Cooperative Energy Broadcasting System With Massive MIMO

Long Zhao and Kan Zheng, *Senior Member, IEEE*

***Abstract*—Different from information transmission, inter-cell interference benefits energy harvesting of energy users (EUs) in multi-cell scenario. Therefore, the objective of this letter is to maximize the average energy harvesting utility of multiple EUs by leveraging inter-cell cooperation. Considering channel state information (CSI) delay, a cooperative energy precoder with centralized implementation is first proposed when the energy stations (ESs) employ massive multiple-input multiple-output. Then, its distributed implementation is presented in terms of a local constraint at each ES and information exchange among ESs. Results indicate that the cooperative energy transfer significantly outperforms the non-cooperative energy transfer with either perfect or delay CSI, and the proposed energy precoder with proportional fairness utility can balance the harvested energy and fairness among different EUs.**

***Index Terms*—Massive MIMO, wireless energy transfer, precoder, cooperation.**

I. Introduction

WIRELESS energy transfer mainly includes two types, namely the near-field coupling based on inductive coils and the long-distance transfer based on radio-frequency [1], [2]. The second type is regarded as a promising technique for prolonging the lifetime of batteries and also for cutting the last mile limiting the "true wireless" communications [3]. However, the distance or efficiency of this type still can not satisfy the practical requirements of wireless communication systems. In order to improve the performance of energy transfer, massive multiple-input multiple-output (MIMO) has been employed for multi-user energy transfer with space-division multiple access (SDMA) [4], [5]. Taking advantage of the extremely narrow beams, the transfer efficiency has been significantly improved by massive MIMO [4], [6].

However, only a single energy station (ES) is considered for energy transfer in most of the current research [4], [5], multi-ES scenario is less studied for energy transfer compared with information transmission [7]. Different from information transmission, inter-cell interference can increase the energy harvesting of energy users (EUs) as of power superposition. Moreover, the Max-Min principle is generally employed for multiple EUs [5], [8], which guarantees the absolute fairness among EUs at the cost of energy transfer efficiency of the whole system. Another, the perfect channel state information (CSI) and estimated CSI are typically discussed for flat fading channel, and less attention was paid on the impact of time-varying channel or CSI delay [4], [5], [8].

Therefore, exploiting the inter-cell interference and noting the impact of CSI delay, the objective of this letter is to maximize the average energy harvesting utility of multiple EUs by cooperative energy transfer in multi-ES scenario. Based on the optimal energy precoder for single EU, namely the maximum ratio transmission (MRT) precoder [9], a centralized structure of energy precoder is first proposed and its expression is derived for cooperative energy transfer. Then its distributed implementation is presented in terms of a local constraint at each ES and information exchange among ESs.

Manuscript received March 24, 2016; accepted April 18, 2016. Date of publication April 22, 2016; date of current version June 8, 2016. This work was supported by the Fundamental Research Funds for the Central Universities, the National High-Tech R&D Program (863 Program 2015AA01A705), and China Natural Science Funding (61271183). The associate editor coordinating the review of this letter and approving it for publication was L. Wang.

The authors are with the Wireless Signal Processing and Network Laboratory, Beijing University of Posts and Telecommunications, Beijing 100876, China (e-mail: z.long.gm@gmail.com; zkan@bupt.edu.cn).

Digital Object Identifier 10.1109/LCOMM.2016.2557800

II. System Model and Problem Formulation

Consider an energy broadcasting system, where L ESs cooperatively serve K EUs with SDMA scheme. M-antenna ($M \gg 1$) and a single-antenna are employed by each ES and EU, respectively.

A. Channel Model

Denote $\mathbf{g}_{lk}(t) = \theta_{lk}^{1/2}\mathbf{h}_{lk}(t) \in \mathbb{C}^{M\times 1}$ as the channel vector from the kth EU to the lth ES in time t, where the large-scale fading θ_{lk} contains the path loss and shadow fading, and the fast fading vector $\mathbf{h}_{lk}(t) = \left[h_{lk,1}(t), h_{lk,2}(t), \cdots, h_{lk,M}(t)\right]^{\mathrm{T}} \sim \mathbb{CN}(0, \mathbf{I}_M)$. A time-varying channel is assumed in this letter and a delay channel model is adopted in consideration of the feedback delay in frequency-division duplex (FDD) system or the precessing delay in time-division duplex (TDD) system [10]. Then, the relation between $\mathbf{h}_{lk}(t)$ and $\mathbf{h}_{lk}(t-\tau)$ can be written as

$$\mathbf{h}_{lk}(t) = \rho(\tau)\mathbf{h}_{lk}(t-\tau) + \sqrt{1-\rho^2(\tau)}\mathbf{e}_{lk}(t), \quad (1)$$

where the error vector $\mathbf{e}_{lk}(t) \sim \mathbb{CN}(0, \mathbf{I}_M)$ is independent of channel $\mathbf{h}_{lk}(t-\tau)$ and the correlation coefficient $\rho(\tau) = \mathbb{E}\left[h_{lk,m}^{*}(t)\, h_{lk,m}(t-\tau)\right]$ follows Gaussian fading spectrum, namely $\rho(\tau) = \exp\left\{-\pi^2 f_{\mathrm{d}}^2 \tau^2\right\}$ with the maximum Doppler frequency shift f_{d} [10].

B. Transmission Model

On one hand, MRT is the optimal precoder for energy transfer [9]; on the other hand, the EUs only harvest energy from the radio frequency signals and do not demodulate the received signals, therefore different EUs can share the same modulation symbol s with $|s| = 1$. Thus, the proposed cooperative energy precoder can be expressed as $\mathbf{w}(\boldsymbol{\alpha}) = \left[\mathbf{w}_1^{\mathrm{T}}(\boldsymbol{\alpha}), \mathbf{w}_2^{\mathrm{T}}(\boldsymbol{\alpha}), \cdots, \mathbf{w}_L^{\mathrm{T}}(\boldsymbol{\alpha})\right]^{\mathrm{T}}$ with the global constraint $\|\mathbf{w}(\boldsymbol{\alpha})\|^2 = 1$ and the local precoder at the lth ES is given by

$$\mathbf{w}_l(\boldsymbol{\alpha}) = \sum_{k=1}^{K} \alpha_k \mathbf{g}_{lk}^{*}(t-\tau), \quad (2)$$

where $\boldsymbol{\alpha} = [\alpha_1, \alpha_2, \cdots, \alpha_K]^{\mathrm{T}}$ represents the combination coefficient vector of cooperative energy precoder.

When the total transmit power of all ESs is p/M, the received signal of the kth EU in time t is given by

$$y_k(\boldsymbol{\alpha}, t) = \sqrt{\frac{p}{M}} \sum_{l=1}^{L} \mathbf{g}_{lk}^{\mathrm{T}}(t)\, \mathbf{w}_l(\boldsymbol{\alpha})\, s + n_k(t), \tag{3}$$

where the additive white Gaussian noise $n_k(t) \sim \mathbb{CN}\left(0, \sigma^2\right)$.

C. Problem Formulation

Denoting η as the energy conversion efficiency, the harvested energy of the kth EU during the time range $[t_{\mathrm{m}}, t_{\mathrm{M}}]$ is given by

$$\mathcal{E}_k(\boldsymbol{\alpha}) = \eta \int_{t_{\mathrm{m}}}^{t_{\mathrm{M}}} \mathbb{E}\left[|y_k(\boldsymbol{\alpha}, \tau)|^2\right] \mathrm{d}\tau. \tag{4}$$

Considering the overall transfer efficiency and the fairness among different EUs, the proportional fairness (PF) utility [7] is employed in this letter and therefore the average energy harvesting utility of each EU is given by

$$U(\boldsymbol{\alpha}) = \frac{1}{K} \sum_{k=1}^{K} \log\left[\mathcal{E}_k(\boldsymbol{\alpha})\right]. \tag{5}$$

The objective of this letter is to maximize the average energy harvesting utility, namely

$$\max_{\boldsymbol{\alpha}} \ \{U(\boldsymbol{\alpha})\} \tag{6}$$

$$\text{s.t. } \|\mathbf{w}(\boldsymbol{\alpha})\|^2 = 1. \tag{7}$$

As the combination coefficients for the same EU at different ESs are the same, the precoders of different ESs in (2) are constructed by a central controller. Therefore, (6) is first solved for its centralized implementation in the next section and its distributed implementation is then presented in Sec. IV, respectively.

III. Centralized Energy Precoder

Considering the centralized implementation for energy precoder, we have the following theorem.

Theorem 1: The optimal combination coefficients of the cooperative energy precoder in problem (6) are given by

$$\alpha_k = \sqrt{\frac{1}{M}\left(\sum_{l=1}^{L}\theta_{lk}\right)^{-1}\left[\frac{1}{\lambda K} - \frac{\sigma^2}{p\bar{\rho}^2}\left(\sum_{l=1}^{L}\theta_{lk}\right)^{-1}\right]^{+}}, \tag{8}$$

where $[x]^{+} = \max\{0, x\}$, the Lagrange multiplier λ is determined by equation $M\sum_{k=1}^{K}\left(\alpha_k^2 \sum_{l=1}^{L}\theta_{lk}\right) = 1$, and the average of quadratic correlation coefficient $\bar{\rho}^2 = \left[\mathrm{erf}\left(\sqrt{2}\pi f_{\mathrm{d}} t_{\mathrm{M}}\right) - \mathrm{erf}\left(\sqrt{2}\pi f_{\mathrm{d}} t_{\mathrm{m}}\right)\right] \Big/ \left[2\sqrt{2\pi} f_{\mathrm{d}}(t_{\mathrm{M}} - t_{\mathrm{m}})\right]$ with Gaussian error function $\mathrm{erf}(x) = \frac{2}{\sqrt{\pi}}\int_0^x \exp\left(-t^2\right)\mathrm{d}t$.

Proof: The energy harvesting expression is first derived and then the solution to problem (6) is presented in this proof.

According to the properties of massive MIMO, namely channel harden phenomenon, i.e., $\frac{1}{M}\mathbf{g}_{lk}^{\mathrm{T}}(t)\,\mathbf{g}_{lk}^{*}(t) \to \theta_{lk}$, and asymptotic orthogonality, i.e., $\frac{1}{M}\mathbf{g}_{lk}^{\mathrm{T}}(t)\,\mathbf{g}_{li}^{*}(t) \to 0$ $(i \neq k)$, for large M [6], we obtain

$$\begin{aligned}\sum_{l=1}^{L}\mathbf{g}_{lk}^{\mathrm{T}}(t)\,\mathbf{w}_l(\boldsymbol{\alpha}) &= \sum_{l=1}^{L}\mathbf{g}_{lk}^{\mathrm{T}}(t)\sum_{i=1}^{K}\alpha_i \mathbf{g}_{li}^{*}(t-\tau)\\ &\approx M\alpha_k\rho(\tau)\sum_{l=1}^{L}\theta_{lk},\ M \gg 1.\end{aligned} \tag{9}$$

On the other hand, the average of quadratic correlation coefficient is given by

$$\bar{\rho}^2 = \frac{\int_{t_{\mathrm{m}}}^{t_{\mathrm{M}}} \mathrm{e}^{-2\pi^2 f_{\mathrm{d}}^2\tau^2}\mathrm{d}\tau}{t_{\mathrm{M}} - t_{\mathrm{m}}} = \frac{\mathrm{erf}\left(\sqrt{2}\pi f_{\mathrm{d}} t_{\mathrm{M}}\right) - \mathrm{erf}\left(\sqrt{2}\pi f_{\mathrm{d}} t_{\mathrm{m}}\right)}{2\sqrt{2\pi} f_{\mathrm{d}}(t_{\mathrm{M}} - t_{\mathrm{m}})}. \tag{10}$$

Then, substituting (3) into (4) and taking advantage of (9) and (10) give rise to the harvested energy of the kth EU, i.e.,

$$\mathcal{E}_k(\boldsymbol{\alpha}) = \eta(t_{\mathrm{M}} - t_{\mathrm{m}})\left[pM\bar{\rho}^2\alpha_k^2\left(\sum_{l=1}^{L}\theta_{lk}\right)^2 + \sigma^2\right]. \tag{11}$$

Based on the channel harden phenomenon and asymptotic orthogonality of massive MIMO, (7) can be rewritten as

$$M\sum_{k=1}^{K}\left(\alpha_k^2\sum_{l=1}^{L}\theta_{lk}\right) = 1,\ M \gg 1. \tag{12}$$

Therefore, in terms of (5), (11) and (12), the Lagrange function of (6) is then expressed as

$$\begin{aligned}\mathcal{L}(\boldsymbol{\alpha};\lambda) = &-\frac{1}{K}\sum_{k=1}^{K}\log\left[pM\bar{\rho}^2\alpha_k^2\left(\sum_{l=1}^{L}\theta_{lk}\right)^2 + \sigma^2\right]\\ &-\log\left[\eta(t_{\mathrm{M}} - t_{\mathrm{m}})\right] + \lambda\left[M\sum_{k=1}^{K}\left(\alpha_k^2\sum_{l=1}^{L}\theta_{lk}\right) - 1\right],\end{aligned} \tag{13}$$

and the first-order partial derivative of $\mathcal{L}(\alpha;\lambda)$ with respect to α_k satisfies

$$\frac{\partial\mathcal{L}(\boldsymbol{\alpha};\lambda)}{2M\alpha_k\partial\alpha_k} = -\frac{1}{K}\frac{1}{M\alpha_k^2 + \frac{\sigma^2}{p\bar{\rho}^2}\left(\sum_{l=1}^{L}\theta_{lk}\right)^{-2}} + \lambda\sum_{l=1}^{L}\theta_{lk}. \tag{14}$$

Letting $\partial\mathcal{L}(\boldsymbol{\alpha};\lambda)/\partial\alpha_k = 0$ [11] leads to (8) and considering (12) results in the theorem. ■

Based on theorem 1, the Lagrange multiplier λ should be first obtained in order to construct the centralized energy precoder. On one hand, assuming the EUs in set $\{1, 2, \cdots, \tilde{K}\}$ $(\tilde{K} \leq K)$ have positive combination coefficients for the optimal energy transfer, i.e., $\alpha_k > 0$ $(k \leq \tilde{K})$, substituting (8) into (12) leads to

$$\lambda\left(\tilde{K}\right) = \left[1 + \frac{\sigma^2}{p\bar{\rho}^2}\sum_{k=1}^{\tilde{K}}\left(\sum_{l=1}^{L}\theta_{lk}\right)^{-1}\right]^{-1}; \tag{15}$$

On the other hand, if the kth EU with $\sum_{l=1}^{L}\theta_{lk}$ has positive combination coefficient, the jth EU with $\sum_{l=1}^{L}\theta_{lj}$

Algorithm 1 Centralized Energy Precoder

Initialization:

- All ESs send the large-scale fading, namely $\{\theta_{lk}\}$, to the central controller.
- The controller rearranges EUs according to $\sum_{l=1}^{L}\theta_{lk}$ in decreasing order.
- The controller sets the initial number of EUs with positive combination coefficients $\tilde{K}=0$.

Do { **Step 1**: $\tilde{K}=\tilde{K}+1$.
Step 2: Compute $\lambda(\tilde{K})$ based on (15).
Step 3: Calculate $\alpha_{\tilde{K}}$ based on (8) and $\lambda(\tilde{K})$. }
While $\{\tilde{K}<K$ and $\alpha_{\tilde{K}}>0\}$
if $\alpha_{\tilde{K}}=0$, let $\tilde{K}=\tilde{K}-1$; **Else** $\tilde{K}=K$.
With the obtained $\tilde{K}$, the central controller calculates $\lambda(\tilde{K})$ based on (15), then computes $\alpha_k (k=1,2,\cdots,K)$ based on (8), and further transmits α_k $(k=1,2,\cdots,K)$ to all ESs.

$(\geq \sum_{l=1}^{L}\theta_{lk})$ should also have positive combination coefficient according to (8). Thus, a low-complexity implement of the centralized energy precoder is given in Alg. 1 based on the above discussion and linear searching method.

According to the steps of Alg. 1, the complexity is $\mathcal{O}(K)$ and there is no accuracy error compared with the traditional water-filling algorithms [11].

IV. Distributed Energy Precoder

Equation (7) of problem (6) is a global constraint, therefore the energy precoder $\mathbf{w}(\boldsymbol{\alpha})$ with (8) is a centralized scheme and should be constructed in a centralized controller. By contrast, a distributed implementation of energy precoder is proposed in terms of a local constraint at each ES in this section. The local constraint is given by $\|\mathbf{w}_l(\boldsymbol{\alpha}_l)\|^2=p_l/p$ $(l=1,2,\cdots,L)$, where $\boldsymbol{\alpha}_l=[\alpha_{l1},\alpha_{l2},\cdots,\alpha_{lK}]^{\mathrm{T}}$ contains the combination coefficients of the local precoder $\mathbf{w}_l(\boldsymbol{\alpha}_l)$ at the lth ES, and p_l/M represents the power consumed by the lth ES and satisfies the total power constraint $\sum_{l=1}^{L}p_l=p$.

In terms of the channel harden phenomenon and the asymptotic orthogonality of massive MIMO, for large M, the local constraint can be rewritten as

$$M\sum_{k=1}^{K}\alpha_{lk}^2\theta_{lk}=\frac{p_l}{p},(l=1,2,\cdots,L). \tag{16}$$

When all ESs assume $\{p_l/M, l=1,2,\cdots,L\}$ as the optimal power allocation, i.e., $\alpha_k=\alpha_{lk}$ $(l=1,2,\cdots,L)$, the combination coefficients of problem (6) with the local constraint (16), i.e., the combination coefficients obtained at the lth ES, are given as follows taking advantage of Lagrange method,

$$\alpha_{lk}=\sqrt{\frac{1}{M}\left(\sum_{l=1}^{L}\theta_{lk}\right)^{-1}\left[\frac{1}{\lambda_l K}-\frac{\sigma^2}{p\bar{\rho}^2}\left(\sum_{l=1}^{L}\theta_{lk}\right)^{-1}\right]^{+}}, \tag{17}$$

where the Lagrange multiplier λ_l satisfies (16).

Denote $\Lambda=\{\lambda_1,\lambda_2,\cdots,\lambda_L\}$, and further $\lambda_{l_{\mathrm{m}}}=\min_l\{\Lambda\}$ and $\lambda_{l_{\mathrm{M}}}=\max_l\{\Lambda\}$. In order to make $\alpha_{lk}=\alpha_{ok}$, $\forall l$, $o\in\{1,2,\cdots,L\}$ and $\forall k\in\{1,2,\cdots,K\}$, $\lambda_{l_{\mathrm{m}}}$ should approximate to $\lambda_{l_{\mathrm{M}}}$ by noting that α_{lk} is a monotonically decreasing function of λ_l in terms of (17); on the other hand, λ_l increases with the decreasing p_l based on (16) and (17), then we should decrease p_j and simultaneously increase p_i if $\lambda_j<\lambda_i$. Therefore, initialized by equal power allocation, a distributed implementation of cooperative energy precoder is given in Alg. 2 based on the exchange of λ_l $(l=1,2,\cdots,L)$ among ESs.

Algorithm 2 Distributed Energy Precoder

Initialization $(t=0)$**:**

- Tolerable error $\varepsilon>0$, adjustable power ratio $\delta^0\in(0,1)$ and initial power allocation $p_l^0=p/L$ $(l=1,2,\cdots,L)$.
- All ESs exchange the large-scale fading, namely $\{\theta_{lk}\}$.
- Using Alg. 1, the lth $(\in\{1,2,\cdots,L\})$ ES calculates λ_l^0 by (16) and (17), then broadcasts λ_l^0 to other ESs. Therefore, each ES obtains the vector $\Lambda^0=\left[\lambda_1^0,\lambda_2^0,\cdots,\lambda_K^0\right]^{\mathrm{T}}$.

Do { **Step 1**: Each ES calculates $l_{\mathrm{m}}^t=\arg\min\left\{\Lambda^{t-1}\right\}$ and $l_{\mathrm{M}}^t=\arg\max\left\{\Lambda^{t-1}\right\}$.
Step 2: The ESs in cells $\left\{l_{\mathrm{m}}^t,l_{\mathrm{M}}^t\right\}$ update $p_{l_{\mathrm{m}}^t}^t=p_{l_{\mathrm{m}}^t}^{t-1}-p\delta^{t-1}$ and $p_{l_{\mathrm{M}}^t}^t=p_{l_{\mathrm{M}}^t}^{t-1}+p\delta^{t-1}$, respectively.
Step 3: Using Alg. 1, the jth $\left(\in\left\{l_{\mathrm{m}}^t,l_{\mathrm{M}}^t\right\}\right)$ ES calculates λ_j^t by (16) and (17), then broadcasts λ_j^t to other ESs.
Step 4: **If** $l_{\mathrm{M}}^{t-1}=l_{\mathrm{m}}^t$ or $l_{\mathrm{m}}^{t-1}=l_{\mathrm{M}}^t$ {Each ES updates $\delta^t=\delta^{t-1}/2$, $\Lambda^t=\Lambda^{t-1}$, $p_{l_{\mathrm{m}}^t}^t=p_{l_{\mathrm{m}}^t}^{t-1}$ and $p_{l_{\mathrm{M}}^t}^t=p_{l_{\mathrm{M}}^t}^{t-1}$.}
Else {Each ES updates $\delta^t=\delta^{t-1}$, and Λ^t with $\lambda_{l_{\mathrm{m}}^t}^t$, $\lambda_{l_{\mathrm{M}}^t}^t$, $\lambda_l^t=\lambda_l^{t-1}\left(l\neq l_{\mathrm{m}}^t,l_{\mathrm{M}}^t\right)$.}
}
While $\max\left\{\Lambda^t\right\}-\min\left\{\Lambda^t\right\}\geq\varepsilon$
Suppose $\left\{\lambda_j, j=1,2,\cdots,L\right\}$ is globally optimal, the lth ES constructs $\mathbf{w}_l(\boldsymbol{\alpha}_l)$ with $\{\alpha_{lk}\}$ and transmits the signal $\mathbf{x}_l=\sqrt{p/M}\,\mathbf{w}_l(\boldsymbol{\alpha}_l)\,s$.

In Alg. 2, Step 2 can keep the total transmit power of all ESs constant and the objective of the "If" statement in Step 4 is to avoid the ping-pong phenomenon between ES l_{m} and ES l_{M}. Moreover, we have $\lim_{t\to\infty}(\lambda_{l_{\mathrm{M}}}^t-\lambda_{l_{\mathrm{m}}}^t)\to 0$ with the tolerable error $\varepsilon\to 0$, and then $\lambda_{l_{\mathrm{m}}}^t\leq\lambda_l^t\leq\lambda_{l_{\mathrm{M}}}^t$ $(t=0,1,2,\cdots)$ leads to $\lambda=\lambda_l$ $(l=1,2,\cdots,L)$. Hence, the L local constraints are equivalent to the global constraint (12), and the distributed energy precoder converges to the centralized energy precoder.

V. Numerical Results

A. Parameter Setup

In the simulation, the number of antennas at each ES $M=256$, the normalized noise power $\sigma^2=1$, the signal-to-noise ratio $p/(M\sigma^2)=15+10\log_{10}(L)$ dB, the energy conversion efficiency $\eta=0.8$, the maximum Doppler frequency shift $f_{\mathrm{d}}=20$ Hz, $t_{\mathrm{m}}=1$ ms and $t_{\mathrm{M}}=6$ ms. The large-scale fading $\theta_{lk}=10^{-3}d_{lk}^{-3}\xi_{lk}$ with d_{lk} (in meters) being the distance between the kth EU and the lth ES, and the shadow fading $10\log_{10}(\xi_{lk})\sim\mathbb{N}(0,8\text{ dB})$. Apart form the inner circle region with radius 1 m, 5 EUs are uniformly distributed in each hexagon cell with the side length 10 m, and there is an

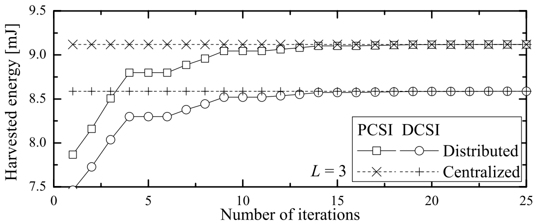

Fig. 1. Convergence of the distributed energy precoder.

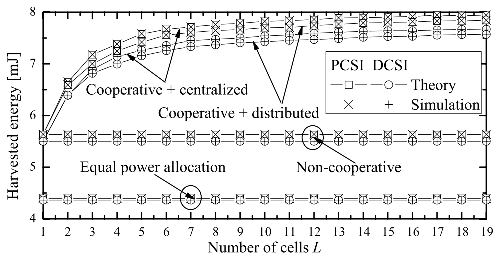

Fig. 2. Harvested energy versus the number of cells.

ES in the center of each hexagon cell. "PCSI" and "DCSI" represent the energy precoders are formed by "perfect CSI" and "delay CSI" in the following figures, respectively.

B. Convergence of Distributed Energy Precoder

When the number of cooperative cells $L = 3$ and the initially adjustable power ratio $\delta^0 = 1/K = 1/15$, the convergence of the distributed energy precoder is illustrated in Fig. 1 with one-time realization of EU distribution. With the increase of iteration number under PCSI or DCSI, the average harvested energy per EU of the distributed energy precoder gradually increases and eventually converges to that of the centralized energy precoder, which validates the convergence of the distributed implementation of energy precoder.

C. Comparison Among Different Energy Transfer Schemes

Fig. 2 shows the average harvested energy per EU versus the number of cooperative cells under different schemes. The combination coefficients of energy precoder are $\alpha_{lk} = 1\Big/\sqrt{MK\theta_{lk}}$ and (8) with $L = 1$ for the equal power allocation scheme and the non-cooperative energy transfer scheme, respectively. The initial values $\delta^0 = 1/K$ and $\varepsilon = 10^{-5}$ for the distributed energy precoder. From Fig. 2, the simulation results and the theoretical results coincide to each other; the proposed energy precoder performs better than the equal power allocation; the cooperative energy transfer outperforms the non-cooperative energy transfer; DCSI significantly deteriorates the energy harvesting performance compared to PCSI; the performance of the distributed energy precoder approximates to that of the centralized energy precoder. However, for cooperative energy transfer schemes, the overhead increases and the gain of harvested energy diminishes with the increasing number of cooperative cells, therefore adjacent cell cooperation is a more practical solution for the cooperative energy transfer.

Suppose $\sum_{l=1}^{L} \theta_{lk}$ as the large-scale fading of the kth EU, the power allocation with Max-Min criterion in [5] can be extended to cooperative energy transfer in multi-ES scenario. When the ESs cooperatively transmit energy to the EU with $\max_k\{\sum_{l=1}^{L} \theta_{lk}\}$, the power allocation with maximum channel gain (MaxCG) criterion in [9] can also be extended to cooperative energy transfer in multi-ES scenario. With the same parameter setup in Fig. 2, Fig. 3 illustrates the harvested energy and fairness performance of different criterions with PCSI. The fairness is quantified by Jain's fairness index, which is defined by $\mathcal{F} = (\sum_{k=1}^{K} \mathcal{E}_k)^2/(K\sum_{k=1}^{K} \mathcal{E}_k^2)$ [12]. Compared to the power allocation with MaxMin or MaxCG criterion, the proposed energy precoder with PF criterion can balance the harvested energy and fairness among different EUs.

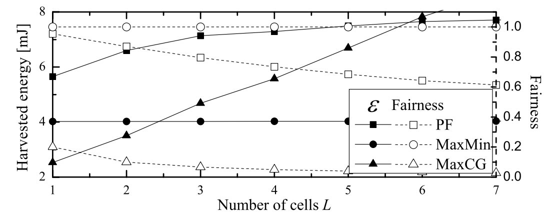

Fig. 3. Harvested energy and fairness performance of different schemes.

VI. Conclusion

This letter studies the cooperative energy transfer in order to improve the average energy harvesting utility of multiple EUs in multi-ES scenario. When massive MIMO is employed at each ES, a cooperative energy precoder is proposed with centralized implementation and distributed implementation, respectively. Results indicate that the cooperative energy transfer performs better than the non-cooperative energy transfer, and can balance the energy harvesting and fairness performance compared with other schemes.

References

[1] A. Massa, G. Oliveri, F. Viani, and P. Rocca, "Array designs for long-distance wireless power transmission: State-of-the-art and innovative solutions," *Proc. IEEE*, vol. 101, no. 6, pp. 1464–1481, Jun. 2013.

[2] S. Bi and R. Zhang, "Placement optimization of energy and information access points in wireless powered communication networks," *IEEE Trans. Wireless Commun.*, vol. 15, no. 3, pp. 2351–2364, Mar. 2016.

[3] K. Huang and X. Zhou, "Cutting the last wires for mobile communications by microwave power transfer," *IEEE Commun. Mag.*, vol. 53, no. 6, pp. 86–93, Jun. 2015.

[4] S. Kashyap, E. Björnson, and E. G. Larsson, "On the feasibility of wireless energy transfer using massive antenna arrays," *IEEE Trans. Wireless Commun.*, doi: 10.1109/TWC.2016.2521739.

[5] G. Yang, C. K. Ho, R. Zhang, and Y. L. Guan, "Throughput optimization for massive MIMO systems powered by wireless energy transfer," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 8, pp. 1640–1650, Aug. 2015.

[6] K. Zheng, L. Zhao, J. Mei, B. Shao, W. Xiang, and L. Hanzo, "Survey of large-scale MIMO systems," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 3, pp. 1738–1760, Third Quarter 2015.

[7] W. Xu and X. Wang, "Pricing-based distributed downlink beamforming in multi-cell OFDMA networks," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 9, pp. 1605–1613, Oct. 2012.

[8] L. Zhao, X. Wang, and K. Zheng, "Downlink hybrid information and energy transfer with massive MIMO," *IEEE Trans. Wireless Commun.*, vol. 15, no. 2, pp. 1309–1322, Feb. 2016.

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

[10] Y. Ma, D. Zhang, A. Leith, and Z. Wang, "Error performance of transmit beamforming with delayed and limited feedback," *IEEE Trans. Wireless Commun.*, vol. 8, no. 3, pp. 1164–1170, Mar. 2009.

[11] S. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge, U.K.: Cambridge Univ. Press, 2004.

[12] R. K. Jain, D.-M. W. Chiu, and W. R. Hawe, "A quantitative measure of fairness and discrimination for resource allocation in shared computer systems," Eastern Res. Lab., Digit. Equip. Corp., Hudson, MA, USA, Tech. Rep. DEC-TR-301, Sep. 1984.