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Energy Efficient Optimization for Large-Scale Multiple Antenna System with Wireless Power Transfer

Zheng Chang, Shan Zhang, Zhongyu Wang, Xijuan Guo, Zhu Han, and Tapani Ristaniemi

***Abstract*—In this work, an energy efficient optimization scheme for a large scale multiple antenna system with wireless power transfer (WPT) is presented. In the considered system, the user is charged by a base station (BS) with a large number of antennas via downlink WPT and then utilizes the received power to carry out uplink data transmission. Novel antenna selection, time allocation and power allocation schemes are presented to optimize the energy efficiency (EE) of the overall system. In addition, we also consider channel state information (CSI) cannot be perfectly obtained when designing the resource allocation schemes. The Nonlinear fractional programming based algorithm is utilized to address the formulated problem. Our proposed schemes are validated by extensive simulations and it shows superior performance over the existing schemes.**

***Index Terms*—energy efficiency, antenna selection, resource allocation, wireless power transfer, imperfect channel estimation**

I. INTRODUCTION

A. Background

The high data rate wireless network have brought the explosive growth of intelligent mobile devices and applications, which has greatly enriched our daily life. However, frequent online activities and the high data rate transmission bring a higher requirement on the battery of the mobile terminals (MTs) while the development of battery technique is in a relevantly slow speed. Such a mismatch leads to a increasingly interest on how to prolong the lifetime of MTs, especially for those MTs that require continuous operations and have the difficulty to replace the battery.

One way of prolonging the lifetime of a MT is to provide energy supply whenever needed. However, in some cases, recharging and replacing the batteries of the MTs may be inconvenient or even impossible. In this context, energy harvesting techniques, can be leveraged into energy-constrained wireless networks, to prolong the system lifetime in a sustainable way. Conventional energy harvesting technologies mainly utilize solar, wind and vibration effects or other physical phenomena, which are location-dependent and sometimes can not be provided constantly. Therefore, scavenging energy from radio frequency (RF) or electromagnetic signals offers an alternate way for energy supply [1]. The investigation on the simultaneously wireless information and power transfer (SWIPT), whereby the wireless nodes can harvest energy from RF signals, has received great interests recently and provides traditional energy constrained networks with a promising solution for the convenient and permanent energy supply. As the RF signal is not location-dependent and almost everywhere, the SWIPT has the potential to make a great contribution on prolonging the battery life time and improving the energy efficiency (EE) performance of the wireless system.

Meanwhile, in order to accommodate the high speed transmission with limit amount of spectrum, the spectrum utilization should be significantly improved. As one potential solution, employing large number of antennas at the Base Station (BS) to build up so called massive multiple input multiple output (massive MIMO) system, can make a great improvement on the spectrum efficiency Comparing with the current MIMO system, a large number of extra antennas in the massive MIMO can focus transmit power into ever-smaller regions of space and correspondingly bring huge improvements in spectral efficiency (SE). However, employing a large number of antennas may bring some disadvantages on system complexity and additional energy consumption, which are caused by using a separate RF chain for each antenna [2]. To date, most of the energy efficient algorithm development of the MIMO system typically focused on the transmit power minimization, which is reasonable assuming the number of used RF chains is small. However, it is worthwhile to investigate whether some of the antennas can be switched off when the circuit power consumption can be comparable to or even dominates the transmit power [3], and spectrum and transmit power can be allocated accordingly to improve the EE performance in the a large scale multiple antenna system.

B. Related Work

Recently it can be found that the SWIPT system design has received increasing attention, and energy efficient resource allocation is one of its major research topics. In [4], the authors present a throughput maximum scheme for the SWIPT system. In [5], the authors focus on the problem of distributed power splitting for SWIPT in relay interference channels. The authors

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of [6] investigate the tradeoff between wireless power transfer in DL and information transfer in UL in a SWIPT system. In [7], the authors explore the average throughput performance by proposing novel energy beamforming schemes in a wireless powered MIMO communication system. In [8], the authors investigate the resource allocation scheme for a mobile cloud powered by the wireless power transfer.

Meanwhile, the investigation of EE performance for a multiple antenna system has also received increasing attentions [2], [9]-[12]. In [2], the authors have proposed an transmit antenna selection scheme to improve the EE of a massive MIMO system. Considering a MIMO system, the authors of [9] has explored the mutual information optimization problem and it can be found that increasing the number of antennas can lead to the SE improvement. On the other hand, although the use of MIMO can improve the system spectrum efficiency, the use of large number of antennas may lead to a significant decrease on the EE performance [2]. However, the corresponding energy consumption is also increased. Therefore, in terms of EE, the number of selected antennas should be decided in an optimized manner. In [10], with the assumption of imperfect channel state information (CSI) estimation, a rate adaptation and antenna selection scheme is introduced. The problem of the transmitting and receiving antenna selection is also investigated in [12] when channel estimation error exists. In order to improve the EE of the multiple antenna system, different beamforming methods have been explored in [3] and [13] as well.

It can be observed that in most of the aforementioned works, CSI is assumed to be obtained perfectly at the BS or MTs. However, such an assumption may be too idealistic, since in practice, the CSI cannot be perfectly known due to the estimation error and/or feedback. Therefore, if the proposed algorithm cannot properly take imperfect CSI into consideration, system performance may be degraded. In [14], a robust beamforming algorithm for the multiple antenna system with SWIPT is proposed under the assumption of imperfect CSI at the transmitter. In [15], the authors investigate the resource allocation problem for an OFDMA-based network with diverse quality of service (QoS) requirements and assume imperfect CSI is available at the BS. In [16], the SE performance of an OFDMA multiple relays system is investigated with the assumption of imperfect CSI . So far, as we can observe, the system optimization of imperfect CSI in WPT system is at its start phrase and typically under-investigated.

C. Contribution

Motivated by the previous works and existing problems, the main target is to design novel resource allocation algorithms to optimize the EE performance of a large scale multiple antenna point-to-point (P2P) system. In particular, we first present an antenna selection scheme to determine the optimal number of antennas to deliver wireless energy to the user and to receive data transmission from the MT. Moreover, with downlink WPT and uplink data transmission, we propose a time allocation scheme to optimize the WPT time duration as well as a power allocation scheme to optimize the transmit power consumption of the BS. In addition, as the CSI cannot be perfect obtained in the practical system, the influence of imperfect CSI cannot be neglected. Thus, in this work, the impact of imperfect CSI is also considered when designing the algorithm. The contributions can be summarized as follows,

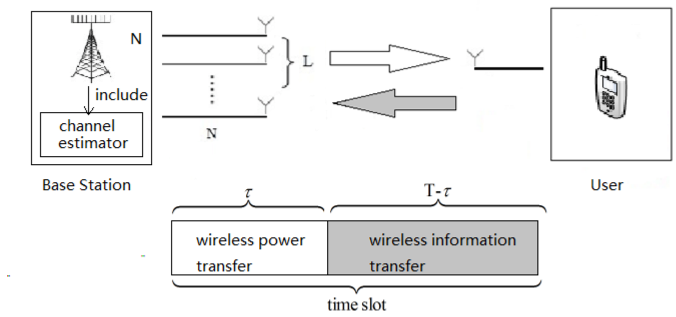

Fig. 1. System model

- First, a novel resource allocation algorithm is proposed to improve the EE of the considered system with imperfect CSI. The proposed binary searching-based antenna selection scheme is to find the optimal number of used antennas at the BS. Moreover, energy beamforming scheme is also adopted to improve the system EE performance based on imperfect CSI.
- Secondly, the mutual information distributions with/without antenna selection of the considered system are derived. Accordingly, the expression of spectrum efficiency is derived with the consideration of channel estimation error.
- Thirdly, based on the above theoretical analysis, the time and power allocation schemes are proposed, where the time allocation for WPT and WIT, and the power allocation at the base station (BS) are jointly optimized. A nonlinear fractional programming-based scheme is then applied to solve the formulated problem.
- Through extensive simulation studies, the proposed schemes are illustrated and validated. The simulation results demonstrate the effectiveness and its superior performance of the proposed schemes.

The reminder of this paper is organized as follows. In Section II, the system model and corresponding studies on mutual information distribution of the massive MIMO system are introduced. The optimization problem and resource allocation algorithm are presented in Section III. Performance evaluations are conducted in Section IV. Finally, we conclude this study in Section V.

II. System Model and Mutual Information

A. System Model

As shown in Fig. 1, we consider a P2P massive MIMO system with bi-directional transmission. The BS has $N \gg 1$ antennas and user is equipped with one antenna. In the considered system, the BS is able to provide energy via WPT in the downlink to the user during the scheduled time, and the user has no other energy supplements. The user can store the energy obtained from the BS and then utilize it transmit data to the BS in the uplink. Therefore, in the first time slot, through the WPT, the user can harvest the wireless power from the signal of the BS, and store it in a rechargeable battery. Then, in the second time slot, the user can utilize the collected energy to transmit the data to the BS. The entire transmission block is denoted as T, the first time slot is denoted as τ, and the second time slot is represented with $T-\tau$.

Further, we assume the channel is quasi-static block fading ,i.e., given transmission block T, the channel is constant and it can vary independently from one block to another. In each transmission block, the user can get the channel estimation via a channel estimator, and the estimated channel coefficient is $\widehat{\mathbf{H}}$. The estimation error is $\triangle\mathbf{H}$ and the CSI can be feedback to the BS. We denote σ_e^2 as the variance of estimation error, i.e., $\triangle\mathbf{H}\sim\mathcal{CN}(0,\sigma_e^2 I_e)$, where I_e is the identity matrix. Thus, denoting the channel coefficient as $\mathbf{H}$, we have [15]-[16]

$$\mathbf{H}=\widehat{\mathbf{H}}+\triangle\mathbf{H}. \tag{1}$$

In order to improve the efficiency of WPT, the energy beamforming is employed. Where, we assume that the RF chain architecture has no impact on the energy model. In order to maximize the system EE, an antenna selection scheme is presented at the BS, to select L antennas from N antennas, where $1<L<N$. Accordingly, the received power at the user can be given as follows,

$$P_U=\eta d P_t|\mathbf{H}^H\mathbf{w}|^2, \tag{2}$$

where P_t is the transmit power of the BS, and η is the conversion efficiency from harvested energy into electric energy stored by the user. d is the distance-depend path loss between the BS and user. When L out of N antennas are selected, the estimated channel becomes $\hat{\mathbf{H}}\in\mathbb{C}^{L\times 1}$. $\mathbf{w}$ is the energy beamforming matrix, and we consider the maximum ratio transmission (MRT) [3] for the design of $\mathbf{w}$ as $\mathbf{w}=\frac{\hat{\mathbf{H}}}{\|\hat{\mathbf{H}}\|}$. Therefore, the obtained energy can be given as follows [17]:

$$E_U=\eta d P_t Q\tau. \tag{3}$$

where $Q=\frac{\sigma_e^2}{1+\sigma_e^2}+\frac{\|\widehat{\mathbf{H}}\|^2}{(1+\sigma_e^2)^2}$. During the time slot $T-\tau$, the harvested energy can be used to transmit data from the user to the BS. At the BS, the received signal is given as [2]

$$y=\sqrt{\frac{E_U}{T-\tau}d}\widehat{\mathbf{H}}^T\mathbf{x}+n, \tag{4}$$

where $\mathbf{x}\in\mathbb{C}^{L\times 1}$ is the information signal and n is additive Gaussian noise. $n\sim\mathcal{CN}(0,\sigma_n^2)$. $\frac{E_U}{T-\tau}$ is the transmit power of the user.

B. Mutual Information Distribution under Imperfect Channel Estimation

In a large scale multiple antenna system, the channel hardening effect emerges as the number of antennas grows [9]. Thus, at first, we explore the mutual information distributions with/without antenna selection with imperfect CSI. Based on the analytic results, we can then obtain the presentation of the expected throughput. We first derive **Theorem 1** about the mutual information distribution of the considered system without antenna selection.

Theorem 1. *When the BS is with $N\gg 1$ antennas, a numerical approximation of the mutual information in the uplink of the considered system with the imperfect CSI is given as,*

$$I\sim\mathcal{N}\left(\log_2\left(1+N\frac{\frac{E_U d}{T-\tau}}{\sigma_n^2+\frac{E_U d}{T-\tau}\sigma_e^2}\right),\frac{(\log_2 e)^2}{N}\right), \tag{5}$$

where $\mathcal{N}$ represents standard normal distribution, and σ_n^2 is noise variance.

Proof. The proof of **Theorem1** is similar to the Appendix A of [18], so we omit here. ☐

Theorem 1 presents the distribution of mutual information when considering N antennas. Based on **Theorem 1**, we can obtain the expression of mutual information when L antennas are selected out of N in **Theorem 2**.

Theorem 2. *In the considered system, when L antennas are selected, the mutual information distribution is given as follows:*

$$I_{sel}\sim\mathcal{FN}\Big(\log_2\left(1+\left(1+\ln\frac{N}{L}\right)\rho L\right),\frac{(\log_2 e)^2\rho^2 L(2-\frac{L}{N})}{(1+(1+\ln\frac{N}{L})\rho L)^2}\Big), \tag{6}$$

where ρ is the SNR with imperfect CSI and channel noise, i.e., $\rho=\frac{\frac{E_U d}{T-\tau}}{\sigma_n^2+\frac{E_U d}{T-\tau}\sigma_e^2}$. $\mathcal{FN}$ is the folded normal distribution.

Proof. The proof of **Theorem2** is similar to the Appendix B of [18], so we omit here. ☐

As one can observe, if $L=N$, the expected value of the distribution is as same as that of the system without antenna selection, and the variance is approximately the same as well. Therefore, selecting a relatively big number of antennas in a massive MIMO system does not necessarily affect the channel hardening phenomenon. Thus, in each time block, the expected channel capacity under imperfect channel estimation is denoted by $E[I]_{im}$:

$$E[I]_{im}=\log_2\left(1+\left(1+\ln\frac{N}{L}\right)\frac{\frac{E_U d}{T-\tau}}{\sigma_n^2+\frac{E_U d}{T-\tau}\sigma_e^2}L\right). \tag{7}$$

III. Energy Efficient Antenna Selection and Resource Allocation

A. Problem Formulation

After obtaining the mutual information of the considered system, the EE in [bits/J/Hz] is defined as:

$$\Sigma(P_t,\tau,L)=\frac{E[I]_{im}(T-\tau)}{U(P_t,\tau,L)}. \tag{8}$$

$U(P_t,\tau,L)$ denotes the total energy consumption in a time block T and it can be expressed as

$$U(P_t,\tau,L)=P_t\tau+P_cT, \tag{9}$$

where P_c is the circuit power consumption of the BS and the user. Thus, the power consumption P_c after antenna selection is [2] [19]:

$$P_c \approx P_{user}+LP_{bs}, \tag{10}$$

where P_{user} is the power consumption of the user and P_{bs} denotes the power consumption related to the RF chain of antenna. Since the antennas of the BS need to be active for the whole time block T, the total power consumption in (9) can be rewritten as:

$$U(P_t,\tau,L)=(P_{user}+LP_{bs})T+P_t\tau. \tag{11}$$

Therefore, the EE can be expressed as

$$\Sigma(P_t,\tau,L)=\frac{E[I]_{im}(T-\tau)}{(P_{user}+LP_{bs})T+P_t\tau}. \tag{12}$$

From the (3), (7) and (12), the EE can be given as follows:

$$\Sigma(P_t,\tau,L)=\frac{\log_2\left(1+\left(1+\ln\frac{N}{L}\right)\frac{\frac{E_Ud}{T-\tau}}{\sigma_n^2+\frac{E_Ud}{T-\tau}\sigma_e^2}L\right)(T-\tau)}{(P_{user}+LP_{bs})T+P_t\tau}. \tag{13}$$

To maximize the EE, the optimization problem can be presented as follows,

$$\mathbf{P_1}: \quad \max_{P_t,\tau,L}\Sigma(P_t,\tau,L), \tag{14}$$

s.t.

$$\begin{aligned}
&\mathbf{C1}: \quad P_t \le P_{bs,max},\\
&\mathbf{C2}: \quad E[I]_{im} \ge R_{min},\\
&\mathbf{C3}: \quad \tau \le T,\\
&\mathbf{C4}: \quad \frac{E_U}{T-\tau} \le P_{user,max},\\
&\mathbf{C5}: \quad L \le N.
\end{aligned} \tag{15}$$

Where, $P_{bs,max}$ denotes the maximum of transmit power of BS and $P_{user,max}$ denotes the maximum of transmit power of the user. In (15), **C1** is the BS transmit power constraint. **C2** can ensure that QoS R_{min} is satisfied. **C3** is the WPT time allocation constraint and **C4** is the transmit power constraint for the user. **C5** is to ensure that the number of selected antennas is no bigger than N. We can substitute (3) into **C4**, and arrive at

$$P_t \le \frac{P_{user,max}(T-\tau)}{\eta dQ\tau}. \tag{16}$$

After combining **C1** and (16), one can arrive

$$\tau \le \frac{P_{user,max}T}{(\eta dP_{bs,max}Q+P_{user,max})}=\tau_{max}. \tag{17}$$

B. Proposed Antenna Selection Scheme Analysis

Before we propose to address the formulated resource allocation problem, we first determine the number of used antenna. A binary search-based scheme is applied here for antenna selection, and presented presented in Algorithm 1.

In this algorithm, we initialize three variables: the upper bound κ_h, intermediate κ_i, and lower bound of the number of antennas κ_l, respectively. We use $\kappa_i=\frac{\kappa_l+\kappa_h}{2}$. At the beginning, we consider $\kappa_l=1$ and $\kappa_h=N$. In each iteration, two values, i.e. $\Sigma(\kappa_i)$ and $\Sigma(\kappa_i+1)$ should be compared. Then we can find which subset of the maximum value is located. If $\Sigma(\kappa_i)<\Sigma(\kappa_i+1)$, κ_i+1 is assigned to κ_l, and if $\Sigma(\kappa_i)>\Sigma(\kappa_i+1)$, κ_i is assigned to κ_h. Consequently, by selecting the optimal number of antennas, the maximum EE can be obtained. The value of κ_i is updated at the end of each iteration. When $\kappa_h-\kappa_l=1$, the algorithm ends and optimal L can be found.

Algorithm 1 Antenna Selection Algorithm

```
Initialize N, EE value Σ(N) ,κ_l = 1 ,κ_h = N ,κ_i = (κ_l+κ_h)/2.
while (κ_h − κ_l) > 1 do
    if Σ(κ_i) < Σ(κ_i + 1) then
        set κ_l = κ_i + 1;
    else if Σ(κ_i) > Σ(κ_i + 1) then
        set κ_h = κ_i;
    else
        break;
    end if
end while
if κ_h − κ_l = 1 then
    Σ(L) = max{Σ(κ_l), Σ(κ_h)};
else
    Σ(L) = Σ(κ_i);
end if
```

C. Proposed Time and Power Allocation Schemes

As we can see, the objective function in $\boldsymbol{P_1}$ is the ratio of $E[I]_{im}(T-\tau)$ to $U(P_t,\tau,L)$, resulting in $\boldsymbol{P_1}$ a nonlinear fractional problem, which is generally not convex. However, this type of problems can be transformed into non-fractional format. According to [20] and [21], we can convert it into a subtractive form. First, given L antennas are selected, we consider q^* as the global optimal solution of the EE, i.e.,

$$q^*=\frac{E[I]_{im}(T-\tau^*)}{(P_{user}+LP_{bs})T+P_t^*\tau^*}, \tag{18}$$

where P^* is the optimal solution for power allocation and τ^* is the optimal solution for time allocation. **Theorem 3** gives the necessary and sufficient condition for obtaining optimal q.

Theorem 3. *Optimal q can be reached if and only if (iff) [20]*

$$\max_{P_t,\tau,L} E[I]_{im}(T-\tau)-q[(P_{user}+LP_{bs})T+P_t\tau]=0. \tag{19}$$

Accordingly, the problem $\mathbf{P_1}$ can be transformed into a problem $\mathbf{P_2}$:

$$\mathbf{P_2}: \quad \max_{P_t,\tau}\Omega(P_t,\tau), \tag{20}$$

s.t.

$$\begin{aligned}
&\hat{\mathbf{C1}}: \quad P_t \le P_{bs,max},\\
&\hat{\mathbf{C2}}: \quad E[I]_{im} \ge R_{min},\\
&\hat{\mathbf{C3}}: \quad \tau \le T,\\
&\hat{\mathbf{C4}}: \quad \tau < \tau_{max},
\end{aligned} \tag{21}$$

where

$$\Omega(P_t,\tau) = E[I]_{im}(T-\tau) - q^*[(P_{user}+LP_{bs})T + P_t\tau]. \tag{22}$$

We can see that $\Omega(P_t,\tau)$ is a concave function with respect to P_t and τ. Therefore, the original problem can be transformed to a convex optimization problem $\mathbf{P_2}$ with constraints. Consequently, it can be solved in dual domain. The Lagrange dual function of $\mathbf{P_2}$ is:

$$\begin{aligned}
&\mathcal{L}(P_t,\tau,\alpha,\beta,\mu,\varphi) = E[I]_{im}(T-\tau) - q^*[(P_{user}\\
&+ LP_{bs})T + P_t\tau] - \alpha(P_t - P_{bs,max}) - \beta(\tau - \tau_{max})\\
&- \mu(\tau - T) - \varphi(R_{min} - E[I]_{im})
\end{aligned} \tag{23}$$

where $\alpha > 0, \beta > 0, \mu > 0, \varphi > 0$ are the Lagrange multipliers associated with the constraint in (21), respectively. Correspondingly, the dual problem is presented as follows:

$$\mathbf{P_3}: \min_{\alpha,\beta,\mu,\varphi} \max_{P_t,\tau} \mathcal{L}(P_t,\tau,\alpha,\beta,\mu,\varphi) \tag{24}$$

Then optimal P_t^* and τ^* can be obtained via the Karush-Kuhn-Tucker (KKT) condition:

$$\begin{aligned}
&\frac{\partial \mathcal{L}(P_t,\tau,\alpha,\beta,\mu,\varphi)}{\partial P_t}\\
&= (T-\tau)\frac{\partial E[I]_{im}}{\partial P_t} - q^*\tau - \alpha + \varphi\frac{\partial E[I]_{im}}{\partial P_t}\\
&= (T-\tau+\varphi)\frac{\partial E[I]_{im}}{\partial P_t} - q^*\tau - \alpha\\
&= \frac{AB}{(\ln 2)(B+DP_t)(B+CP_t)}(T-\tau+\varphi) - q^*\tau - \alpha\\
&= 0,
\end{aligned} \tag{25}$$

and

$$\begin{aligned}
&\frac{\partial \mathcal{L}(P_t,\tau,\alpha,\beta,\mu,\varphi)}{\partial \tau}\\
&= (T-\tau)\frac{\partial E[I]_{im}}{\partial \tau} - E[I]_{im} - q^*P_t - \beta - \mu\\
&+ \varphi\frac{\partial E[I]_{im}}{\partial \tau}\\
&= (T-\tau+\varphi)\frac{\partial E[I]_{im}}{\partial \tau} - E[I]_{im} - q^*P_t - \beta - \mu\\
&= \frac{A_1B_1(T-\tau+\varphi)}{(\ln 2)(B_1+C_1\tau)(B_1+D_1\tau)} - \log_2\left(\frac{B_1+C_1\tau}{B_1+D_1\tau}\right)\\
&- q^*P - \beta - \mu = 0,
\end{aligned} \tag{26}$$

where $A, B, C, D, A_1, B_1, C_1, D_1$ are given as

$$\begin{aligned}
&A = \eta d\|\widehat{\mathbf{H}}\|^2\tau(L + L\ln\frac{L}{N}),\\
&B = (T-\tau)\sigma_n^2,\\
&C = \eta d\|\widehat{\mathbf{H}}\|^2\tau\sigma_e^2,\\
&D = A + C,\\
&A_1 = \eta dP_t\|\widehat{\mathbf{H}}\|^2(L + L\ln\frac{L}{N}),\\
&B_1 = T\sigma_n^2,\\
&C_1 = \eta dP_t\|\widehat{\mathbf{H}}\|^2(\sigma_e^2 + L + L\ln\frac{L}{N}) - \sigma_n^2,\\
&D_1 = \eta dP_t\|\widehat{\mathbf{H}}\|^2\sigma_e^2 - \sigma_n^2,
\end{aligned} \tag{27}$$

From (25), we can obtain

$$\frac{AB}{(B+DP_t)(B+C\cdot P_t)} = \frac{(\ln 2)(\alpha+q^*\tau)}{T-\tau+\varphi}. \tag{28}$$

Let $\frac{T-\tau+\varphi}{(\ln 2)(\alpha+q^*\tau)} = F$, then $\frac{A\cdot B}{(B+D\cdot P)(B+C\cdot P)} = \frac{1}{F}$. As a result, we can obtain P_t^* as

$$P_t^* = \frac{-(D+C)B + \sqrt{(C-D)^2B^2 + 4ABCDF}}{2DC}. \tag{29}$$

τ^* can be obtained by addressing (26) numerically. To obtain the Lagrangian multiplier $\alpha, \beta, \mu, \varphi$, the gradient method can be applied, i.e.,

$$\begin{aligned}
\alpha(a+1) &= [\alpha(a) - \triangle\alpha(P_{bs,max} - P_t)]^+,\\
\beta(a+1) &= [\beta(a) - \triangle\beta(\tau_{max} - \tau)]^+,\\
\mu(a+1) &= [\mu(a) - \triangle\mu(T-\tau)]^+,\\
\varphi(l+1) &= [\varphi(a) - \triangle\varphi(E[I]_{im} - R_{min})]^+,
\end{aligned} \tag{30}$$

where a is iteration index, $[x]^+ = max\{0, x\}$, $\triangle\alpha$, $\triangle\beta$, $\triangle\mu$, $\triangle\varphi$ are the step sizes. The proposed power and time allocation algorithm is summarized in Algorithm 2 together with the proposed antenna selection scheme. If the convergence is not reached, the loop continues to find the optimal solution. During the loop, the dual variables are updated according to (30). The power allocation and time allocation solutions are obtained by (26) and (29). If $E[I]_{im}(T-\tau') - q[(P_{user} + LP_{bs})T + P_t'\tau'] \le \varepsilon$ where ε is a sufficiently small number, we can consider the convergence condition is reached and optimal solution can be obtain. As the output of the Algorithm 2, the optimal solutions for power and time allocation and antenna selection can be achieved. To address the formulated problem $\boldsymbol{P_1}$, the problem has a linear time complexity where c is a constant. The time complexity of antenna selection algorithm is $O(log_2N)$. Therefore, the overall problem has a time complexisty $O(c \times log_2N)$ where c is a constant.

IV. Performance Evaluation

In this section, extensive simulations have been conducted to evaluate the proposed algorithm. In Table IV, the key parameters based on the ones in [19] are given. In this table, we consider P_{DAC}, and P_{ADC} denote the power consumption of the Digital to Analogue Converter (DAC)

Algorithm 2 Energy Efficient Resource Allocation

Initialization:
N, L, η, γ, P_{bs}, P_{user}, $P_{bs,max}$, $P_{user,max}$, R_{min}, $\triangle\alpha$, $\triangle\beta$, $\triangle\mu$, $\triangle\varphi$,
$\Sigma(P_t, \tau, L)$, $\kappa_l = 1$, $\kappa_h = N$, $\kappa_i = \frac{\kappa_l+\kappa_h}{2}$
ε is a small positive real number.
while (!Convergence) **do**
  Update $\alpha, \beta, \mu, \varphi$ according to (30).
  Obtaining the P'_t and τ' by solving the equations (26) and (29).
  if $E[I]_{im}(T-\tau') - q[(P_{user} + LP_{bs})T + P'_t\tau'] \geq \varepsilon$, **then**
    Convergence $=$ false,
    while $(\kappa_h - \kappa_l) > 1$ **do**
      if $\Sigma(P'_t, \tau', \kappa_i) < \Sigma(P'_t, \tau', \kappa_{i+1})$, **then**
        Set $\kappa_l = \kappa_{i+1}$;
      else if $\Sigma(P'_t, \tau', \kappa_i) > \Sigma(P'_t, \tau', \kappa_{i+1})$, **then**
        Set $\kappa_h = \kappa_i$;
      else
        break;
      end if
    end while
    if $(\kappa_h - \kappa_l) = 1$ **then**
      $\Sigma(P'_t, \tau', L) = max\{\Sigma(P'_t, \tau', \kappa_l), \Sigma(P'_t, \tau', \kappa_h)\}$.
    else
      $\Sigma(P'_t, \tau', L) = \Sigma(P'_t, \tau', \kappa_i)$
    end if
    return $q = E[I]_{im}(T-\tau')/((P_{user} + LP_{bs})T + P'_t\tau')$.
  else
    Convergence $=$ true,
    return $P^*_t = P'_t$, $\tau^* = \tau'$, and obtain optimal q^*.
  end if
end while
return Obtain P^*_t, τ^* and L.

TABLE I
SIMULATIONS PARAMETERS

Parameter	Value
N	100
$P_{bs,max}$	$46dBm$
$P_{user,max}$	$23dBm$
R_{min}	$1bit/s/Hz$
$\triangle\alpha, \triangle\beta, \triangle\mu, \triangle\varphi$	0.001
C	2
η	0.35
ε	0.001
P_{DAC}, P_{ADC}	$10mW$
P_{filt}, P_{filr}	$2.5mW$
P_{mix}	$30.3mW$
P_{syn}	$50mW$
P_{LNA}	$20mW$
P_{IFA}	$3mW$

and ADC, respectively., $P_{syn}, P_{filt}, P_{mix}, P_{LNA}, P_{IFA}$, and P_{filr}, is the power consumption of the frequency synthesizer, transmit filter, the mixer, the low noise amplifier, the frequency amplifier, the receiver filter , respectively. Further, we have $P_{user} = 2P_{syn} + P_{LNA} + P_{mix} + P_{IFA} + P_{filr} + P_{ADC}$ and $P_{bs} = P_{DAC} + P_{mix} + P_{filt}$.

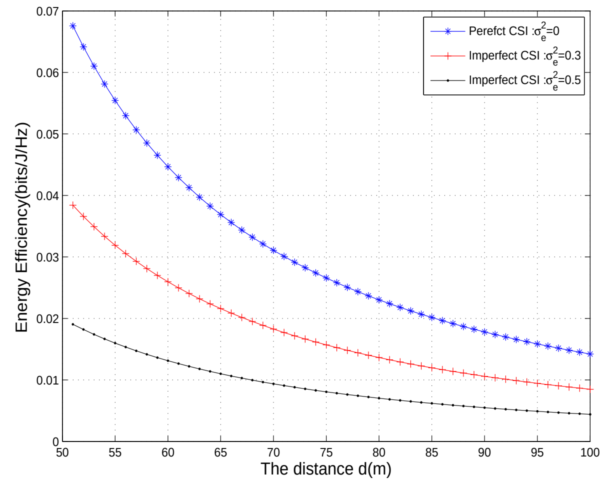

Fig. 2. Effect of imperfect CSI

In Fig. 2, the impact of imperfect CSI on the EE performance is illustrated. In this figure, we vary the variance of σ_e^2, which is the estimation error and also change the distance between the BS and user. In addition, the EE performance of the proposed scheme is compared to that of the system with perfect CSI, and we set $\sigma_e^2 = 0.3$ and $\sigma_e^2 = 0.5$. The simulation results show that the system with perfect CSI shows superior performance over the ones with imperfect CSI. and the EE performance degrades when the value of σ_e^2 increases. Moreover, when the distance becomes larger, the EE performance decreases as well due to the channel degradation. For example, when the distance is 50m, EE of the system when $\sigma_e^2 = 0.5$ is about 4 times lower comparing with the one of perfect CSI case. However, when the distance becomes 100m, there is about only 3 times difference. From Fig. 2, the EE of the system with $\sigma_e^2 = 0.3$ is higher than that of $\sigma_e^2 = 0.5$, which evidences the significant impact that the imperfect CSI on the EE.

In Fig. 3, the effectiveness of the proposed antenna selection and time allocation schemes are evaluated. We compare our proposed schemes with the one without antenna selection, e.g. the one that is modified from [3], to investigate the advantages of the presented antenna selection method. It can be observed from Fig. 3 that the system EE can be improved by selecting optimal number of antennas. The performance increases 8 times higher with proposed antenna selection scheme. Meanwhile, our proposed scheme is also compared with the one with equal time allocation, i.e., $\tau = 0.5$. As one can see, the proposed scheme shows a superior performance, which evidences that proper design of time allocation is needed for a SWIPT system. Similar to the observation in Fig. 2, it is shown that the EE of the system decreases with the increase of the distance between the BS and user.

In order to examine the impact of number of selected antennas, we plot the EE performance in Fig. 4 by varying the number of antennas on x-axis. The optimal time allocation scheme is considered in this case. In addition, we also change

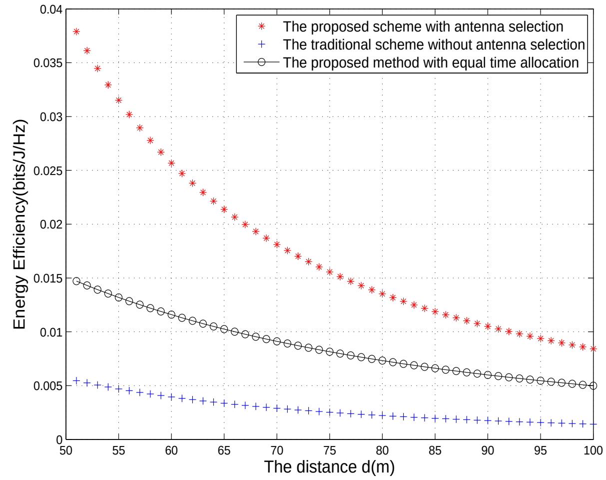

Fig. 3. EE w/wo antenna selection and time allocation

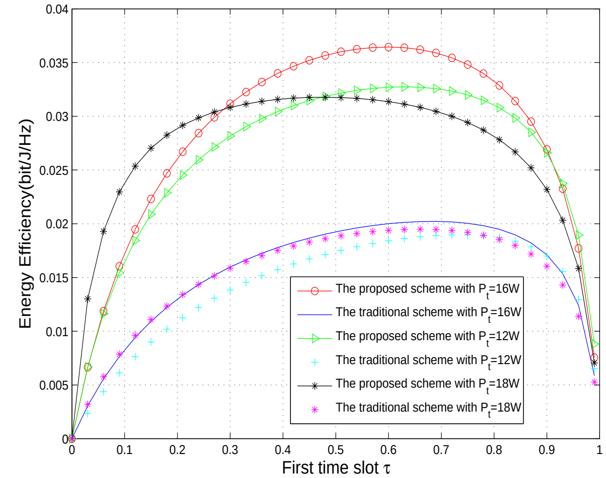

Fig. 5. EE vs. time allocation

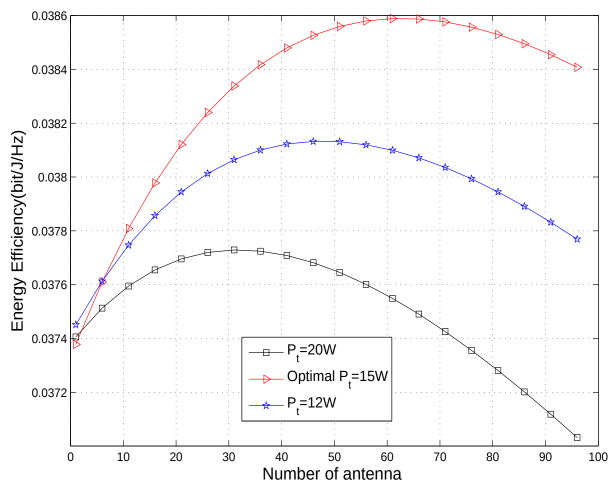

Fig. 4. Impact of number of selected antennas

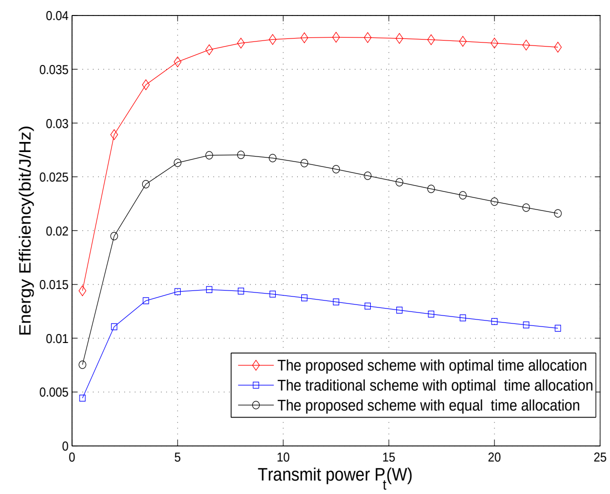

Fig. 6. EE vs. transmit power

the value of transmit power P_t. It shows that the EE of the considered system first increases and then decreases after reaching the maximum as the increase of the number of antennas, regardless of the value of transmit power level. Therefore, the number of used antenna needs to be optimized to enhance the system performance. Moreover, the results also reveal that the optimal antenna number is different for different values of transmit power. For example, the optimal $L^* = 45$ for the case that when transmit power is $12W$. However, when transmit power is $20W$, we can see $L^* = 35$. Meanwhile, it can be found that when power allocation (transmit power is $15W$) is optimal, the EE performance is better comparing to the case with bigger transmit power, which confirms the advantages of using the power allocation algorithm.

Fig. 5 demonstrates the influence of time allocation on the EE performance and present the EE performance with different transmit power P_t. The proposed antenna selection scheme is considered here. The result shows that there is an optimal value of first time slot τ for certain transmit power to maximize the EE. In general, with the increase of time τ, the system EE first increases, then reaches its optimal value and finally decreases. Such phenomenon can be observed for the cases with different values of transmit power. In addition, it can be seen that the optimal EE is different when different transmit power is advocated, which further evidences the effectiveness of proposed time and power allocation scheme. For example, when $P_t = 16W$, the optimal EE is higher than the one when $P_t = 12W$ and $P_t = 18W$. Furthermore, the proposed scheme is also compared with the one without antenna selection [3] which is marked as "traditional scheme". As we can see, our proposed scheme with different transmit power outperforms the traditional scheme, which confirms the necessity of using antenna selection to improve the EE.

Fig. 6 plots the EE by changing the transmit power P_t and allocated time slot τ. The performance of the proposed scheme with optimal time allocation is compared with the one

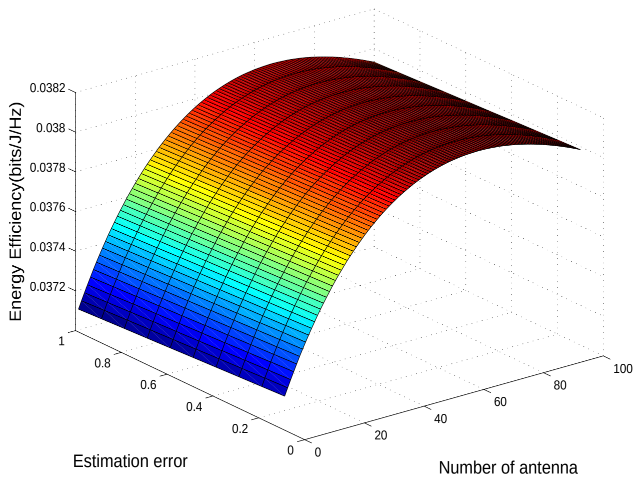

Fig. 7. EE vs. number of antenna and estimation error

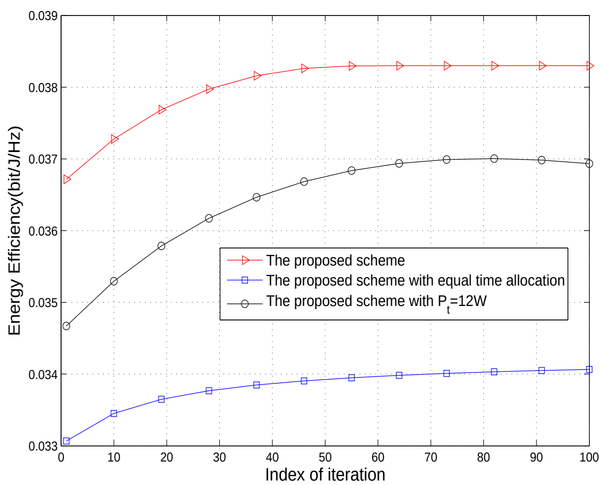

Fig. 8. Convergence performance

of traditional method with optimal time allocation, and the one of the proposed scheme with equal time allocation, e.g. $\tau = 1/2T$. By the comparison among these three curves, we can observe that with the increase of transmit power, the EE of the system first ascends and then descends. Similar to the results in Fig. 4, Fig. 6 shows that the transmit power has an optimal value, which confirms the advantages of power allocation scheme. Moreover, the proposed time allocation scheme can obtain additional EE gain when comparing with the equal time allocation scheme. We can also observe find that the EE of our proposed scheme with antenna selection is the highest among all three, which validates the effectiveness of the presented schemes.

In Fig. 7, The impacts of number of selected antenna L and estimation error σ_e^2 are illustrated. In this figure, the x-axis is the number of antennas, the y-axis is the estimation error, and the z-axis is the EE. From Fig. 7, we can observe that the EE first increases with the increased number of antennas and then decreases after reaching its optimum. While we can also see that the increment of the estimation error can also deteriorate the performance of the EE, which is similar to the Fig. 2.

Finally, in Fig. 8, the convergence performance of our proposed Algorithm 2 is presented. We also plot the EE performance of the proposed power allocation and antenna selection schemes considering an equal time allocation scheme, and the performance of the presented time allocation and antenna selection schemes with a fixed power allocation. The results demonstrate that the proposed scheme is able to converge to a stable stage within a few iterations, which evidences the convergence of the proposed scheme. We can also see that the proposed scheme can outperform the other two schemes in terms of EE and the one with equal time allocation has the worst performance.

V. Conclusion

In this work, an energy efficient optimization scheme for a large scale multiple antennas P2P system with wireless power transfer (WPT) is presented. Novel antenna selection, time allocation and power allocation schemes are presented to optimize the EE. We also take the imperfect CSI into account when designing the resource allocation schemes. Through extensive simulations, the effectiveness of our proposed schemes are validated and the impact of optimization variables on the system EE is also evaluated.

References

[1] P. Grover and A. Sahai, "Shannon meets tesla: wireless information and power transfer," *in Proc. of IEEE International Symposium on Information Theory*, Austin, TX, June 2010.

[2] H. Li, L. Song, and M. Debbah, "Energy efficiency of large-scale multiple antenna systems with transmit antenna selection," *IEEE Trans. Commun.*, vol. 62, no. 2, pp. 638-647, February 2014.

[3] X. Chen, X. Wang, and X. Chen, "Energy-efficient optimization for wireless information and power transfer in large-scale MIMO systems employing energy beamforming," *IEEE Wireless Commun. Lett.*, vol. 2, no. 6, pp. 667-670, December 2013.

[4] Y. Zeng and R. Zhang, "Full-duplex wireless-powered relay with self-energy recycling," *IEEE Wireless Commun. Lett.*, vol. 4, no. 2, pp. 201-204, April 2015.

[5] H. Chen, Y. Li, Y. Jiang, Y. Ma, B. Vucetic, "Distributed power splitting for SWIPT in relay interference channels using game theory", *IEEE Transactions on Wireless Communications*, vol. 14, no. 1, pp. 410-420, Jan. 2015.

[6] Y. Ma, H. Chen, Z. Lin, Y. Li and B. Vucetic, "Distributed and optimal resource allocation for power beacon-assisted wireless-powered communications", *IEEE Transaction on Communications*, vol. 63, no. 10, pp.3569-3583, Oct. 2015.

[7] W. Huang, H. Chen, Y. Li, and B. Vucetic, "On the performance of multi-antenna wireless-powered communications with energy beamforming," *IEEE Trans. Veh. Technol.*, vol. 65, no. 3, pp. 1801-1808, March 2016.

[8] Z. Chang, J. Gong, Y. Li, Z. Zhou, T. Ristaniemi, G. Shi, Z. Han and Z. Niu, "Energy efficient resource allocation for wireless power transfer enabled collaborative mobile clouds," *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 12, Dec. 2016.

[9] B. Hochwald, T. Marzetta, and V. Tarokh, "Multiple antenna channel-hardening and its implications for rate feedback and scheduleing," *IEEE Trans. Inf. Theory*, vol. 50, no. 9, pp. 1893-1909, September 2004.

[10] T. Ramya and S. Bhashyam, "Rate adaptation in MIMO antenna selection system with imperfect CSIT," *in Proc. 2010 COMSNETS*, Bangalore, India, January 2010.

[11] V. Kristem, and N. Mehta, "Receive antenna selection with imperfect channel knowledge from training," *in Proc. NCC*, IIT Guwahati, January 2009.

[12] T. Gucluoglu and E. Panayirci, "Performance of transmit and receive antenna selection in the presence of channel estimation errors," *IEEE Commun. Lett.*, vol. 12, no. 5, pp. 371-373, May 2008.

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

[14] Z. Xiang and M. Tao, "Robust beamforming for wireless information and power transmission," *IEEE Wireless Commun. Lett.*, vol. 1, no. 4, pp. 372-375, August 2012.

[15] M. Awad, V. Mahinthan, M. Mehrjoo, X. Shen, and J. Mark, "A dual-decomposition-based resource allocation for OFDMA networks with imperfect CSI," *IEEE Trans. Veh. Technol.*, vol. 59, no. 5, pp. 2394-2403, June 2010.

[16] Z. Chang, T. Ristaniemi, and Z. Niu, "Radio resource allocation for collaborative OFDMA relay networks with imperfect channel state information," *IEEE Trans. Wireless Commu.*, vol. 13, no. 5, pp. 2824-2835, May 2014.

[17] G. Yang, C. K. Ho, and Y. L. Guan, "Dynamic resource allocation for multiple-antenna wireless power transfer," *IEEE Trans. on Signal Proc.*, vol. 62, no. 14, pp. 3565-3577, July 2014.

[18] Z. Chang, Z. Wang, X. Guo, Z. Han and T. Ristaniemi, "Energy-efficient resource allocation for wireless powered massive MIMO System with imperfect CSI," *IEEE Transactions on Green Communications and Networking*, vol. 1, no. 2, June 2017.

[19] S. Cui, A. J. Goldsmith, and A. Bahai, "Energy-efficiency of MIMO and cooperative MIMO techniques in sensor networks," *IEEE Journal on Selected Areas in Commu.*, vol. 22, no. 6, pp. 1089-1098, June 2004.

[20] W. Dinkelbach, "On nonlinear fractional programming," *Management Science*, vol. 13, pp. 492-498, March 1967.

[21] C. Zhang, H. Zhao, W. Li, K. Zheng and J. Yang, "Energy efficiency optimization of simultaneous wireless information and power transfer system with power splitting receiver," *in proc. of IEEE PIMRC*, Washington, DC, Sep. 2014.

[22] P. Billingsley, *Probability and Measure*, 2nd ed. New York: Wiley, 1986.

[23] A. Gupta and D. Nagar, *Matrix Variate Distributions*. Boca Raton, FL: Chapman & Hall, 2000.

[24] Y. S. Chow and H. Teicher, *Probability Theory: Independence, Interchangeability, Martingales*. New York: Springer-Verlag, 1988.

[25] S. Stigler, "The asymptotic distribution of the trimmed mean," *The Annals of Statistics*, vol. 1, no. 3, pp. 472-477, May 1973.

[26] P. Hesami and J. Laneman, "Limiting behavior of receive antenna selection," *in Proc. 2011 Annual CISS*, Baltimore, MD, 23-25 March 2011.