overcome these problems, let us tackle the non-convex constraint (15b) first. Without loss of generality, we can rewrite (15b) as [9]

$$\sum_{i=1}^K \mathbf{h}_{\mathsf{D}_k}^H \mathbf{W}_{1,i} \mathbf{h}_{\mathsf{D}_k} + \mathbf{h}_{\mathsf{D}_k}^H \mathbf{V} \mathbf{h}_{\mathsf{D}_k} + \sigma_k^2 \geq z_{1,k}\tau_{1,k} \quad (16a)$$

$$\sum_{i=1,i\neq k}^K \mathbf{h}_{\mathsf{D}_k}^H \mathbf{W}_{1,i} \mathbf{h}_{\mathsf{D}_k} + \mathbf{h}_{\mathsf{D}_k}^H \mathbf{V} \mathbf{h}_{\mathsf{D}_k} + \sigma_k^2 \leq \tau_{1,k}. \quad (16b)$$

where $\tau_{1,k}$ is additional optimization variable to deal with the interference at the user D_k in phase I. Since the constraint (16b) is a convex one, we now only deal with the constraint (16a). By utilizing the results in [9], [11], we have the following inequality

$$f_1(z_{1,k}, \tau_{1,k}) \leq F_1(z_{1,k}, \tau_{1,k}, \beta_{1,k}^{(n)}) \triangleq \frac{1}{2\beta_{1,k}^{(n)}} z_{1,k}^2 + \frac{1}{2}\beta_{1,k}^{(n)} \tau_{1,k}^2 \quad (17)$$

where $\beta_{1,k}^{(n)}$ is a given positive constant. Since $F_1(z_{1,k}, \tau_{1,k}, \beta_{1,k}^{(n)})$ is a convex function in $z_{1,k}$ and $\tau_{1,k}$, and is an upper bound of $f_1(z_{1,k}, \tau_{1,k})$, we recall the following property of the approximation shown in (17). The equality of (17) is obtained by setting $\beta_{1,k}^{(n)} = z_{1,k}/\tau_{1,k}$ and then $\nabla_{z_{1,k},\tau_{1,k}} f_1(z_{1,k}, \tau_{1,k}) = \nabla_{z_{1,k},\tau_{1,k}} F_1(z_{1,k}, \tau_{1,k}, \beta_{1,k}^{(n)})$.

Letting $f_2(z_{2,k}, \tau_{2,k}) \triangleq z_{2,k}\tau_{2,k}$ with $\tau_{2,k}$ being additional optimization variable to deal with the interference at the user D_k in phase II. Similarly, we can approximate the constraint $1 + \gamma_{2,k} \geq z_{2,k}$ in (15c) for a given $\beta_{2,k}^{(n)} > 0$ as

$$\sum_{i=1}^{K} \tilde{\mathbf{h}}_{\mathsf{D}_k}^H \mathbf{W}_{2,i} \tilde{\mathbf{h}}_{\mathsf{D}_k} + \sum_{\ell=1}^{L} p_\ell |g_{\ell k}|^2 + \sigma_k^2 \geq F_2(z_{2,k}, \tau_{2,k}, \beta_{2,k}^{(n)}) \triangleq \frac{1}{2\beta_{2,k}^{(n)}} z_{2,k}^2 + \frac{1}{2}\beta_{2,k}^{(n)} \tau_{2,k}^2 \quad (18a)$$

$$\sum_{i=1, i\neq k}^{K} \tilde{\mathbf{h}}_{\mathsf{D}_k}^H \mathbf{W}_{2,i} \tilde{\mathbf{h}}_{\mathsf{D}_k} + \sum_{\ell=1}^{L} p_\ell |g_{\ell k}|^2 + \sigma_k^2 \leq \tau_{2,k}. \quad (18b)$$

Next, we now focus on treating the constraint (15d). By introducing an auxiliary variable θ_ℓ, we can rewrite (15d) into the equivalent form as

$$-\theta_\ell^2 \mathbf{h}_{\mathsf{U}_\ell}^H \mathbf{Q}_\ell^{-1} \mathbf{h}_{\mathsf{U}_\ell} \leq 1 - v_\ell \quad (19a)$$

$$p_\ell \geq \theta_\ell^2. \quad (19b)$$

We note that $h(\theta_\ell, \mathbf{p}, \{\mathbf{W}_{2,k}\}) \triangleq \theta_\ell^2 \mathbf{h}_{\mathsf{U}_\ell}^H \mathbf{Q}_\ell^{-1} \mathbf{h}_{\mathsf{U}_\ell}$ is convex with respect to $(\theta_\ell, \mathbf{p}, \{\mathbf{W}_{2,k}\})$, which can be justified by using Schur complement in [12]. Let $\theta_\ell^{(n)}, \mathbf{p}^{(n)}$, and $\{\mathbf{W}_{2,k}^{(n)}\}$ denote the value of $\theta_\ell, \mathbf{p}$, and $\{\mathbf{W}_{2,k}\}$ at iteration n-th, respectively. For a nondecreasing objective function, the consideration of upper bound of the left hand side in (19a) is needed. To doing so, we decompose the first order approximation of $-h(\theta_\ell, \mathbf{p}, \{\mathbf{W}_{2,k}\})$ around $(\theta_\ell^{(n)}, \mathbf{p}^{(n)}, \{\mathbf{W}_{2,k}^{(n)}\})$ as

$$-h(\theta_\ell, \mathbf{p}, \{\mathbf{W}_{2,k}\}) \leq \mathcal{H}(\theta_\ell, \mathbf{p}, \{\mathbf{W}_{2,k}\}, \theta_\ell^{(n)}, \mathbf{p}^{(n)}, \{\mathbf{W}_{2,k}^{(n)}\}) = -\Big(h(\theta_\ell^{(n)}, \mathbf{p}^{(n)}, \{\mathbf{W}_{2,k}^{(n)}\}) + 2\theta_\ell^{(n)} \mathbf{h}_{\mathsf{U}_\ell}^H (\mathbf{Q}_\ell^{(n)})^{-1} \mathbf{h}_{\mathsf{U}_\ell} (\theta_\ell - \theta_\ell^{(n)}) - \mathrm{tr}\Big[(\theta_\ell^{(n)})^2 (\mathbf{Q}_\ell^{(n)})^{-1} \mathbf{h}_{\mathsf{U}_\ell} \mathbf{h}_{\mathsf{U}_\ell}^H (\mathbf{Q}_\ell^{(n)})^{-1} \Big(\mathbf{Q}_\ell - \mathbf{Q}_\ell^{(n)}\Big)\Big]\Big). \quad (20)$$

By replacing (15b), (15c), and (15d) with (16), (18), and (19), respectively, the approximate convex problem at $(n+1)$-th iteration of the proposed design is reformulated as the SDP, which is given at the top of the next page, where $\boldsymbol{\tau}_1 = \{\tau_{1,k}\}$, $\boldsymbol{\tau}_2 = \{\tau_{2,k}\}$, and $\boldsymbol{\theta} = \{\theta_\ell\}$. To arrive at a second-order cone (SOC) program, we rewrite the constraints (21b)-(21f) to as an SOC constrains. The proposed iterative algorithm is summarized in Algorithm 1, where the optimal solutions at each iteration can be found efficiently by using numerical solver such as SeDuMi [7].

Since the objective value of (21) is increased after each iteration but upper bounded due to the power constraint (13d), the proposed algorithm is then guaranteed to convergence to an optimum locally. Note that the proposed design does not guarantee rank one solutions to satisfy (13f). Thus, (21) generally provides suboptimal solutions for (12). Nevertheless,

Algorithm 1 The proposed numerical algorithm

Initinalization: $\mathbf{p}^{(0)} = \mathbf{1}; \boldsymbol{\theta}^{(0)} = \mathbf{1}; \beta_{1,k}^{(0)} = 1, \beta_{2,k}^{(0)} = 1, \mathbf{W}_{2,k}^{(0)} = \mathbf{I}, \forall k;\ n := 1.$

1: **repeat**
2: Solve (21) to obtain the optimal solutions $\mathbf{p}^*, \mathbf{W}_1^*, \mathbf{W}_2^*, \mathbf{V}^*, \mathbf{z}_1^*, \mathbf{z}_2^*, \mathbf{v}^*, \boldsymbol{\phi}^*, \boldsymbol{\omega}^*, \boldsymbol{\tau}_1^*, \boldsymbol{\tau}_2^*, \boldsymbol{\theta}^*$.
3: Update: $\mathbf{p}^{(n)} := \mathbf{p}^*$, $\boldsymbol{\theta}^{(n)} := \boldsymbol{\theta}^*$, $\mathbf{W}_2^{(n)} := \mathbf{W}_2^*$, $\beta_{1,k}^{(n)} := z_{1,k}^*/\tau_{1,k}^*$, and $\beta_{2,k}^{(n)} := z_{2,k}^*/\tau_{2,k}^*$.
4: Set $n := n+1$
5: **until** Convergence

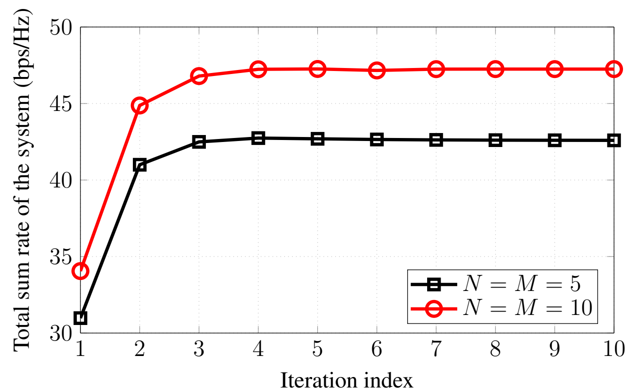

Fig. 3. Convergence behavior of Algorithm 1 with different number of antennas at the BS over one channel realization ($K = L = 3$, $P_{\mathsf{BS}} = 20$ dB, $\rho = 0.4, \alpha = 0.4, \eta = 0.5, \bar{R}_{\mathsf{U}} = 1$ bps/Hz).

we can show the optimal solutions for (21) must be rank one by constructing an equivalent problem, which follows the same steps in [13, Proposition 4.1].

IV. Numerical Results

In this section, we provide the numerical results to evaluate the performance of the proposed approach. All channel entries are generated as i.i.d. complex Gaussian random variables with $\mathcal{CN}(0,1)$ and the background thermal noise at each receiver is assumed to be as $\mathcal{CN}(0,1)$. All other parameters are given in the caption. For a comparison purpose, we compare the performance of our design with FD MU-MIMO conventional scheme, where the BS uses separate N transmit and M receive antennas in the first phase. In addition, we also compare with HD system where the BS uses all the antennas, i.e., $M+N$ for communication.

Fig. 3 shows the convergence behavior of the Algorithm 1. In particular, we plot the convergence rate as a function of the number of antennas at the secondary BS. As can be observed from this figure that the proposed algorithm converges to the optimal solution within several iterations even increasing number of antennas at the BS.

In Fig. 4, we compare the total SR of the proposed design with the conventional approaches. As can be seen from Fig. 4, in the high sum power regime, the total SR of the FD designs is significantly improved, compared to the HD mode. However, the total SR of the FD designs is lower than the one in the

$$\underset{\substack{\mathbf{p},\mathbf{W}_1,\mathbf{W}_2,\mathbf{V},\mathbf{z}_1,\\ \mathbf{z}_2,\mathbf{v},\boldsymbol{\phi},\boldsymbol{\omega},\boldsymbol{\tau}_1,\boldsymbol{\tau}_2,\boldsymbol{\theta}}}{\text{maximize}} \quad \alpha \prod_{k=1}^{K} z_{1,k} + (1-\alpha)\prod_{k=1}^{K} z_{2,k}\prod_{\ell=1}^{L} v_\ell \tag{21a}$$

$$\text{s. t.} \ \Big\|\Big[\frac{1}{\sqrt{2\beta_{1,k}^{(n)}}} z_{1,k} \quad \sqrt{\frac{\beta_{1,k}^{(n)}}{2}}\tau_{1,k}\Big]^T\Big\|_2 \le \Big[\mathbf{h}_{\mathsf{D}_k}^H\big(\sum_{i=1}^{K}\mathbf{W}_{1,i}+\mathbf{V}\big)\mathbf{h}_{\mathsf{D}_k}+\sigma_k^2\Big]^{1/2}, \forall k \tag{21b}$$

$$\Big\|\Big[\frac{1}{\sqrt{2\beta_{2,k}^{(n)}}} z_{2,k} \quad \sqrt{\frac{\beta_{2,k}^{(n)}}{2}}\tau_{2,k}\Big]^T\Big\|_2 \le \Big[\sum_{i=1}^{K}\tilde{\mathbf{h}}_{\mathsf{D}_k}^H\mathbf{W}_{2,i}\tilde{\mathbf{h}}_{\mathsf{D}_k}+\sum_{\ell=1}^{L}p_\ell|g_{\ell k}|^2+\sigma_k^2\Big]^{1/2}, \forall k \tag{21c}$$

$$\Big\|\Big[\sqrt{\mathbf{h}_{\mathsf{D}_k}^H\mathbf{W}_{1,1}\mathbf{h}_{\mathsf{D}_k}}\cdots\sqrt{\mathbf{h}_{\mathsf{D}_k}^H\mathbf{W}_{1,k-1}\mathbf{h}_{\mathsf{D}_k}}\ \sqrt{\mathbf{h}_{\mathsf{D}_k}^H\mathbf{W}_{1,k+1}\mathbf{h}_{\mathsf{D}_k}}\cdots\sqrt{\mathbf{h}_{\mathsf{D}_k}^H\mathbf{W}_{1,K}\mathbf{h}_{\mathsf{D}_k}}\ \sqrt{\mathbf{h}_{\mathsf{D}_k}^H\mathbf{V}\mathbf{h}_{\mathsf{D}_k}}\ \ 0.5(\tau_{1,k}-\sigma_k^2-1)\Big]^T\Big\|_2 \le 0.5(\tau_{1,k}-\sigma_k^2+1), \forall k \tag{21d}$$

$$\Big\|\Big[\sqrt{\tilde{\mathbf{h}}_{\mathsf{D}_k}^H\mathbf{W}_{2,1}\tilde{\mathbf{h}}_{\mathsf{D}_k}}\cdots\sqrt{\tilde{\mathbf{h}}_{\mathsf{D}_k}^H\mathbf{W}_{2,k-1}\tilde{\mathbf{h}}_{\mathsf{D}_k}}\ \sqrt{\tilde{\mathbf{h}}_{\mathsf{D}_k}^H\mathbf{W}_{2,k+1}\tilde{\mathbf{h}}_{\mathsf{D}_k}}\cdots\sqrt{\tilde{\mathbf{h}}_{\mathsf{D}_k}^H\mathbf{W}_{2,K}\tilde{\mathbf{h}}_{\mathsf{D}_k}}\ \sqrt{p_1|g_{1k}|^2}\cdots\sqrt{p_L|g_{Lk}|^2}\ \ 0.5(\tau_{2,k}-\sigma_k^2-1)\Big]^T\Big\|_2 \le 0.5(\tau_{2,k}-\sigma_k^2+1), \forall k \tag{21e}$$

$$\|\theta_\ell \ \ 0.5(p_\ell-1)\|_2 \le 0.5(p_\ell+1), \forall \ell \tag{21f}$$

$$\mathcal{H}(\theta_\ell, \mathbf{p}, \{\mathbf{W}_{2,k}\}, \theta_\ell^{(n)}, \mathbf{p}^{(n)}, \{\mathbf{W}_{2,k}^{(n)}\}) \le 1 - v_\ell, \forall \ell \tag{21g}$$

$$(15e), (15f), (15g), (15h), (13d), (13e). \tag{21h}$$

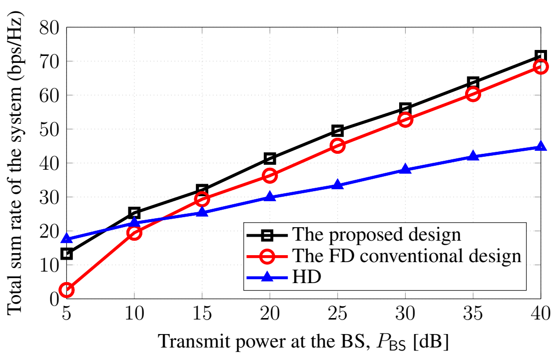

Fig. 4. The total sum rate of the system versus the transmit power at the BS ($K = L = 3, N = M = 5$, $\rho = 0.5, \eta = 0.5$, $\bar{R}_{\mathsf{U}} = 1$ bps/Hz).

low sum power regime due to the rate constrain in (12b). Interestingly, the total SR of proposed design in this paper is higher than that of the FD conventional design.

V. Conclusion

In this paper, a FD MU-MIMO in WPCN has been studied where the users in the UL channel are designed to harvest energy from the BS before transmitting their information. We develop an iterative algorithm which jointly designs harvested energy and power control to maximize the sum rate of the system using the approximate convex method. Numerical results show the superior convergence rate and demonstrate the great improvement of performance compared to the known solutions.

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