Min-SINR Maximization with DL SWIPT and UL WPCN in Multi-Antenna Interference Networks

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Abstract—A novel multicell communication and energy harvesting scheme is proposed, in which downlink (DL) simultaneous wireless information and power transfer (SWIPT) and uplink (UL) wireless powered communication network (WPCN) concepts are jointly considered. Specifically, a DL beamforming with energy harvesting and UL power allocation (PA) scheme is proposed, where each cell is composed of a base station (BS) with multiple antennas and power-limited users each with single antenna. The joint optimization of DL beamforming vector design and UL PA is known to be challenging due to unpredictable future channel conditions, and thus we propose an efficient cascaded design for the DL and UL problems in pursuit of maximizing the minimum DL and UL signal-to-interference-plus-noise ratios (SINRs). Simulation results show that the proposed scheme achieves higher minimum DL and UL SINRs region as well as higher UL energy efficiency than the existing schemes.

Index Terms—Energy harvesting, simultaneous wireless information and power transfer (SWIPT), downlink beamforming, wireless powered communication network (WPCN), uplink power allocation

I. INTRODUCTION

Recently, energy harvesting (EH) from ambient RF signals has received intense research interest to save energy consumption on battery-limited devices such as low power sensors and mobile devices. Several studies have shown the feasibility of EH systems based on ambient RF signals in practical environments [1] and cellular network [2]. To utilize interference signals for energy harvesting, the concept of simultaneous wireless information and power transfer (SWIPT) has been extensively studied both theoretically and practically [3]. It becomes more crucial to harvest energy from intercell interference signals in wireless sensor networks or ultra dense networks, where the intercell interference is even comparable in strength to the desired signal. In downlink (DL) cellular network based on global channel state information (CSI) [4] or local CSI [5], [6], multi-antenna beamforming or precoding at the base stations (BSs) can guarantee the data rate of information transfer as well as the amount of energy harvested at the users. In particular, the benefit of the SWIPT is emphasized in highly dense networks such as small cells, since strong intercell interference (ICI) in such a network can be utilized as a source of EH [7]. However, these previous schemes merely focus on DL signal-to-interference-plus-noise ratios (SINRs) and the amount of energy harvested without any explicit consideration of the uplink (UL) SINRs.

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Another framework “wireless powered communication network (WPCN)” [8] has been proposed to consider UL information transmission, where each user is powered by the energy that it harvests from the DL signals in DL time slots. The authors of [8] optimized the time allocation for the DL wireless energy transfer and UL information transmission to maximize UL sum-throughput. This work has been extended to multiuser single-output (MU-MISO) [9] and MU multi-input multi-output (MIMO) [10] channels. Nevertheless, these WPCN schemes only consider energy transfer without information transmission in DL time slots, and thus they are not applicable to the case with the presence of DL data, which is highly likely in practical systems. In addition, these works considered only the single cell case, and the extension to the multicell scenario is non-trivial in managing the ICI both in the DL and UL time slots.

In this letter, we tackle a general communication and energy transfer scenario for multicell networks composed of BSs with multiple antennas and users each with a single antenna, where there exist both DL and UL data to exchange. In the proposed scheme, the concepts of SWIPT and WPCN are jointly considered for the DL and UL time slots, and the UL power allocation (PA) is also considered in the UL time slots. Specifically, in a DL time slot, while a user receives DL data, another user scavenges all the ambient signals transmitted by the BSs. In the subsequent DL time slot, the role of the two users is swapped. For each DL time slot, beamforming vectors at the BSs are optimized. In the following UL time slot, the two users transmit UL data simultaneously with a proper UL PA by each BS. In fact, the coupled DL and UL problems are known to be challenging to solve since the optimality of the DL and UL parameter design at each time slot does not exist in time-varying channels. Therefore, we propose an efficient cascaded DL and UL design scheme maximizing the minimum DL and UL SINRs in pursuit of maximizing the rate fairness. Simulation results show that the proposed scheme not only achieves larger minimum DL and UL SINRs region but also exhibits much improved energy efficiency.

II. SYSTEM MODEL AND PROPOSED PROTOCOL

An $N_C$-cell network, each cell of which is composed of a BS with $N_T$ antennas and two users each with a single antenna, is considered. The extension to the case with more users is trivial assuming each pair of users is orthogonalized with the

Figure 1. Proposed joint time switching SWIPT and WPCN protocol

An $N_C$-cell network, each cell of which is composed of a BS with $N_T$ antennas and two users each with a single antenna, is considered. The extension to the case with more users is trivial assuming each pair of users is orthogonalized with the
other pairs of users based on multi-carrier modulation such as orthogonal frequency division multiplexing. We consider frame-based with a three-time slot protocol shown in Fig. 1. In the first time slot, user 1 receives the DL data while the other harvests energy from the DL signals transmitted by the BSs. In the second time slot, the two users switch their roles. In the third time slot, all the users transmit UL signals simultaneously using the energy harvested from the DL time slots. That is, ‘time switching’ SWIPT is assumed, which requires only a circuit switch for implementation. Compared to ‘power splitting’ SWIPT, where each user can split the received energy into two parts for EH and information decoding by an additional power splitting circuit at each RF chain, the time switching SWIPT requires relatively low implementation cost [3].

It is also assumed that each user is equipped with a battery such that the energy unused can be stored. The channel vector between the BS in cell $i$ and user $m$ in cell $j$ at the $n$-th slot is denoted by $h_{i,j,n}(m) \in \mathbb{C}^{N_T \times 1}$, $i, j = 1, \ldots, N_C$, $m = 1, 2$, and $n = 1, 2, 3$. It is assumed that the channel coefficients remain constant for a time slot and then change to another values randomly at the next time slot, i.e., quasi-static fading. Each BS is assumed to be able to acquire its incoming and outgoing channels through channel sounding and UL pilot signals at each time slot and share them with other BSs via backhaul.

At the $n$-th time slot, $n = 1, 2$, i.e., the DL time slot, the beamforming vector at the BS in cell $j$ is denoted by $w^{[n]}_j \in \mathbb{C}^{N_T \times 1}$, where $\|w^{[n]}_j\|^2 = 1$. The DL SINR for user $n$ in cell $j$ is thus

$$\rho^{[n]}_j = \frac{P_j h^{[n]}_j h^{[n]}_j^H}{\sum_{k=1, k \neq j}^{N_C} P_k h^{[n]}_k h^{[n]}_k^H + N_0},$$

(1)

where $P_j$ is the transmit power of the BS in cell $j$, and $N_0$ is the variance of additive white Gaussian noise. In addition, $u^{[n]}_{j,\bar{n}}$ denotes the energy harvested at user $(3-n)$ in cell $j$, defined by

$$u^{[n]}_{j,\bar{n}} = \gamma_{j,\bar{n}} \sum_{k=1}^{N_C} \left| \frac{h^{[n]}_k}{w^{[n]}_k} \right|^2,$$

(2)

where $\bar{n} = 3-n$, and $0 < \gamma_{j,\bar{n}} \leq 1$ denotes the EH efficiency, the ratio of the energy stored in the battery to the total received power of user $\bar{n}$ in cell $j$ [3].

At the third time slot, i.e., the UL time slot, we assume a linear receiver with successive interference cancellation [11] based on the decoding order $\pi_j$ at the BS in cell $j$, where $\pi_j = [\pi_{(j,1)}, \pi_{(j,2)}]$, $\pi_{(j,1)}, \pi_{(j,2)} \in \{1, 2\}$. The user with index $\pi_{(j,1)}$ is decoded first and the user with index $\pi_{(j,2)}$ is decoded second after the subtraction of the interference due to user $\pi_{(j,1)}$’s signal. The interference-plus-noise spatial covariance matrix of user $\pi_{(j,m)}$ in cell $j$ is given by

$$Z^{[\pi_{(j,m)}]}_j = p_{\pi_{(j,m)}} h^{[3]}_{\pi_{(j,\pi_{(j,m)}}} h^{[3]}_{\pi_{(j,\pi_{(j,m)}}}^H + C_j + N_0 I,$$

(3)

where $p_{\pi_{(j,m)}}$ is the UL transmit power from user $\pi_{(j,m)}$ and $C_j = \sum_{k=1, k \neq j}^{N_C} p_k h^{[3]}_{j,k} h^{[3]}_{j,k}^H$. Denoting the receiver beamforming vector for user $\pi_{(j,m)}$ by $u^{[n]}_{j,\pi_{(j,m)}} \in \mathbb{C}^{N_T \times 1}$, where $\|u^{[n]}_{j,\pi_{(j,m)}}\|^2 = 1$, we obtain the UL SINR as

$$\rho^{[3]}_{j,\pi_{(j,m)}} = \frac{p_{\pi_{(j,m)}} (u^{[n]}_{j,\pi_{(j,m)}} h^{[3]}_{\pi_{(j,m)}}^H)^2}{\|u^{[n]}_{j,\pi_{(j,m)}} Z^{[\pi_{(j,m)}]}_j u^{[n]}_{j,\pi_{(j,m)}}\|^2}.$$  

(5)

The goal is to maximize the minimum DL and UL SINRs by optimizing $w^{[n]}_j$ and $p_{\pi_{(j,m)}}$, $j = 1, \ldots, N_C$, $n = 1, 2$, which requires a joint optimization for the three time slots. To decouple the optimization at each time slot, we propose to design $w^{[n]}_j$ to maximize the minimum DL SINR at the first and second time slots while guaranteeing the minimum amount of harvested energy for UL information transmission at each user. In the third time slot, the UL power $p_{\pi_{(j,m)}}$ is optimized to maximize the minimum UL SINR.

III. OPTIMIZATION OF THE DL BEAMFORMING

We begin with defining the augmented variable vector by $\tilde{w}^{[n]} = \left[ (w^{[n]}_1)^T \ldots (w^{[n]}_{N_C})^T \right] \in \mathbb{C}^{(N_C \cdot N_T) \times 1}$. Then, each beamforming vector can be expressed by $w^{[n]}_j = E_j \tilde{w}^{[n]}$, where $E_j \in \mathbb{C}^{N_C \times (N_C \cdot N_T)}$ consists of all zeros except for the $(j-1)N_T + 1$-th to $(jN_T)$-th columns equal to the $N_T \times N_T$ identity matrix. We can rewrite (1) as

$$\rho^{[n]}_j = \frac{(\tilde{w}^{[n]}_j)^H \tilde{A}^{[n]}_j \tilde{w}^{[n]}_j}{(\tilde{w}^{[n]}_j)^H \tilde{B}^{[n]}_j \tilde{w}^{[n]}_j},$$

(6)

where

$$A^{[n]}_j = P_j E_j h^{[n]}_{j,(j,n)} h^{[n]}_{j,(j,n)}^H E_j,$$

(7)

$$B^{[n]}_j = \sum_{k=1, k \neq j}^{N_C} P_k E_k h^{[n]}_{k,(j,n)} h^{[n]}_{k,(j,n)}^H E_k + N_0 I,$$

(8)

and $I$ is the $(N_C \cdot N_T) \times (N_C \cdot N_T)$ identity matrix. We also rewrite (2) as $\nu^{[n]}_{j,\bar{n}} = \gamma_{j,\bar{n}} \sum_{k=1}^{N_C} \left| \frac{h^{[n]}_{k,(j,\bar{n})}}{w^{[n]}_k} \right|^2$. The optimization problem at the $n$-th time slot, $n = 1, 2$, is formulated by

$$F^{[n]}_{\text{DI}} : \max_{\tilde{w}^{[n]}_j} \min \left\{ \frac{(\tilde{w}^{[n]}_j)^H \tilde{A}^{[n]}_j \tilde{w}^{[n]}_j}{(\tilde{w}^{[n]}_j)^H \tilde{B}^{[n]}_j \tilde{w}^{[n]}_j} \right\}$$

(9)

s.t. $\nu^{[n]}_{j,\bar{n}} \geq \gamma_{j,\bar{n}} - \Delta_{j,\bar{n}}, \quad \|E_j \tilde{w}^{[n]}_j\|^2 \leq 1, \quad j = 1, \ldots, N_C.$

(10)

In addition, $\Delta_{j,\bar{n}}$ is the minimum energy to be stored at user $\bar{n}$ in cell $j$ for UL transmit in the UL time slot, and $\Delta_{j,\bar{n}}$ is the power left in the battery of user $\bar{n}$ in cell $j$. By controlling $\Delta_{j,\bar{n}}$, the proposed protocol can cover general scenarios with different EH constraints, while minimizing unnecessary energy consumption at the BSs. Due to the constraint (10), the feasible set of problem $F^{[n]}_{\text{DI}}$ becomes non-convex, which in general is difficult to solve. To convert the problem into a convex form, the
maximization of the minimum of DL SINRs in (9) is rewritten employing one additional variable $\theta$ by

$$
P_{D2}^{[n]}: \max_{\mathbf{w}[n]} \theta$$

subject to

$$
(\mathbf{w}[n])^H \mathbf{A}_{j,n} \mathbf{w}[n] \geq \theta (\mathbf{w}[n])^H \mathbf{B}_{j,n} \mathbf{w}[n],
$$

$$
(\mathbf{w}[n])^H \mathbf{C}_{j,n} \mathbf{w}[n] \geq \frac{\lambda_{i,n} - \Delta_{j,n}}{\gamma_{j,n}},
$$

$$
(\mathbf{w}[n])^H \mathbf{D}_j \mathbf{w}[n] \leq 1, \quad j = 1, \ldots, N_C,
$$

where

$$
\mathbf{C}_{j,n} = \sum_{k=1}^{N_C} \mathbf{E}_{[k]} \mathbf{h}_{k,(j,n)} (\mathbf{h}_{k,(j,n)})^H \mathbf{E}_k,
$$

$$
\mathbf{D}_j = \mathbf{E}_j^H \mathbf{E}_j.
$$

The problem $P_{D2}^{[n]}$ is still in a non-convex form due to the non-convex constraints (13) and (14). Therefore, defining a rank-1 variable matrix by $\mathbf{W}[n] \triangleq (\mathbf{w}[n])^H \in \mathbb{C}^{(N_C \times N_T) \times (N_C \times N_T)}$, for given cost value $\theta$, we consider the following feasibility problem:

$$
P_{D3}^{[n]}(\theta): \text{Find } \mathbf{W}[n]$$

subject to

$$
\text{tr}(\mathbf{A}_{j,n} \mathbf{W}[n]) \geq \theta \text{tr}(\mathbf{B}_{j,n} \mathbf{W}[n]),
$$

$$
\text{tr}(\mathbf{C}_{j,n} \mathbf{W}[n]) \geq \frac{\lambda_{i,n} - \Delta_{j,n}}{\gamma_{j,n}},
$$

$$
\text{tr}(\mathbf{D}_j \mathbf{W}[n]) \leq 1, \quad j = 1, \ldots, N_C,
$$

$$
\mathbf{W}[n] \succeq 0,
$$

$$
\text{rank}(\mathbf{W}[n]) = 1,
$$

where $\text{tr}(\cdot)$ denotes the trace operation and $\mathbf{W}[n] \succeq 0$ implies that $\mathbf{W}[n]$ is positive semidefinite.

The feasibility problem $P_{D3}^{[n]}(\theta)$ without the constraint (23) is a convex problem with respect to the variable $\mathbf{W}[n]$, and can be evaluated with polynomial computational complexity by the semidefinite programming (SDP) to get the solution $\mathbf{W}[n]$. However, the solution $\mathbf{W}[n]$ obtained ignoring the constraint (23) becomes in general a full rank matrix, which contradicts the baseline assumption of a rank-1 matrix. To find the rank-1 matrix closest to $\mathbf{W}[n]$, the rank-1 randomization method [12] is used. Specifically, let us denote the rank of $\mathbf{W}[n]$ by $r$, the eigenvalues by $\lambda_i$, $i = 1, \ldots, r$, with the order $\lambda_1 \geq \lambda_2 \geq \ldots \geq \lambda_r > 0$, and the corresponding eigenvectors by $\mathbf{q}_i \in \mathbb{C}^{(N_C \times N_T) \times 1}$. Then, the rank-1 approximated solution can be written by $\mathbf{W}[n] = \lambda_1 \mathbf{q}_1 \mathbf{q}_1^H$, and the solution for the beamforming vector for given $\theta$, is given by

$$
\bar{\mathbf{w}}[n]^* = \sqrt{\lambda_1} \mathbf{q}_1.
$$

Now, the final step is to find the maximum $\theta$ that results in a feasible solution of $\bar{\mathbf{w}}[n]^*$, which can be readily obtained by a line search algorithm such as the bisection line search.

IV. OPTIMIZATION OF THE UL POWER ALLOCATION

As seen from Fig. 1, each BS acquires the UL channel information for all its serving users and exchanges it to all other BSs. The UL PA problem is then formulated and solved at the BS side, and the solution is forwarded to the users.

In the UL time slot, all the users simultaneously transmit UL signals using the energy harvested in the previous time slots. The UL power and corresponding receiver beamforming vector optimization at BS in cell $j$ for the min-SINR is formulated by

$$
P_{U1}: \max_{\mathbf{u}_j, \pi(j,m)} \min_{j,m} \{ \rho_j \pi(j,m) \}
$$

subject to

$$
0 \leq \rho_j \pi(j,m) \leq \mu_j \pi(j,m) + \Delta_j \pi(j,m),
$$

$$
\|\mathbf{u}_j, \pi(j,m)\|_2 = 1, \quad m = 1, 2, \quad j = 1, \ldots, N_C.
$$

The variables $\mathbf{u}_j, \pi(j,m)$ and $\rho_j, \pi(j,m)$ in $P_{U1}$ are coupled and need to be jointly optimized, and the problem is non-convex. To make $P_{U1}$ tractable, we find the solution by finding the optimal $\mathbf{u}_j, \pi(j,m)$ for given $\rho_j, \pi(j,m)$, and then vice versa iteratively. Inserting the optimal beamforming vector known as the MMSE receiver [11] into (5), the UL SINR for given $\rho_j, \pi(j,m)$ is written by

$$
\tilde{\rho}_j \pi(j,m) = \rho_j \pi(j,m) (\mathbf{h}_{j,(j,j)}^H (\mathbf{Z}_{j,\pi(j,m)})^{-1} \mathbf{h}_{j,(j,j)}),
$$

and the optimization of $\rho_j, \pi(j,m)$ can be formulated by

$$
P_{U2}: \max_{\rho_j, \pi(j,m)} \min_{\pi(j,m)} \{ \tilde{\rho}_j \pi(j,m) \}
$$

subject to

$$
0 \leq \rho_j \pi(j,m) \leq \mu_j \pi(j,m) + \Delta_j \pi(j,m),
$$

$$
j = 1, \ldots, N_C, \quad m = 1, 2.
$$

Since the cost function (30) is still non-convex, we introduce an additional variable $\omega$ and modify the cost function as

$$
\max_{\rho_j, \pi(j,m)} \omega
$$

subject to

$$
\tilde{\rho}_j \pi(j,m) \geq \omega.
$$
Therefore, for given $\omega$ and with (32), the problem $\mathcal{P}_{U2}$ can be formulated by

$$
\mathcal{P}_{U3}(\omega): \quad \text{Find} \quad p_{j,\pi'(j,m)}^* \quad \text{s.t.} \quad \bar{p}_{j,\pi'(j,m)} \geq \omega, \quad 0 \leq p_{j,\pi'(j,m)} \leq \nu_{j,\pi'(j,m)} + \Delta_j,\pi'(j,m), \quad j = 1, \ldots, N_C, \quad m = 1, 2.
$$

The feasibility problem $\mathcal{P}_{U3}(\omega)$ is now in a linear problem form, and can be readily solved by LP with polynomial time. The maximum $\omega$ resulting in a feasible solution of $\mathcal{P}_{U3}(\omega)$ can be obtained using a linear search such as the bisection method.

After finding the optimal UL power $p_{j,\pi'(j,m)}^*$, for user $\pi'(j,m)$, each BS announces it to their serving users and the users transmit UL data with the power $p_{j,\pi'(j,m)}^*$. The unused power is stored at the battery, and the battery level is updated as

$$
\Delta_j,\pi'(j,m) \leftarrow \nu_{j,\pi'(j,m)} + \Delta_j,\pi'(j,m) - p_{j,\pi'(j,m)}^*, \quad j = 1, \ldots, N_C, \quad m = 1, 2.
$$

By using the proposed update algorithm in (20), unnecessary energy consumption at the BSs can be minimized, thereby improving the energy efficiency. Finally, we propose a cascaded DL and UL design as shown in Fig. 2.

V. NUMERICAL RESULTS

For comparison of the average minimum user rate, the random beamforming and DL sum-rate maximizing [3] schemes are considered as baseline schemes, in which the beamforming vector is randomly designed and jointly designed across all the cells to maximize the DL sum-rate, respectively. In addition, the maximum EH scheme with and without the minimum SINR constraint [5] are considered. Moreover, we also evaluate the proposed scheme with and without UL PA. It is assumed that the average SNR is the same for all the channels, and that each channel coefficient is an i.i.d. complex Gaussian random variable with zero mean and unit variance. It is also assumed that $\Lambda_{j,n} = P \in [0,2]$, $\gamma_{j,n} = 0.5$ and $\pi_j = [1,2]$, $j = 1, \ldots, N_C$, $n = 1, 2$.

Fig. 3 demonstrates the boundaries of DL and UL achievable minimum user rate pairs for $N_C = 3$, $N_P = 2$, and SNR = 5dB and 25dB. The choice of the parameter $P$ in the proposed scheme and the choice of the minimum SINR constraint in the max EH with a minimum DL SINR constraint scheme determine respective maximum achievable DL-UL minimum user rates on the rate boundary. The convex hull inside the rate boundary of each scheme is also achievable by controlling the time duration of DL and UL. As seen from Fig. 3, the proposed scheme even without UL PA outperforms the existing schemes in terms of the minimum DL and UL rates for all SNR regime, since the DL beamforming design can be more emphasized for maximizing the minimum DL rate owing to the consideration of unused UL power in the problem.

With UL PA, the proposed scheme achieves much broader rate region than the existing schemes, which in turn shows that merely maximizing the harvested energy does not guarantee a high achievable rate due to UL ICI and that the UL PA is essential to significantly improve the UL rate. Table I shows the relative energy efficiency defined as the ratio of the minimum UL user rate to the total UL power consumption in comparison to that of the maximum EH scheme with the minimum SINR constraint.

Due to the cascaded DL and UL design with the consideration of the unused UL power, UL power can be significantly saved in the proposed scheme achieving the same or even higher minimum UL rate as seen from Fig. 3. As a result, the proposed scheme with UL PA shows the highest UL energy efficiency among all compared schemes for all SNR regime, as seen from Table I.

### REFERENCES


