Downlink Base Station Cooperation with Energy Harvesting

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Abstract—**This paper considers a downlink cellular network with two base stations (BSs) powered by harvested energy that cooperatively serve two users. To tackle the problem that BSs are of different energy arrival rates, in each transmission block, the time is divided into to fractions, i.e., one of the BSs keeps silent for some time to store energy while the other transmits to one of the users, and then they perform zero-forcing joint processing (ZF-JP) in the rest time of the block. We propose an algorithm to optimize the sum rate by jointly deciding which BS should store the energy, how long does it keep silent, and how much transmit power should be used in single BS transmission mode and ZF-JP mode. Simulation results show that the proposed algorithm can achieve much higher sum rate compared with the ZF-JP only scheme, and the gain increases as the difference between BSs' energy arrival rates grows.**

I. INTRODUCTION

Wireless communications with energy harvesting technology, which exploits the renewable energy to support wirless devices, is expected as one of the promising technologies to meet the target of green communications in the future. The advantages of energy harvesting include the sustainability with renewable energy source, and the flexibility of network deployment without power line, which also reduces the cost for network planning. Recently, wireless cellular networks with renewable energy is rapidly developing. For instance, China Mobile has built about 12,000 renewable energy powered base stations (BSs) [1]. However, there are some challenges of energy harvesting based communications, including: the energy shortage due to the causality of energy arrival, the mismatch between the energy profile and the traffic profile or the channel condition, and etc.

In the literature, energy harvesting based communications have attracted many recent research efforts. For single-link case, the power allocation structure, *directional water-filling*, is found in both SISO channel [2] and MIMO channel [3]. The research efforts are further extended to the network case, and the power allocation policies are studied in broadcast channel [4], multiple access channel [5], interference channel [6], as well as relay networks [7]. Nevertheless, there lacks related work about the effect of energy harvesting on the multi-node cooperation (i.e., network MIMO). Although the network MIMO technology with conventional non-energy harvesting case has been extensively studied in [8], [9], [10], and has already been standardized in 3GPP as Coordinated Multi-Point (CoMP) [11], how the dynamic energy arrival influences its performance still remains open. The various energy arrival rates introduces asymmetric power constraints, and the energy storage property further complicates the power allocation.

In this paper, we try to effectively allocate the harvested energy to maximize the system sum data rate. We consider two BSs serving two users. Due to the asymmetric per-BS power constraints, the harvested energy may not be fully utilized in CoMP transmission mode. To tackle this problem, we divide each transmission frame into two subframes. In the first subframe, one of the BSs serves one user while the other stores energy. In the second subframe, the two BSs perform joint processing (JP) to simultaneously serve the two users. With the stored energy, the power gap between two BSs is filled, and hence, CoMP can achieve higher capacity. We solve the sum rate maximization problem by jointly deciding which BS to store energy in the first subframe, and adjusting the length of the subframes and the transmit power in each subframe. Simulations are run to evaluate the proposed transmission algorithm compared with the conventional CoMP technology.

The rest of the paper is organized as follows. Section II describes the system model and the problem formulation. In Section III, the optimization problem is solved in each frame. Simulation study is presented in Section IV. Finally, Section V concludes the paper.

Notations: Bold upper case and lower case letters denote matrices and vectors, respectively. $|\cdot|$ denotes the absolute value of a scalar, and $[x]^+ = \max\{x, 0\}$. $(\cdot)^T$ and $(\cdot)^H$ denote the transpose and transpose conjugate of a matrix, respectively. $\mathbb{E}$ represents the expectation operation.

II. SYSTEM MODEL AND PROBLEM FORMULATION

We consider a wireless communication network consisting of two BSs powered by renewable energy (e.g. solar energy, wind energy, etc.) and two users as shown in Fig. 1. Assume

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This work is sponsored in part by the National Science Foundation of China (NSFC) under grant No. 61201191, the National Basic Research Program of China (973 Program: 2012CB316001), the Creative Research Groups of NSFC under grant No. 61321061, and Hitachi R&D Headquarter.

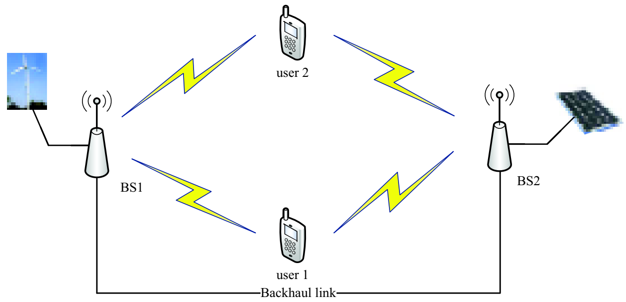

Fig. 1. System model for joint processing with 2 BSs and 2 users.

the BSs have a battery with infinite capacity to store the harvested energy. All the BSs and the users are equipped with single antenna. The BSs are interconnected via an error-free backhaul link sharing all the data and the channel state information, so that they can perform JP to eliminate the interference. The users are assumed located at the cell boundary so that their average channel gains are comparable, which is the typical scenario to apply CoMP. The wireless channel is assumed block fading, i.e., the channel state is constant during each fading block, but changes from block to block. The perfect channel state information are assumed known to the BSs at the beginning of each block via some training and feedback scheme. In the i-th fading block, if the JP technique is utilized, the received signals $\mathbf{y}_i = [y_{i,1}, y_{i,2}]^T$ at the users is

$$\mathbf{y}_i = \mathbf{H}_i \mathbf{W}_i \mathbf{x}_i + \mathbf{n}_i, \tag{1}$$

where $\mathbf{H}_i$ is the channel matrix with components $h_{i,jk}, 1 \leq j, k \leq 2$ indicating the channel coefficient from BS k to user j, $\mathbf{W}_i$ is the precoding matrix with components $w_{i,kj}, 1 \leq k, j \leq 2$, $\mathbf{x}_i = [x_{i,1}, x_{i,2}]^T$ is the intended signals for the users with $\mathbb{E}(\mathbf{x}_i \mathbf{x}_i^H) = \text{diag}(p_{i,1}, p_{i,2})$, where $p_{i,j}, j = 1, 2$ is the power allocated to user j, and $\mathbf{n}_i$ is the additive white Gaussian noise with zero mean and variance $\mathbb{E}(\mathbf{n}_i \mathbf{n}_i^H) = \sigma_n^2 \mathbf{I}$, where $\mathbf{I}$ is a 2×2 unit matrix.

In this paper, zero-forcing (ZF) precoder is adopted to completely mitigate the interference. Specifically, we have

$$\mathbf{W}_i = \mathbf{H}_i^H [\mathbf{H}_i \mathbf{H}_i^H]^{-1}. \tag{2}$$

Hence, the data rate is

$$R_{i,j} = \log_2(1 + \frac{p_{i,j}}{\sigma_n^2}) \tag{3}$$

with per-BS power constraint

$$\sum_{j=1}^{2} |w_{i,kj}|^2 p_{i,j} \leq P_{i,k}, \quad k = 1, 2. \tag{4}$$

where $P_{i,k}$ is the maximum available transmit power of BS k in fading block i. As the BSs are powered by the renewable energy, $P_{i,k}$ is constrained by the energy harvesting rate. As was pointed out in [7], [12] that in real systems, the energy harvesting rate changes in a much slower speed than the channel fading. Specifically, the fading block in current wireless communication systems is usually measured in the time scale of milliseconds, while the renewable energy such as solar power may keep constant for at least several seconds. Hence, the energy harvesting rate can be assumed constant over a sufficient number of fading blocks, denoted by $E_k, k = 1, 2$. The value of E_k is assumed i.i.d. for different k. In this paper, we mainly focus on a single energy harvesting period, i.e., the energy harvesting rate is constant.

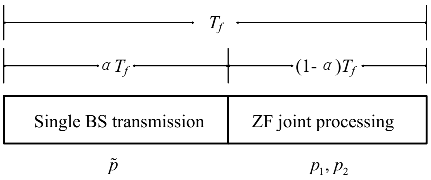

Fig. 2. Frame structure. The frame length is T_f.

We aim to maximize the sum-rate of the system with JP under energy harvesting power constraints. Notice that JP may not always be sum-rate optimal as the energy harvesting rates of the two BSs are i.i.d. For instance, if the channel conditions are similar, and one BS higher energy harvesting rate comparing with the other, its energy storage may tend to infinity if JP is always applied. It may be more efficient to firstly serve the two users by the former in single BS transmission mode, and then operate JP when the latter stores enough energy. Based on this intuition, we rename the fading block as the transmission frame, and further divide each transmission frame into to two subframes as shown in Fig. 2. The frame length is T_f. In the first subframe with length $\alpha_i T_f, 0 \leq \alpha_i \leq 1$, one of the BSs $k_i \in \{1, 2\}$ selects one of the users to transmit data according to some scheduling policy, and the other BS denoted by $\bar{k}_i \neq k_i$ keeps silent to store energy. We adopt the proportional fair scheduling policy [13]. Specifically, the user j^* is scheduled when satisfying

$$j^* = \arg \max_{1 \leq j \leq 2} \frac{\bar{R}_{i,j}}{T_{i,j}}, \tag{5}$$

where $\bar{R}_{i,j} = \log_2(1 + \bar{P}|h_{i,jk_i}|^2/\sigma_n^2)$ is the expected data rate of user j with transmit power $\bar{P} = E_{k_i}$, and $T_{i,j}$ is the average throughput which is updated as

$$T_{i+1,j} = \begin{cases} (1-\frac{1}{\tau})T_{i,j} + \frac{1}{\tau}(1-\alpha_i)R_{i,j}, & j \neq j^* \\ (1-\frac{1}{\tau})T_{i,j} + \frac{1}{\tau}(\alpha_i \tilde{R}_{i,j} + (1-\alpha_i)R_{i,j}), & j = j^* \end{cases} \tag{6}$$

where the parameter τ is the fairness factor, $\tilde{R}_{i,j}, R_{i,j}$ is the actual data rate in the first and the second subframe, respectively. Then in the second subframe with length $(1-\alpha_i)T_f$, the two BSs jointly transmit to the two users with ZF-JP as explained earlier in this section.

Now we describe the power constraints. The available energy in the battery of BS k at the beginning of each frame i is denoted by $B_{i,k}$. Then the power in the first subframe satisfies

$$\tilde{p}_i \leq \frac{B_{i,k_i}}{\alpha_i T_f} + E_{k_i}. \tag{7}$$

At the beginning of the second subframe, the available energy in the two BSs become $B_{i,k_i}+\alpha_i T_f E_{k_i}-\alpha_i T_f \tilde{p}_i$ and $B_{i,\bar{k}_i}+\alpha_i T_f E_{\bar{k}_i}$, respectively. As a result, the power constraint (4) for ZF-JP becomes

$$\sum_{j=1}^{2}|w_{i,k_i j}|^2 p_{i,j} \le \frac{B_{i,k_i}+\alpha_i T_f(E_{k_i}-\tilde{p}_i)}{(1-\alpha_i)T_f}+E_{k_i}, \tag{8}$$

$$\sum_{j=1}^{2}|w_{i,\bar{k}_i j}|^2 p_{i,j} \le \frac{B_{i,\bar{k}_i}+\alpha_i T_f E_{\bar{k}_i}}{(1-\alpha_i)T_f}+E_{\bar{k}_i}. \tag{9}$$

The battery energy states are updated according to

$$B_{i+1,k_i}=B_{i,k_i}+T_f(E_{k_i}-\alpha_i\tilde{p}_i-(1-\alpha_i)\sum_{j=1}^{2}|w_{i,k_i j}|^2 p_{i,j}), \tag{10}$$

$$B_{i+1,\bar{k}_i}=B_{i,\bar{k}_i}+T_f(E_{\bar{k}_i}-(1-\alpha_i)\sum_{j=1}^{2}|w_{i,\bar{k}_i j}|^2 p_{i,j}), \tag{11}$$

with initial state $B_{1,k_i}=B_{1,\bar{k}_i}=0$. In (7), (8), and (9), we have $0<\alpha<1$ as the denominator can not be zero. We can reform the constraints so that $\alpha=0,1$ is also included. Our optimization problem can be formulated as

$$\max_{k_i,\alpha_i,\tilde{p}_i,p_{i,j}} \mathbb{E}_{\mathbf{H}}\left[\frac{1}{N}\sum_{i=1}^{N}\left(\alpha_i\tilde{R}_{i,j^*}+(1-\alpha_i)\sum_{j=1}^{2}R_{i,j}\right)\right] \tag{12}$$

$$\begin{aligned}
\text{s.t. } & \alpha_i(\tilde{p}_i-E_{k_i}) \le \frac{B_{i,k_i}}{T_f},\\
& (1-\alpha_i)\sum_{j=1}^{2}|w_{i,k_i j}|^2 p_{i,j}+\alpha_i\tilde{p}_i \le \frac{B_{i,k_i}}{T_f}+E_{k_i},\\
& (1-\alpha_i)\sum_{j=1}^{2}|w_{i,\bar{k}_i j}|^2 p_{i,j} \le \frac{B_{i,\bar{k}_i}}{T_f}+E_{\bar{k}_i},\\
& 0 \le \alpha_i \le 1.
\end{aligned}$$

where $\tilde{R}_{i,j^*}=\log_2(1+\tilde{p}_i|h_{i,j^*k_i}|^2/\sigma_n^2)$, $R_{i,j}$ is expressed as (3), N is the number of frames which satisfies that NT_f is less than an energy harvesting period. The optimization parameters include the transmit power $\tilde{p}_i, p_{i,k}, k=1,2$, the frame division parameter α_i, and the selection of BSs k_i for non-cooperative transmission. To find the optimal solution, we need to calculate the integration of the channel distribution over N frames and exhaustively search all the possible power allocation and frame division policies, which is computationally overwhelming. In the work, we reform the problem into a per-frame optimization to find some properties of the power allocation. The solution for the original problem (12) will be left for future work.

III. PER-FRAME RESOURCE ALLOCATION OPTIMIZATION

As mentioned above, the original problem (12) is difficult to be solved. Hence, we firstly try to solve the sum rate maximization problem in each frame based on the current channel information and energy battery state. For simplicity, we ignore the time index i in the rest of the paper. The per-frame optimization problem can be formulated as

$$\max_{k,\alpha,\tilde{p},p_j} \alpha\log_2\left(1+\frac{\tilde{p}|h_{j^*k}|^2}{\sigma_n^2}\right)+(1-\alpha)\sum_{j=1}^{2}\log_2\left(1+\frac{p_j}{\sigma_n^2}\right) \tag{13}$$

$$\text{s.t. } \alpha(\tilde{p}-E_k) \le \frac{B_k}{T_f}, \tag{14}$$

$$(1-\alpha)\sum_{j=1}^{2}|w_{1j}|^2 p_j+\alpha\tilde{p} \le \frac{B_k}{T_f}+E_k, \tag{15}$$

$$(1-\alpha)\sum_{j=1}^{2}|w_{2j}|^2 p_j \le \frac{B_{\bar{k}}}{T_f}+E_{\bar{k}}, \tag{16}$$

$$0 \le \alpha \le 1. \tag{17}$$

As $k\in\{1,2\}$, the optimization over k can be done by solving the problem for all k, and selecting the one with larger sum rate. In the rest of this section, we assume k is fixed, and discuss the properties of the problem (13). The optimal policy for the given k is denoted by $\alpha^*,\tilde{p}^*$, and $p_j^*, j=1,2$. Firstly, we have the following observation:

Proposition 1. *For any given k and α, the problem (13) with constraints (14) - (16) is a convex optimization problem.*

Proof. Once α is fixed, the objective function is the maximization of a sum of concave functions, and all the constraints are linear. As a result, the problem is convex. ☐

Proposition 1 tells us that for a given k, the optimal solution can be found by a one-dimensional search over $0\le\alpha\le 1$ and for each α solving a convex optimization problem to find the optimal power allocation policy. The detailed solution is described in Algorithm 1.

Algorithm 1 Per-frame optimization algorithm

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1:  Set $R^* = 0$.
2:  for all $k = 1$ to 2 do
3:      Set $\alpha = 0$.
4:      while $\alpha \le 1$ do
5:          With fixed $k,\alpha$, solve the convex optimization problem (13) to find the maximum sum rate $R(k,\alpha)$ and the power allocation policy $\tilde{p},p_1,p_2$.
6:          if $R(k,\alpha) > R^*$ then
7:              Set $R^* = R(k,\alpha), k^* = k, \alpha^* = \alpha, \tilde{p}^* = \tilde{p}, p_1^* = p_1, p_2^* = p_2$.
8:          end if
9:          Update the time fraction by $\alpha + \delta\alpha \to \alpha$.
10:     end while
11:     The optimal policy $k^*,\alpha^*,\tilde{p}^*,p_1^*,p_2^*$ is found.
12: end for
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Notice that $\delta\alpha$ is the exhaustive search granularity of α, which in real system is determined by the length of the minimum transmission time unit. For the convex optimization in step 5, we can adopt the classic algorithm proposed in [14]. Next we examine the KKT conditions [14] and discuss the properties of the problem. Define the Lagrangian function for any multipliers $\lambda \geq 0, \mu \geq 0, \eta \geq 0$ as

$$\begin{aligned}\mathcal{L} = & -\Bigg(\alpha\log_2\Big(1+\frac{\tilde{p}|h_{j^*k}|^2}{\sigma_n^2}\Big)+(1-\alpha)\sum_{j=1}^{2}\log_2\Big(1+\frac{p_j}{\sigma_n^2}\Big)\Bigg)\\ & + \lambda\Big(\alpha(\tilde{p}-E_k)-\frac{B_k}{T_f}\Big)\\ & + \mu\Big((1-\alpha)\sum_{j=1}^{2}|w_{1j}|^2p_j+\alpha\tilde{p}-(\frac{B_k}{T_f}+E_k)\Big)\\ & + \eta\Big((1-\alpha)\sum_{j=1}^{2}|w_{2j}|^2p_j-(\frac{B_{\bar{k}}}{T_f}+E_{\bar{k}})\Big) \qquad (18)\end{aligned}$$

with additional complementary slackness conditions

$$\lambda\Big(\alpha(\tilde{p}-E_k)-\frac{B_k}{T_f}\Big)=0, \qquad (19)$$

$$\mu\Big((1-\alpha)\sum_{j=1}^{2}|w_{1j}|^2p_j+\alpha\tilde{p}-(\frac{B_k}{T_f}+E_k)\Big)=0, \qquad (20)$$

$$\eta\Big((1-\alpha)\sum_{j=1}^{2}|w_{2j}|^2p_j-(\frac{B_{\bar{k}}}{T_f}+E_{\bar{k}})\Big)=0. \qquad (21)$$

Notice that we ignore the non-negative power constraints in the above formulation for simplicity. It can be directly added to the result. We apply the KKT optimality conditions to the Lagrangian function (18). By setting $\partial\mathcal{L}/\partial\tilde{p}=\partial\mathcal{L}/\partial p_j=0$, we obtain

$$\tilde{p}^* = \left[\frac{1}{\lambda+\mu}-\frac{\sigma_n^2}{|h_{j^*k}|^2}\right]^+, \qquad (22)$$

$$p_j^* = \left[\frac{1}{\mu|w_{1j}|^2+|w_{2j}|^2\eta}-\sigma_n^2\right]^+, j=1,2. \qquad (23)$$

Notice that to guarantee the validity of (23), either μ or η should be non-zero, which means that at least one of (15) and (16) is satisfied with equality. As a result, we have the following conclusion.

Proposition 2. *If the optimal policy for the problem (13) is applied in each frame, at the beginning of each frame, at least one of the energy batteries is empty.*

Proof. If $\alpha^*=1$, the optimal power allocation policy is simple: $\tilde{p}^*=B_k/T_f+E_k$. It results in an empty battery of BS k at the beginning of the next frame.

If $\alpha<1$, ZF-JP is performed in the second subframe. Thus, at least one of (15) and (16) is satisfied with equality, otherwise, we can always increase p_1^* or p_2^* to obtain a higher sum rate. As a result, at least one of the batteries is empty. □

Based on Proposition 2, to maximize per-frame sum rate, the BSs will greedily use their harvested energy in each frame, i.e., at least one of the batteries does not remain any energy. Compared with the joint optimization over N frames, such an per-frame optimization policy losses the degree of freedom in time domain. Hence, the performance may degrade due to the greedy energy usage. However, the complexity of the problem is greatly reduced.

Proposition 3. *Denote* $\tilde{R}(\tilde{p})=\log_2\left(1+\frac{\tilde{p}|h_{j^*k}|^2}{\sigma_n^2}\right)$, $R(p_1,p_2)=\sum_{j=1}^{2}\log_2\left(1+\frac{p_j}{\sigma_n^2}\right)$. *If* $B_k=0$ *and* $0<\alpha^*<1$, *we have*

$$\tilde{R}(\tilde{p}^*) \leq R(p_1^*,p_2^*). \qquad (24)$$

Proof. The proposition can be proved by contradiction. If the optimal policy $\alpha^*,\tilde{p}^*,p_1^*,p_2^*$ satisfies $\tilde{R}(\tilde{p}^*)>R(p_1^*,p_2^*)$, we can increase α^* by $\Delta\alpha$ ($\alpha^*+\Delta\alpha\leq 1$) without violating any constraints. Specifically, it is obvious that (14) and (17) hold. Since for a fixed $\tilde{p}^*\leq E_k$, $(E_k-\alpha\tilde{p}^*)/(1-\alpha)$ in an nondecreasing function of α, the constraint (15) is still satisfied for $\alpha^*+\Delta\alpha,\tilde{p}^*,p_1^*,p_2^*$. Similarly, the constraint (16) also holds. However, the sum rate

$$\begin{aligned}&(\alpha^*+\Delta\alpha)\tilde{R}(\tilde{p}^*)+(1-\alpha^*-\Delta\alpha)R(p_1^*,p_2^*)\\ =&\alpha^*\tilde{R}(\tilde{p}^*)+(1-\alpha^*)R(p_1^*,p_2^*)+\Delta\alpha(\tilde{R}(\tilde{p}^*)-R(p_1^*,p_2^*))\\ >&\alpha^*\tilde{R}(\tilde{p}^*)+(1-\alpha^*)R(p_1^*,p_2^*),\end{aligned}$$

i.e., $\alpha^*,\tilde{p}^*,p_1^*,p_2^*$ is not the optimal policy, which contradicts the assumption. □

An immediate conclusion from Proposition 3 is that if $\tilde{R}(\tilde{p})>R(p_1,p_2)$, we should increase the time length of the first subframe until $\alpha=1$ or $\tilde{R}(\tilde{p})\leq R(p_1,p_2)$ to achieve the maximum sum rate. As a result, the ZF-JP transmission mode can obtain data rate gain only when it is better than single BS transmission. Once a BS is of very low energy arrival rate, pure ZF-JP ($\alpha=0$) performance greatly degrades and single BS transmission is necessary.

Finally, we propose a conjecture that if $B_k=0$, the optimal transmit power $\tilde{p}^*$ in the first subframe should be equal or close to E_k. The intuition is that the single-BS transmission benefits when the constraint (15) is loose for $\alpha=0$. In this case, increasing α on the one hand increase the power for the second subframe as (16) becomes loose, on the other hand obtain additional rate from the first subframe. And it is obvious that $\tilde{p}^*=E_k$ when (15) is still loose. Once (15) becomes tight, one may keep on increasing the sum rate by increasing α and slightly reducing $\tilde{p}$ so that the power for the second subframe can increase, but there is not much room for adjustment. We will justify this conjecture through simulations.

IV. SIMULATION STUDY

We study the performance of the proposed base station cooperation scheme by simulations. We adopt the outdoor pico-cell physical channel model from 3GPP standard [15]. The BSs are equipped with energy harvesting devices (e.g. solar panels). The pathloss is PL $=140.7+36.7\log_{10}d$ (dB), where the distance d is measured in km. The inter-distance between pico BSs is 100m. The shadowing fading follows log-normal distribution with variance 10dB. The small-scale fading follows Rayleigh distribution with zero mean and unit variance. The average SNR at the cell edge (50m to the pico BS) with transmit power 30dBm is set to 10dB. We set the two

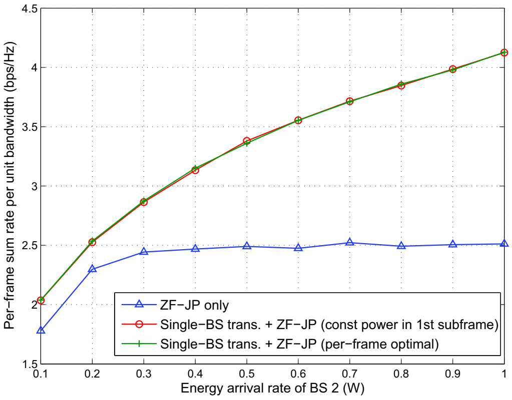

Fig. 3. Per-frame sum rate performance versus energy arrival rate with $B_1 = B_2 = 0$ for every frame simulation.

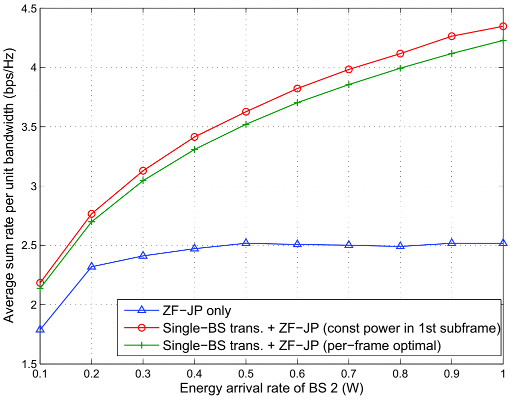

Fig. 4. Average sum rate performance versus energy arrival rate with B_1, B_2 updated in the end of each frame.

users are placed in the cell edge of the two pico BSs depicted in Fig. 1. Hence, they experience the same large-scale fading. We fix the energy arrival rate of BS 1 as 0.1W, and change that of BS 2.

Firstly, we justify our conjecture that when $B_k = 0$, $\tilde{p}^*$ should be equal or close to E_k. We set $B_1 = B_2 = 0$ for each frame, and compare the power allocation $\tilde{p} = E_k$ in the first subframe with the per-frame optimization result. The result is shown in Fig. 3. It can be seen that setting $\tilde{p} = E_k$ achieves the same sum rate with the per-frame optimal solution, which validates our conjecture. In addition, the proposed policy achieves much higher sum rate compared with using ZF-JP in the whole frame, and the gap grows as the energy arrival asymmetry increases.

In addition, we evaluate the performance of the proposed algorithm for the original problem considering the energy storage between frames. Surprisingly, as shown in Fig. 4, the policy with constant power $\tilde{p} = E_k$ in the first subframe performs better than the per-frame optimal policy. As the per-frame optimal policy is not optimal any more when considering frame correlation due to energy storage, further study on the optimal policy for the original problem (12) is required in the future work.

V. CONCLUSION

In this paper, we have proposed a BS cooperation scheme that divides a transmission block to firstly apply single-BS transmission and then adopt ZF-JP transmission to enhance the sum rate of CoMP technique with energy harvesting. We have solved the per-frame optimization problem by one-dimensional search and convex optimization. The proposed algorithm has been shown to achieve much higher sum rate compared with the ZF-JP only scheme. As the energy arrival asymmetry increases, the achievable rate of ZF-JP saturates (2.5bps/Hz in our settings), while the proposed policy reveals a logarithmic increase. As the simulation has shown that when evaluating the average sum rate with energy storage, the per-frame optimal solution performs worse than the simple policy that fixes the power in the first subframe, future work should consider the policy design targeting at average sum rate optimization.

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